APPENDIX A

Notice of Preparation, Initial Study, and Comment Letters

County of San Diego

MARK WARDLAW
DIRECTOR

PLANNING & DEVELOPMENT SERVICES
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KATHLEEN A. FLANNERY
ASSISTANT DIRECTOR

NOTICE OF PREPARATION DOCUMENTATION

DATE: February 14, 2019

PROJECT NAME: BOULDER BRUSH GEN-TIE LINE AND SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT

PROJECT NUMBER(S): PDS2019-MUP-19-002

PROJECT APPLICANT: BOULDER BRUSH, LLC

ENV. REVIEW NUMBER: PDS2019-ER-19-16-001

PROJECT DESCRIPTION:
Boulder Brush, LLC proposes an overhead 230 kilovolt (kV) gen-tie transmission line, a substation to increase the voltage to 500 kV, and a switchyard on private land under the jurisdiction of the County of San Diego. The gen-tie line would carry wind energy from a proposed wind energy project ("Campo Wind Project" or "Project") on the Campo Indian Reservation ("Reservation") to the existing Sunrise Powerlink. The portion of the gen-tie line on private land would be approximately 3.5 miles in length, and would include 32 steel poles at a maximum height of 150 feet. The applicant also proposes permanent and temporary access roads, temporary staging areas, and a temporary concrete batch plant. Project construction on private land is anticipated to last approximately 9 months. Eventual decommissioning would occur at the end of the Project's useful life. The facilities proposed on private land require one or more Major Use Permits (MUPs) from the County. Primary access is provided from Interstate 8 (I-8) with local access through Ribbonwood Road. Although the majority of the Campo Wind Project is not within the County's jurisdiction and is not subject to the County's land use regulations, the Project for CEQA purposes is considered to be all facilities required for the development of the Campo Wind Project.

PROJECT LOCATION:
The development footprint of the proposed facilities under the County's land use jurisdiction consists of approximately 200 acres in the southeastern portion of unincorporated San Diego County. The facilities would be located entirely on private land in the McCain Valley area, north of the community of Boulevard and Interstate 8 (I-8). The area is located within the Boulevard Subregional Planning Area of the Mountain Empire Subregional Plan area. The site is largely undeveloped ranch land, a portion of which is grazed by cattle. The surrounding area includes two large commercial wind projects, and rural residential homes and ranches. Regional access to the Project site is provided by I-8, and local access is provided by Ribbonwood Road. Land

ownership surrounding the Project site consists of a mixture of private, State of California, Bureau of Land Management, and tribal lands. The wind energy facilities on the Reservation would consist of approximately 60 turbines and related infrastructure on 2,200 acres within the Reservation. The Bureau of Indian Affairs issued a Notice of Intent (NOI) to Prepare an Environmental Impact Statement for the Proposed Campo Wind Energy Project, San Diego, California on November 21, 2018 (see 83 Federal Register 58785). A more complete description of the proposal on the Reservation is contained in the NOI.

A separate application has been filed for a MUP to construct a wind energy project ("Torrey Wind Project") on some of the same parcels on which the gen-tie line, substation and switchyard would be constructed. If the Torrey Wind Project is approved, it would share the substation and switchyard with the Campo Wind Project to reduce environmental impacts. The County is preparing a separate EIR for the Torrey Wind Project.

PROBABLE ENVIRONMENTAL EFFECTS:
The probable environmental effects associated with the Project are detailed in the attached Environmental Initial Study. All questions answered "Potentially Significant Impact" or "Less than Significant with Mitigation Incorporated" will be analyzed further in the Environmental Impact Report. All questions answered "Less than Significant Impact" or "Not Applicable" will not be analyzed further in the Environmental Impact Report. The following is a list of the subject areas to be analyzed in the EIR and the particular issues of concern:

- Aesthetics
- Agricultural Resources
- Air Quality
- Biological Resources
- Cultural Resources
- Energy
- Geology & Soils
- Greenhouse Gas Emissions
- Hazards and Hazardous Materials
- Hydrology & Water Quality
- Land Use & Planning
- Noise
- Public Services
- Transportation & Traffic
- Tribal Cultural Resources
- Utilities & Service Systems
- Wildfire
- Mandatory Findings of Significance

Please note that the Notice of Preparation signifies the beginning of the EIR review and public participation process. At the same time, the County contemplates further agency and public input as the Project proceeds through the County's environmental review process. During this process and before public circulation of the Draft EIR, the County anticipates some changes or additions to the Project, its description, and probable impacts in response to this Notice of Preparation, the comments received at the scoping meeting, and ongoing County staff input as it independently reviews the Project application and supporting documents. The iterative process is a necessary part of the County's EIR review process. However, the County does not anticipate circulating any new or revised Notices of Preparation for the Project provided the project-related changes or additions do not trigger substantial changes in the Project or its circumstances, or present new information of substantial importance as defined by CEQA. Instead, the Draft EIR that will be circulated for agency and public review will provide all interested entities and parties the opportunity to further comment on the Project and its probable environmental impacts when submitting public comments on the Draft EIR. Those comments also will be the subject of written responses that will be included in the Final EIR.

PUBLIC SCOPING MEETING:
Consistent with Section 21083.9 of the CEQA Statutes, a public scoping meeting will be held to solicit comments on the EIR. This meeting will be held on February 28, 2019, at 6:00 p.m. at the County Fire Authority Boulevard Fire Station, 40080 Ribbonwood Road, Boulevard.

Comments on this Notice of Preparation must to be sent to Bronwyn Brown, Planning and Development Services, 5510 Overland Avenue, Suite 310, San Diego, CA 92123 or by email to Bronwyn. Brown@sdcounty.ca.gov. Comments must be received no later than **March 18, 2019 at 4:00 p.m.** (a 30-day public review period). This Notice of Preparation can also be reviewed at the Jacumba Branch Library, 44605 Old Highway 80, Jacumba.

Attachments:
Project Location Map
Environmental Initial Study

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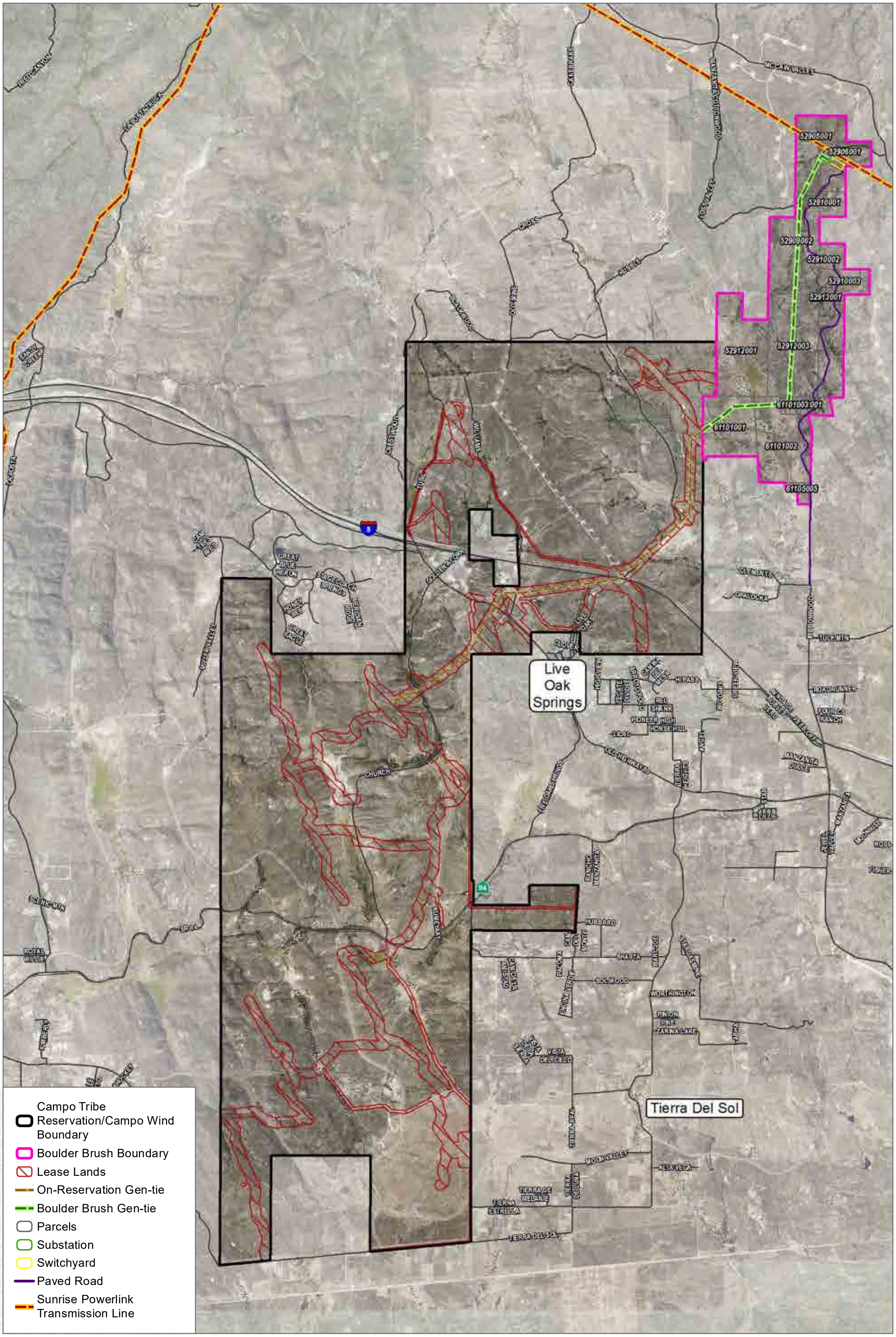

SOURCE: SANGIS 2017

DUDEK

0 2,000 4,000 Feet

FIGURE 1

Project Location Map

Campo Wind and Boulder Brush Facilities

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CEQA Initial Study - Environmental Checklist Form (Based on the State CEQA Guidelines, Appendix G)

1. Project Name:

   Boulder Brush Gen-Tie Line and Switchyard Facilities for the Campo Wind Project; PDS2019-MUP-19-002

2. Lead agency name and address:
   County of San Diego, Planning & Development Services
   5510 Overland Avenue, 3rd Floor
   San Diego, California 92123

3. a. Contact: Bronwyn Brown, Project Manager
   b. Phone number: (858) 495-5375
   c. E-mail: Bronwyn.brown@sdcounty.ca.gov

4. Project location:

   The development footprint of the proposed Boulder Brush facilities for which an application has been received by the County of San Diego (County) consists of approximately 200 acres within in the southeastern portion of San Diego County. The facilities under County jurisdiction are on private land in the McCain Valley area, north of the community of Boulevard and Interstate 8 (I-8) and are intended to interconnect the Campo Wind Project ("Campo Wind Project" or "Project") proposed on the nearby Campo Indian Reservation ("Reservation") to the electric grid. Although the majority of the Campo Wind Project is not within the County's jurisdiction and is not subject to the County's land use regulations, the Project for CEQA purposes is considered to be the Campo Wind Project, including the Boulder Brush facilities on private lands. The private land proposed to contain the Boulder Brush infrastructure for the Campo Wind Project is undeveloped, a portion of which is grazed by cattle. The surrounding area includes two commercial wind energy projects, and rural residential homes and ranches scattered throughout the region. Regional access to the Project site is provided by I-8. Local access is provided by Ribbonwood Road. Land ownership in the surrounding area consists of a mixture of private, State of California, Bureau of Land Management (BLM), and tribal lands. Project facilities on the Reservation include up to 60 turbines on approximately 2,200 acres and associated infrastructure.

5. Project Applicant name and address:

Boulder Brush, LLC, 11455 El Camino Real, Suite 160, San Diego, California 92130

6. General Plan

Community Plan:	Mountain Empire Subregional Plan
Land Use Designation:	Rural Lands 80 (RL-80)
Density:	1 du/80 acres
Floor Area Ratio (FAR)	N/A

7. Zoning

Use Regulation:	S92 (General Rural)
Minimum Lot Size:	8 acres
Special Area Regulation:	N/A/ “A”

8. Description of project:

The applicant proposes to construct an overhead 230 kilovolt (kV) gen-tie transmission line, a substation to increase the voltage to 500 kV, and a switchyard on private land under the jurisdiction of the County. The gen-tie line would carry wind energy from the Campo Wind Project proposed on the Reservation to the existing Sunrise Powerlink transmission line. The proposed wind energy facilities on the Reservation are under the jurisdiction of the Bureau of Indian Affairs (BIA). Although the majority of the Campo Wind Project is not within the County's jurisdiction and is not subject to the County's land use regulations, the EIR will include appropriate analysis of environmental impacts of the Project as a whole. The BIA is preparing an Environmental Impact Statement (EIS) to analyze the impacts of the Campo Wind Project, including the facilities on private land. The environmental analysis in that EIS will inform and be part of the County's analysis of the Project in the EIR. The portion of the proposed gen-tie line on private land under County jurisdiction would be approximately 3.5 miles in length and would include 32 steel poles at a maximum height of 150 feet. The proposed substation and switchyard would be located adjacent to the existing Sunrise Powerlink. The proposed Project also includes permanent and temporary access roads, temporary staging areas, and a temporary concrete batch plant. Primary access to the facilities on private land would be provided from Interstate 8 (I-8) with local access through Ribbonwood Road. The facilities would require one or more Major Use Permits (MUPs) from the County of San Diego and other permits as described herein, or any other approvals necessary or desirable to implement the Project. Project construction on private land is anticipated to last approximately 9 months. Eventual decommissioning would occur at the end of the Project's useful life. Project facilities on the Reservation include up to 60 turbines and associated infrastructure on approximately 2,200 acres. The proposed facilities are described further in the Bureau of Indian Affair's (BIA) Notice of Intent (NOI) to Prepare an Environmental Impact Statement for the Proposed Campo Wind Energy Project, San Diego, California, 11/21/18 (see 83 Federal Register 58785).

Relationship to Torrey Wind Project
On a portion of the same private lands on which the gen-tie line, substation and switchyard would be built, the County has received a separate application for the development of the Torrey Wind Project. If approved, the Torrey Wind Project would be developed independently of the Campo Wind Project but proposes to share the substation and switchyard to reduce environmental impacts.

An analysis of the substation and switchyard will be contained in this EIR, as well as in the Torrey Wind EIR. These private land facilities are also part of the project description in the BIA's Environmental Impact Statement for the Campo Wind Project.

Boulder Brush Components

The Boulder Brush facilities include the following components to be constructed and operated on private land:

- Overhead 230 kV gen-tie transmission line
- 500 kV substation
- Switchyard and In and out 500 kV connection legs between the Sunrise Powerlink and the switchyard
- Permanent access roads
- Temporary improvements, including access roads, staging areas, and a concrete batch plant

Gen-Tie Transmission Line
An overhead 230 kV gen-tie transmission line is proposed to carry wind energy generated by the proposed Campo Wind Project to a proposed substation adjacent to the Sunrise Powerlink. The total gen-tie line is 8.5 miles; however, 5 miles of the gen-tie line is located on the Campo Indian Reservation and not subject to County jurisdiction. The portion of the gen-tie line on private land under the County's jurisdiction would be approximately 3.5 miles in length and would include approximately 32 steel poles. The steel poles would accommodate an optical ground wire for fiber-optic and ground wire for communications. The height of the steel poles would vary by location up to a maximum height of 150 feet. The average footprint for each pole construction pad would be approximately 100 feet by 150 feet. Lighting on poles would only be installed if required by the Federal Aviation Administration (FAA).

Substation
A substation is proposed to increase the voltage received from the Campo Wind Project from 230 kV to 500 kV. As discussed above, the substation would

also be used by the proposed Torrey Wind Project, which is the subject of a separate application pending before the County. The substation would be located on private land adjacent to the existing Sunrise Powerlink transmission line. The substation equipment would include a transformer that would be connected through circuit breakers to a jumper link located within the fenced boundary of the substation to deliver power to the point of interconnection. Most of the equipment at the substation would feature a low-reflectivity finish to minimize glare. Dull-colored insulators would be used to minimize visibility.

The substation site would also include a control house and a parking area for utility vehicles. The cleared area around the substation would be covered with gravel. Security fencing (8 feet in height) would be installed around the perimeter of the substation site. Outdoor nighttime lighting at the substation would be required for security and safety, but lighting would be hooded, directed downward, and turned off when not required. The substation itself would be approximately 220 feet by 350 feet (1.8 acres) and would be located within an approximately 5 to 10-acre fenced area. A 30-foot fuel modification zone would be provided around the perimeter of the switchyard. The substation would generally be an un-staffed facility except for maintenance and repair activities.

Switchyard

The applicant would construct a new 500 kV switchyard to allow connection of the Campo Wind Project to the existing Sunrise Powerlink so that the power generated can access the transmission grid. As discussed above, the substation would also be used by the proposed Torrey Wind Project, if approved. The switchyard would be approximately 330 feet by 701 feet (5.4 acres). The switchyard site would be approximately 7.2 acres. Security fencing would be installed around the perimeter of the substation site. A 30-foot fuel modification zone would be provided around the perimeter of the switchyard. A lot line adjustment is proposed to create a separate parcel for the switchyard. After construction is complete, the switchyard would be transferred to SDG&E. SDG&E would construct the loop in lines that would connect the switchyard to the Sunrise Powerlink. The switchyard would be an un-staffed facility except for maintenance and repair activities.

Roads

Primary access to the site is and would continue to be provided from I-8 with local access through Ribbonwood Road. A new permanent 30-foot wide paved access road is proposed to provide access to the switchyard and substation. In addition, a portion of Ribbonwood not currently paved (approximately one mile) would be paved as part of the proposed project.

Permanent access roads to the gen-tie line would be 16-feet wide with a decompacted gravel surface. A fuel modification zone would be required on either side of the access roads.

Turbines and Related Facilities on the Campo Reservation

Project facilities on the Reservation include up to 60 turbines and associated infrastructure on approximately 2,200 acres under tribal and BIA jurisdiction. The Campo Wind Project facilities on the Reservation are described in the Notice of Intent to prepare an EIS dated November 21, 2018 (see 83 Federal Register 58785). The County has no jurisdiction over the turbines and related facilities on the Reservation.

Construction

Construction of the Boulder Brush facilities on private land is anticipated to last approximately 9 months. It is anticipated that operations would begin by the end of 2020. Construction would involve the following tasks:

Substation and Switchyard

Work would begin with construction of the new access road to the proposed substation and switchyard. Construction of the switchyard/substation would begin with clearing vegetation and organic material from the site. The site would then be excavated to frame and pour foundations. Structural footings, along with electrical conduit and grounding grid would be installed, followed by aboveground structures and equipment. A chain-link fence would be constructed around the new switchyard/substation for security and to restrict unauthorized persons and wildlife from entering the facility.

Gen-Tie Transmission Line

Work would begin with the construction of new access roads to the gen-tie line steel pole structure areas. The gen-tie line access roads would be graded level and generally be 16 feet wide for straight sections and up to 20 feet wide at curves to allow the safe access of construction equipment and vehicles. Access roads to the gen-tie line structures would remain as 16-foot wide graveled roads.

Engineered steel poles would be drilled on pier foundations for turning or deadend structures, and directly embedded structures for tangential poles. Holes would be drilled using a truck-mounted auger or similar equipment. Where required for pier foundations, steel cages and anchor bolt cages would be set in the open hole for reinforcement. Directly embedded structures would be backfilled with native excavated material or light concrete mixture, depending on specific conditions for each pole site. Any remaining excavated material would be placed around the holes or spread onto access roads, or adjacent areas as shown in the Project plans. Cranes would be used to erect the steel poles. The poles would be assembled on-site.

Installation of the new 230 kV conductor would require pull sites along the gen-tie line route. Generally, pull sites would be approximately 100 feet by 150 feet and would be required where 230 kV angle structures are located. The pull sites would be needed to load the tractors and trailers with reels of conductors and the trucks with tensioning equipment.

After the conductor has been pulled into place, the sag between the structures would be adjusted to a pre-calculated level and the line would then be installed. The conductor would then be attached to the end of each insulator, the sheaves would be removed, and the vibration dampers and other accessories would be installed.

Temporary Staging Areas and Batch Plant
Temporary staging areas would be used to stage and store components, construction equipment, and construction materials. The batch plant would generate concrete for construction of the steel pole foundations and other Project related improvements. Sand, aggregate, concrete, and water would be delivered to the temporary batch plant and stored in stock-piles until use.

Work Force
Construction of the gen-tie and switchyard facilities on private land may require up to 48 employees per day during the peak construction period. Construction activities would occur during daytime hours, at least 6 days per week, but may involve extended hours, as needed, to complete certain construction activities.

Construction Access for Right-of-Way
The primary construction access and haul route into the site would be from Ribbonwood Road. Construction contractors would post signs on public roads, alerting the public of increased heavy construction traffic. When possible, delivery times would be planned around local peak travel periods to avoid congestion.

Water Quantities
During construction water is expected to be required, primarily for dust suppression, concrete foundation mixing, and compaction in case of direct embedded structures. Water would be sourced from either on-site groundwater wells, if sufficient yield can be demonstrated, and/or non-potable water from local water purveyors such as Jacumba Community Services District or Padre Dam Municipal Water District.

Turbines and Related Facilities on the Campo Reservation
The turbines and related facilities on the Reservation are under the jurisdiction of the Tribe and the BIA. The County has no jurisdiction over the turbines and related facilities on the Reservation. Construction would involve site preparation, foundations construction, turbine installation, and construction of related infrastructure including an operations and maintenance (O&M) building. Water would be needed for dust suppression and concrete mixing. Construction would require approximately 14 months to complete. The Campo Wind Project facilities on the Reservation are described in the Notice of Intent to prepare an EIS dated November 21, 2018. (see 83 Federal Register 58785).

Operation and Maintenance

Substation and Switchyard
The substation and switchyard would generally be unstaffed facilities except for maintenance activities. The substation would be owned and operated by Boulder Brush, LLC. The ownership of the switchyard would be transferred to SDG&E for operation after construction.

The substation and switchyard would be unstaffed. All monitoring and control functions would be performed remotely. Routine operation would require a single pickup truck visiting the substation and switchyard several times a week for switching. Construction and maintenance truck would visit the substation several times a year for equipment maintenance. Maintenance activities would include equipment testing, equipment monitoring and repair, and emergency and routine procedures for service continuity. No water use is expected to be required during operation.

Lighting would be installed inside the substation and switchyard fenced areas for the purpose of emergency repair work. Since nighttime maintenance activities are not expected to occur more than once per year, the safety lighting inside the substation fence would normally be turned off. Some of the perimeter lighting in would remain on all night for safety purposes.

Gen-Tie Transmission Line
Boulder Brush, LLC would own and operate the gen-tie transmission line. During operations, the gen-tie line would be regularly inspected, maintained, and repaired. Operations and maintenance activities would involve both routine preventive maintenance and emergency procedures to maintain service continuity. Aerial and ground inspections of the facilities would be performed. Aboveground components would be inspected annually, at a minimum, for corrosion, equipment misalignment, loose fittings, and other common mechanical problems.

Turbines and Related Facilities on the Campo Reservation
Operations and maintenance would include activities associated with the O&M building, and routine maintenance, inspections, and periodic repairs of the turbines, gen-tie line, and related facilities. The Campo Wind Project facilities on the Campo Indian Reservation are described in the Notice of Intent to prepare an EIS dated November 21, 2018. (see 83 Federal Register 58785). The County has no jurisdiction over the operations and maintenance of the turbines and related facilities on the Reservation.

Decommissioning

The lifespan of the Boulder Brush facilities would be at least 30 years. The decommissioning of the gen-tie line and substation would be governed by the terms and conditions of the Major Use Permit. Bonding and a decommission plan would be required. The decommissioning plan would be developed in compliance with the County standards and requirements for closing a site and restoration of disturbed areas at the time decommissioning occurs. The switchyard would be transferred to SDG&E; thus, decommissioning would be under SDG&E and would not be subject to the County's decommissioning requirements.

9. Surrounding land uses and setting:

   The regional landscape consists of a mixture of large-lot rural residences and energy generation projects. Wind turbines associated with the Tule Wind Project are located to the east, north, and northwest portions of the Project site. Wind turbines associated with the Kumeyaay Wind Project are located approximately 1 mile west of the Project site. Nearby areas include lands administered by Bureau of Indian Affairs and Bureau of Land Management (BLM).

   The terrain in the area includes rock outcropping, valleys, and prominent ridgelines. The site lies between two major drainage divides: the Tecate Divide to the west, and the In-Ko-Pah Mountains to the east. This area occurs within the Live Oak Springs U.S. Geographic Survey (USGS) topographic quadrangle. The elevation ranges within the Project site ranges from approximately 3,280 feet above mean sea level (AMSL) to approximately 4,120 feet AMSL.

10. Other public agencies whose approval is required may include but is not limited to the following:
    - U.S. Army Corps of Engineers
    - U.S. Fish and Wildlife Service
    - Federal Aviation Administration
    - California Department of Fish and Wildlife
    - Regional Water Quality Control Board

11. Have California Native American tribes traditionally and culturally affiliated with the project area requested consultation pursuant to Public Resources Code section 21080.3.1? If so, is there a plan for consultation that includes, for example, the determination of significance of impacts to tribal cultural resources, procedures regarding confidentiality, etc.?

    Yes.

ENVIRONMENTAL FACTORS POTENTIALLY AFFECTED: The environmental factors checked below would be potentially affected by this project and involve at least one impact that is a "Potentially Significant Impact" or a "Less Than Significant With Mitigation Incorporated," as indicated by the checklist on the following pages.

☒ Aesthetics	☐ Agriculture and Forest Resources	☒ Air Quality
☒ Biological Resources	☒ Cultural Resources	☒ Energy
☒ Geology & Soils	☒ Greenhouse Gas Emissions	☒ Hazards & Hazardous Materials
☒ Hydrology & Water Quality	☒ Land Use & Planning	☐ Mineral Resources
☒ Noise	☐ Population & Housing	☒ Public Services
☐ Recreation	☒ Transportation	☒ Tribal Cultural Resources
☒ Utilities & Service Systems	☒ Wildfire	☒ Mandatory Findings of Significance

DETERMINATION: (To be completed by the Lead Agency)
On the basis of this initial evaluation:

☐ On the basis of this Initial Study, Planning & Development Services finds that the proposed project COULD NOT have a significant effect on the environment, and a NEGATIVE DECLARATION will be prepared.

☐ On the basis of this Initial Study, Planning & Development Services finds that although the proposed project could have a significant effect on the environment, there will not be a significant effect in this case because revisions in the project have been made by or agreed to by the project proponent. A MITIGATED NEGATIVE DECLARATION will be prepared.

☒ On the basis of this Initial Study, Planning & Development Services finds that the proposed project MAY have a significant effect on the environment, and an ENVIRONMENTAL IMPACT REPORT is required.

[signature] 2/14/19

Signature Date

Greg Kazmer Planning Manager

INSTRUCTIONS ON EVALUATION OF ENVIRONMENTAL IMPACTS

1. A brief explanation is required for all answers except "No Impact" answers that are adequately supported by the information sources a lead agency cites in the parentheses following each question. A "No Impact" answer is adequately supported if the referenced information sources show that the impact simply does not apply to projects like the one involved (e.g., the project falls outside a fault rupture zone). A "No Impact" answer should be explained where it is based on project-specific factors as well as general standards (e.g., the project will not expose sensitive receptors to pollutants, based on a project-specific screening analysis).

2. All answers must take account of the whole action involved, including off-site as well as on-site, cumulative as well as project-level, indirect as well as direct, and construction as well as operational impacts.

3. Once the lead agency has determined that a particular physical impact may occur, then the checklist answers must indicate whether the impact is potentially significant, Less Than Significant With Mitigation Incorporated, or less than significant. "Potentially Significant Impact" is appropriate if there is substantial evidence that an effect may be significant. If there are one or more "Potentially Significant Impact" entries when the determination is made, an EIR is required.

4. "Less Than Significant With Mitigation Incorporated" applies where the incorporation of mitigation measures has reduced an effect from "Potentially Significant Impact" to a "Less Than Significant Impact." The lead agency must describe the mitigation measures, and briefly explain how they reduce the effect to a less than significant level.

5. Earlier analyses may be used where, pursuant to the tiering, program EIR, or other CEQA process, an effect has been adequately analyzed in an earlier EIR or negative declaration. Section 15063(c)(3)(D). In this case, a brief discussion should identify the following:
   a) Earlier Analysis Used. Identify and state where they are available for review.
   b) Impacts Adequately Addressed. Identify which effects from the above checklist were within the scope of and adequately analyzed in an earlier document pursuant to applicable legal standards, and state whether such effects were addressed by mitigation measures based on the earlier analysis.
   c) Mitigation Measures. For effects that are "Less Than Significant With Mitigation Incorporated," describe the mitigation measures that were incorporated or refined from the earlier document and the extent to which they address site-specific conditions for the project.

6. Lead agencies are encouraged to incorporate into the checklist references to information sources for potential impacts (e.g., general plans, zoning ordinances). Reference to a previously prepared or outside document should, where appropriate, include a reference to the page or pages where the statement is substantiated.

7. The explanation of each issue should identify:
   a) The significance criteria or threshold, if any, used to evaluate each question; and
   b) The mitigation measure identified, if any, to reduce the impact to less than significant

I. AESTHETICS — Except as provided in Public Resources Code Section 21099. Would the project:

a) Have a substantial adverse effect on a scenic vista?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

A vista is a view from a particular location or composite views along a roadway or trail. Scenic vistas often refer to views of natural lands but may also be compositions of natural and developed areas, or even entirely of developed and unnatural areas, such as a scenic vista of a rural town and surrounding agricultural lands. What is scenic to one person may not be scenic to another, so the assessment of what constitutes a scenic vista must consider the perceptions of a variety of viewer groups.

The items that can be seen within a vista are visual resources. Adverse impacts to individual visual resources or the addition of structures or developed areas may or may not adversely affect the vista. Determining the level of impact to a scenic vista requires analyzing the changes to the vista as a whole and also to individual visual resources.

Potentially Significant Impact: The proposed facilities on private land, subject to the County's land use jurisdiction, include the overhead gen-tie transmission line, a substation, and a switchyard. The overhead gen-tie line on private land would extend approximately 3.5 miles from the proposed Campo Wind Project on the Reservation to the Sunrise Powerlink. The gen-tie line on private land would include approximately 38 steel poles at a maximum height of 150 feet. Project facilities on the Reservation include up to 60 turbines, 5 miles of gen-tie line, and related facilities. A Visual Impact Analysis will be required to identify and address all potential impacts to scenic resources including those of wind turbines on the Reservation. This issue will be addressed in the Draft Environmental Impact Report (DEIR).

b) Substantially damage scenic resources, including, but not limited to, trees, rock outcroppings, and historic buildings within a state scenic highway?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

State Scenic Highways refer to those highways that are officially designated by Caltrans as scenic as per the California Scenic Highway Program. Generally, the area defined within a State Scenic Highway is the land adjacent to and visible from the vehicular right-of-way. The dimension of a scenic highway is usually identified using a motorist's line of vision, but a reasonable boundary is selected when the view extends to the distant horizon. The scenic highway corridor extends to the visual limits of the landscape abutting the Scenic Highway.

Potentially Significant Impact: The project site is located in the vicinity of County Designated Scenic Highway, I-8, as identified in the Open Space and Conservation Element of the County's (2011) General Plan. The turbines on the Reservation would be located near Highway 94 and

I-8. A Visual Impact Analysis will be prepared to identify and address all potential impacts to scenic resources including Scenic Highways. This issue will be addressed in the DEIR.

c) In non-urbanized areas, substantially degrade the existing visual character or quality of public views of the site and its surroundings? (Public views are those that are experienced from publicly accessible vantage point). If the project is in an urbanized area, would the project conflict with applicable zoning and other regulations governing scenic quality?

☒ Potentially Significant Impact	☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated	☐ No Impact

Potentially Significant Impact: The project is located within a non-urbanized area within the Boulevard portion of the Mountain Empire Subregional Plan area. Taking into account the construction and operation of the overhead gen-tie transmission line, substation and switchyard on private land, as well as the turbines and related facilities on Reservation land, a Visual Impact Analysis will be prepared to identify and address all potential impacts to the visual character or quality of public views of the site and its surroundings. This issue will be addressed in the DEIR.

d) Create a new source of substantial light or glare, which would adversely affect day or nighttime views in the area?

☒ Potentially Significant Impact	☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated	☐ No Impact

Potentially Significant Impact: Outdoor nighttime lighting at the substation and switchyard would be kept to the minimum required for security and safety, and all lighting would be hooded, directed downward, and turned off when not required. Lighting on the gen-tie transmission poles on private land, and the gen-tie poles and wind turbines on the Reservation, would only be installed if required by the Federal Aviation Administration. A Visual Impact Analysis will be prepared to identify and address all potential impacts to scenic resources that may occur from new sources of light and glare, and this issue will be addressed in the DEIR.

<u>II. AGRICULTURE AND FORESTRY RESOURCES</u> — Would the project:

a) Convert Prime Farmland, Unique Farmland, or Farmland of Statewide or Local Importance (Important Farmland), as shown on the maps prepared pursuant to the Farmland Mapping and Monitoring Program of the California Resources Agency, or other agricultural resources, to non-agricultural use?

☐ Potentially Significant Impact	☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated	☒ No Impact

No Impact: According to the California Department of Conservation (2018) Farmland Mapping and Monitoring Program (FMMP), the Project site is categorized as “other land.” Use of this categorized land for the Project would not constitute converting any protected or important farmland; therefore, there is no impact. Lands under the jurisdiction of the BIA on the Reservation are not categorized using the Department of Conservation's mapping program but are not considered to be high value agricultural lands. These issues will be further addressed in the DEIR.

b) Conflict with existing zoning for agricultural use or a Williamson Act contract?

☐ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☒ No Impact

No Impact: The site is zoned General Rural (S92), which is generally reserved for large parcels and open space/lands. The site is not subject to a Williamson Act contract and the site is considered "other land" by the California Department of Conservation FMMP. There are no Williamson Act contracts on tribal lands. Because the site is not considered an important agricultural resource, the Project would have no impact on existing zoning for agricultural use; therefore, there is no impact.

c) Conflict with existing zoning for, or cause rezoning of, forest land (as defined in Public Resources Code section 12220(g)), or timberland (as defined by Public Resources Code section 4526), or timberland zoned Timberland Production (as defined by Government Code section 51104(g))?

☐ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☒ No Impact

No Impact: The Project site does not contain forest lands or timberland. Therefore, project implementation would not conflict with existing zoning for, or cause rezoning of, forest land, timberland, or timberland production zones. There would be no impact.

d) Result in the loss of forest land, conversion of forest land to non-forest use, or involve other changes in the existing environment, which, due to their location or nature, could result in conversion of forest land to non-forest use?

☐ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☒ No Impact

No Impact: The Project site does not contain any forest lands as defined in Public Resources Code section 12220(g); therefore, project implementation would not result in the loss or conversion of forest land to a non-forest use. In addition, the project is not located in the vicinity of forest resources. The portion of the Project on the Reservation would not significantly impact forest lands.

e) Involve other changes in the existing environment, which, due to their location or nature, could result in conversion of Important Farmland or other agricultural resources, to non-agricultural use?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: The site is not subject to a Williamson Act contract, and the site is considered "other land" by the California Department of Conservation FMMP. However, due to past and present cattle grazing on site, an Agricultural Resources Report will be prepared. This topic will be further addressed in the DEIR.

<u>III. AIR QUALITY</u> — Where available, the significance criteria established by the applicable air quality management district or air pollution control district may be relied upon to make the following determinations. Would the project:

a) Conflict with or obstruct implementation of the San Diego Regional Air Quality Strategy (RAQS) or applicable portions of the State Implementation Plan (SIP)?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: Although it is not anticipated, the Project has the potential to obstruct implementation of the RAQS or SIP. An air quality study will be completed to identify and address any direct and/or cumulative air quality impacts resulting from the Project, specifically from construction. Air quality will be addressed further in the DEIR.

b) Result in a cumulatively considerable net increase of any criteria pollutant for which the project region is non-attainment under an applicable federal or state ambient air quality standard?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

San Diego County is presently in nonattainment for the 1-hour concentrations under the California Ambient Air Quality Standard (CAAQS) for ozone (O_3). San Diego County is also presently in nonattainment for the annual geometric mean and for the 24-hour concentrations of particulate matter less than or equal to 10 microns (PM_{10}) under the CAAQS. O_3 is formed when VOCs and nitrogen oxides (NO_x) react in the presence of sunlight. VOC sources include any source that burns fuels (e.g., gasoline, natural gas, wood, oil), solvents, petroleum processing and storage, and pesticides. Sources of PM_{10} in both urban and rural areas include motor vehicles, wood burning stoves and fireplaces, dust from construction, landfills, agriculture, wildfires, brush/waste burning, and industrial sources of windblown dust from open lands.

Potentially Significant Impact: Air quality emissions associated with the Project could include emissions of PM_{10}, NO_x, and VOCs from construction/grading activities. An air quality study will be completed to identify and address any direct and/or cumulative air quality impacts resulting from the project. Air quality will be further addressed in the DEIR.

c) Expose sensitive receptors to substantial pollutant concentrations?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Air quality regulators typically define sensitive receptors as schools (preschool–12th Grade), hospitals, resident care facilities, or day-care centers, or other facilities that may house individuals with health conditions that would be adversely impacted by changes in air quality. The County of San Diego also considers residences as sensitive receptors because they house children and the elderly.

Potentially Significant Impact: The Project has the potential to impact sensitive receptors during construction; therefore, an Air Quality Technical Report will be completed in order to identify and address any direct and/or cumulative air quality impacts resulting from the Project on sensitive receptors. Air quality will be further addressed in the DEIR.

d) Result in other emissions (such as those leading to odors) adversely affecting a substantial number of people?

☐ Potentially Significant Impact ☒ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Less than Significant Impact: VOC emissions from architectural coatings and other potential sources of odor are not expected to be significant. Any odor generation would terminate upon completion of the construction phase of the project. As a result, the Project would not result in emissions adversely affecting a substantial number of people, and impacts would be less than significant.

<u>IV. BIOLOGICAL RESOURCES</u> — Would the project:

a) Have a substantial adverse effect, either directly or through habitat modifications, on any species identified as a candidate, sensitive, or special status species in local or regional plans, policies, or regulations, or by the California Department of Fish and Game or U.S. Fish and Wildlife Service?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: The Project has the potential to directly and indirectly impact candidate, sensitive, or special status species. Therefore, a Biological Resources Report will be completed in order to identify and address any direct, indirect, and/or cumulative impacts to biological resources resulting from the Project. This topic will be further addressed in the DEIR.

b) Have a substantial adverse effect on any riparian habitat or other sensitive natural community identified in local or regional plans, policies, regulations or by the California Department of Fish and Game or U.S. Fish and Wildlife Service?

- ☒ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ Less than Significant Impact
- ☐ No Impact

Potentially Significant Impact: The Project has the potential to have an adverse effect on riparian and other sensitive natural communities. Therefore, a Biological Resources Report will be completed in order to identify and address any direct, indirect, and/or cumulative impacts to biological resources resulting from the Project. This topic will be further addressed in the DEIR.

c) Have a substantial adverse effect on state or federally protected wetlands (including, but not limited to, marsh, vernal pool, coastal, etc.) through direct removal, filling, hydrological interruption, or other means?

- ☒ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ Less than Significant Impact
- ☐ No Impact

Potentially Significant Impact: The site contains drainages that may be subject to the Resource Protection Ordinance and/or jurisdictional water regulations of the U.S./State. Therefore, a Biological Resources Report will be completed to identify and address any direct, indirect, and/or cumulative biological resources impacts that may result from the Project. This topic will be further addressed in the DEIR.

d) Interfere substantially with the movement of any native resident or migratory fish or wildlife species or with established native resident or migratory wildlife corridors, or impede the use of native wildlife nursery sites?

- ☒ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ Less than Significant Impact
- ☐ No Impact

Potentially Significant Impact: The Project has the potential to impact native resident or migratory wildlife corridors. Therefore, a Biological Resources Report will be completed to identify and address any direct, indirect, and/or cumulative biological resources impacts resulting from the project. This topic will be further addressed in the DEIR.

e) Conflict with the provisions of any adopted Habitat Conservation Plan, Natural Communities Conservation Plan, other approved local, regional or state habitat conservation plan or any other local policies or ordinances that protect biological resources?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: The project site is located in the draft Multiple Species Conservation Program East County Planning Area and portions of the Project site are located within the designated Focused Conservation Area. The document is still in draft form and thus is being mentioned here for informational purposes. A Biological Resources Report will be completed to identify and address any direct, indirect, and/or cumulative biological resources impacts resulting from the Project. This topic will be further addressed in the DEIR.

V. CULTURAL RESOURCES — Would the project:

a) Cause a substantial adverse change in the significance of a historical resource pursuant 15064.5?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: Historical resources may be located on the Project site and/or in the nearby vicinity, the significance of which will be evaluated within a Cultural Resources Report. Any direct and/or cumulative impacts to cultural resources that result from the Project will be further addressed in the DEIR.

b) Cause a substantial adverse change in the significance of an archaeological resource pursuant to 15064.5?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: The Project has the potential to impact archaeological resources pursuant to 15064.5, the significance of which will be evaluated within a Cultural Resources Report. Any direct and/or cumulative impacts to cultural resources that result from the Project will be further addressed in the DEIR.

c) Disturb any human remains, including those interred outside of dedicated cemeteries?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: Although it is not anticipated, ground-disturbing activities during construction of the Project could have the potential to uncover human remains. Potential impacts would be mitigated for and addressed in the Cultural Resources Report.

VI. ENERGY. Would the project:

a) Result in potentially significant environmental impact due to wasteful, inefficient, or unnecessary consumption of energy resources, during project construction or operation?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: The Project could result in electricity, natural gas, petroleum, and other resources use during the construction phase. Although the Project would provide wind energy and related infrastructure that would contribute to reducing energy use throughout the region, potential impacts from the inefficient, wasteful, and unnecessary consumption of nonrenewable energy will be evaluated in the DEIR.

b) Conflict with or obstruct a state or local plan for renewable energy or energy efficiency?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: The Project's consistency with state and local plans for renewable energy or energy efficiency will be analyzed in the DEIR.

VII. GEOLOGY AND SOILS — Would the project:

a) Directly or indirectly cause potential substantial adverse effects, including the risk of loss, injury, or death involving:
   i. Rupture of a known earthquake fault, as delineated on the most recent Alquist-Priolo Earthquake Fault Zoning Map issued by the State Geologist for the area or based on other substantial evidence of a known fault? Refer to Division of Mines and Geology Special Publication 42.

☐ Potentially Significant Impact ☒ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: The Project site is not located in a fault rupture hazard zone (County of San Diego 2007, Figures 1 and 2) identified by the Alquist-Priolo Earthquake Fault Zoning Act, Special Publication 42, Revised 2018, Fault-Rupture Hazards Zones in California, or located within any other area with substantial evidence of a known fault. This topic will be further addressed in the DEIR.

   ii. Strong seismic ground shaking?

☒ Potentially Significant Impact ☐ Less than Significant Impact

☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: To ensure the structural integrity of the proposed facilities, all components would be required to conform to applicable Seismic Requirements as outlined within the California Building Code. Project facilities on tribal land would be subject to similar requirements. The County Code requires a soils compaction report with proposed foundation recommendations to be approved before the issuance of a building permit. Compliance with the California Building Code and the County Code would minimize potential impacts from the exposure of people or structures to potential adverse effects from strong seismic ground shaking; however, a Geologic Investigation Report will be prepared and this topic will be further addressed in the DEIR.

iii. Seismic-related ground failure, including liquefaction?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: Portions of the Project site contain potential liquefaction areas as identified in the County (2007) Guidelines for Determining Significance for Geologic Hazards. Measures to mitigate potential impacts from liquefaction to levels below significance and environmental design considerations will be covered in the Geologic Investigation Report. Liquefaction will be addressed in the DEIR.

iv. Landslides?

☐ Potentially Significant Impact ☒ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Less-Than-Significant Impact: The project site is not within a “Landslide Susceptibility Area" as identified in the County (2007) Guidelines for Determining Significance for Geologic Hazards. Landslide Susceptibility Areas were developed based on landslide risk profiles included in the Multi-Jurisdictional Hazard Mitigation Plan, San Diego, CA (OES and UDC 2017). Landslide risk areas from this plan were based on data including steep slopes (greater than 25%); soil series data (San Diego Association of Governments (SANDAG) based on U.S. Geological Survey (USGS) 1970s series); soil-slip susceptibility from USGS; and Landslide Hazard Zone Maps (limited to western portion of the County) developed by the California Department of Conservation, Division of Mines and Geology. Also included within Landslide Susceptibility Areas are gabbroic soils on slopes steeper than 15% in grade because these soils are slide prone. Because the Project is not located within an identified Landslide Susceptibility Area and the geologic environment has a low probability to become unstable, the Project would result in a less-than-significant impact associated with the exposure of people or structures to potential adverse effects from landslides.

b) Result in substantial soil erosion or the loss of topsoil?

☒ Potentially Significant Impact ☐ Less than Significant Impact

☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: The portion of the Project on private lands will develop a Minor Stormwater Management Plan that will detail how erodible soils will be protected during grading, construction, and operation of the proposed facilities. Additionally, all new roads would be located away from drainage bottoms, steep slopes, and erodible soils if practicable, and would be designed to maintain current surface water runoff patterns and prevent erosion. If road grade and/or runoff patterns result in added erosion, control measures would be installed to minimize the added erosion. This topic will be addressed in the Minor Stormwater Management Plan and the DEIR.

c) Be located on a geologic unit or soil that is unstable, or that would become unstable as a result of the project, and potentially result in an on- or off-site landslide, lateral spreading, subsidence, liquefaction or collapse?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: The Project involves site grading. In order to assure that any proposed structures and other facilities included in this Project site are adequately supported, a Geologic Investigation Report will be prepared and soil stability will be further discussed in the DEIR.

d) Be located on expansive soil, as defined in Table 18-1-B of the Uniform Building Code (1994), creating substantial direct or indirect risks to life or property?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: As shown in the County of San Diego Geologic Hazards Guidelines (Figure 6, Potential Expansive Soils) the Project site may contain expansive soils (County of San Diego 2007, 2011), as defined by Table 18-I-B of the Uniform Building Code (1994). A Geologic Investigation Report will be prepared and soil expansion will be further discussed in the DEIR.

e) Have soils incapable of adequately supporting the use of septic tanks or alternative wastewater disposal systems where sewers are not available for the disposal of wastewater?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: The Project does not propose septic tanks or alternative wastewater disposal systems on private lands within the County's jurisdiction. The O&M building on the Reservation may include a sceptic system. This issue will be discussed further in the DEIR.

f) Directly or indirectly destroy a unique paleontological resource or site or unique geologic feature?

☐	Potentially Significant Impact	☒	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Less-Than-Significant Impact: A review of the County's (2007b) Paleontological Sensitivity Map indicates that the portion of the Project on private land is located in an area with no paleontological resource potential. However, there could be a potential for indirect impacts. By adhering to the County Guidelines for Determining Significance of Paleontological Resources and the County Grading Ordinance, this project would avoid potential impacts through standard practices, which may include a paleontological monitor as determined by SEC. 87.430 of the Grading Ordinance. Thus, by following standard practices, impacts are anticipated to be less than significant on land under the jurisdiction of the County. The portion of the Project on the Reservation also does not have paleontological resource potential. Therefore, the impacts would be less than significant.

VIII. GREENHOUSE GAS EMISSIONS — Would the project:

a) Generate greenhouse gas emissions, either directly or indirectly, that may have a significant impact on the environment?

☐	Potentially Significant Impact	☒	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Less-Than-Significant Impact: Greenhouse gas (GHG) emissions result in an increase in the Earth's average surface temperature commonly referred to as global warming. This rise in global temperature is associated with long-term changes in precipitation, temperature, wind patterns, and other elements of the Earth's climate system, known as climate change. These changes are now broadly attributed to GHG emissions, particularly those emissions that result from the human production and use of fossil fuels.

GHGs include carbon dioxide, methane, halocarbons, and nitrous oxide, among others. Human induced GHG emissions are a result of energy production and consumption, and personal vehicle use, among other sources. A regional GHG inventory prepared for the San Diego Region (Energy Policy Initiatives Center and Ascent Environmental Inc. 2017) identified on-road transportation (cars and trucks) as the largest contributor of GHG emissions in the region, accounting for 45% of the total regional emissions. Electricity and natural gas combustion were the second (24%) and third (9%) largest regional contributors, respectively, to regional GHG emissions.

Climate changes resulting from GHG emissions could produce an array of adverse environmental impacts including water supply shortages, severe drought, increased flooding, sea level rise, air pollution from increased formation of ground level ozone and particulate matter, ecosystem changes, increased wildfire risk, agricultural impacts, ocean and terrestrial species impacts, among other adverse effects. It should be noted that an individual project's GHG emissions will generally not result in direct impacts under CEQA, as the climate change issue is global in nature; however, an individual project could be found to contribute to a potentially significant cumulative impact.

In 2006, the State of California passed the Global Warming Solutions Act of 2006, commonly referred to as Assembly Bill (AB) 32, which set the GHG emissions reduction goal for the state into law. The law requires that by 2020, state emissions must be reduced to 1990 levels by reducing GHG emissions from significant sources via regulation, market mechanisms, and other actions.

SB 32 and AB 197 (enacted in 2016) are companion bills that set a new statewide GHG reduction target; make changes to CARB's membership, and increase legislative oversight of CARB's climate change-based activities; and expand dissemination of GHG and other air quality-related emissions data to enhance transparency and accountability. More specifically, SB 32 codified the 2030 emissions reduction goal of EO B-30-15 by requiring CARB to ensure that statewide GHG emissions are reduced to 40 percent below 1990 levels by 2030.

The facilities proposed on private land under the County's jurisdiction consist of a gen-tie transmission line, substation and switchyard that would carry wind energy from the Reservation to the Sunrise Powerlink. Although the Project facilitates renewable energy sources in place of a typical fossil fuel-based electrical generation resulting in long-term air quality benefits, the development could have the potential to result in emissions related to construction activities and vehicle trips. Emissions from the construction activities are anticipated to be minimal, temporary, and localized. Operational emissions are anticipated to be minimal and would be generated from vehicle trips for ongoing operation and maintenance activities. The Project is expected to offset GHG emissions by serving as a long-term renewable energy source, thereby decreasing overall emissions attributable to electrical generation in California and assisting the state in meeting its 50% by 2030 Renewable Portfolio Standard. Therefore, the Project is anticipated to result in a less than significant impact. However, a Climate Change Analysis will be prepared in order to quantify GHG emissions. This subject will be further addressed in the DEIR.

b) Conflict with an applicable plan, policy or regulation adopted for the purpose of reducing the emissions of greenhouse gases?

☐ Potentially Significant Impact	☒ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated	☐ No Impact

Less-Than-Significant Impact: The project will be evaluated to determine whether it would impede the implementation of AB 32 and SB 32. For the reasons discussed in response VII (a), the Project is not anticipated to impede the implementation of state reduction targets.

Therefore, the Project is not anticipated to conflict with an applicable plan, policy, or regulation adopted for the purpose of reducing the emissions of GHGs. Regardless, a Climate Change Analysis will be prepared and this topic will be further addressed in the DEIR.

IX. HAZARDS AND HAZARDOUS MATERIALS — Would the project:

a) Create a significant hazard to the public or the environment through the routine transport, storage, use, or disposal of hazardous materials or wastes or through reasonably foreseeable upset and accident conditions involving the release of hazardous materials into the environment?

- ☐ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☒ Less than Significant Impact
- ☐ No Impact

Less-Than-Significant Impact: The Project includes the construction and operation of an overhead gen-tie transmission line and a substation/switchyard. No hazardous materials (40 Code of Federal Regulations 355) are anticipated to be produced, used, stored or disposed of as a result of construction or operation of the facilities. Thus, the Project would not result in a significant hazard to the public or environment because all storage, handling, transport, emission, and disposal of hazardous substances would be in full compliance with local, state, and federal regulations. California Government Code Section 65850.2 requires that no final certificate of occupancy or its substantial equivalent be issued unless there is verification that the owner or authorized agent has met, or is meeting, the applicable requirements of the Health and Safety Code, Division 20, Chapter 6.95, Article 2, Sections 25500–25520.

The San Diego County Department of Environmental Health – Hazardous Materials Division (DEH HMD) is the Certified Unified Program Agency (CUPA) for San Diego County responsible for enforcing Chapter 6.95 of the Health and Safety Code. As the CUPA, the DEH HMD is required to regulate hazardous materials business plans and chemical inventory, hazardous waste and tiered permitting, underground storage tanks, and risk management plans. The hazardous materials business plan is required to contain basic information on the location, type, quantity, and health risks of hazardous materials stored, used, or disposed of on site. The plan also contains an emergency response plan which describes the procedures for mitigating a hazardous release, procedures and equipment for minimizing the potential damage of a hazardous materials release, and provisions for immediate notification of the HMD, the Office of Emergency Services, and other emergency response personnel such as the local Fire Agency having jurisdiction. Implementation of the emergency response plan facilitates rapid response in the event of an accidental spill or release, thereby reducing potential adverse impacts. Furthermore, the DEH HMD is required to conduct ongoing routine inspections to ensure compliance with existing laws and regulations; to identify safety hazards that could cause or contribute to an accidental spill or release; and to suggest preventative measures to minimize the risk of a spill or release of hazardous substances.

Therefore, due to the strict requirements that regulate hazardous substances outlined above and the fact that the initial planning, ongoing monitoring, and inspections would occur in compliance with local, state, and federal regulation, the portion of the Project on private land would not result in any potentially significant impacts related to the routine transport, use, and disposal of hazardous substances or related to the accidental explosion or release of hazardous substances. Similar requirements will apply to the facilities the Reservation. Thus, this will not be further discussed in the DEIR.

b) Emit hazardous emissions or handle hazardous or acutely hazardous materials, substances, or waste within one-quarter mile of an existing or proposed school?

☐ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☒ No Impact

No Impact: The Project is not located within 0.25 mile of an existing or proposed school. No hazardous materials (40 Code of Federal Regulations 355) are anticipated to be produced, used, stored or disposed of as a result of construction, operation, or decommissioning of the facilities. Thus, the Project would not result in a significant hazard to the public or environment because all storage, handling, transport, emission, and disposal of hazardous substances would be in full compliance with local, state, and federal regulations. Therefore, the Project would not emit hazardous materials, substances, or waste within 0.25 mile of an existing or proposed school and this topic would not be further addressed in the DEIR.

c) Be located on a site which is included on a list of hazardous materials sites compiled pursuant to Government Code Section 65962.5, or is otherwise known to have been subject to a release of hazardous substances and, as a result, would it create a significant hazard to the public or the environment?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: Based on an initial regulatory database search, the site is not included in the State of California Hazardous Waste and Substances sites list (Department of Toxic Substances Control 2018), nor is it located within 1,000 feet of a Formerly Used Defense Sites (FUDS) (ACOE 2015). However, a more thorough search of all hazardous materials sites compiled pursuant to Government Code Section 65962.5 will occur and this will be addressed in the Phase 1 ESA. Hazardous materials sites will be further discussed in the DEIR.

d) For a project located within an airport land use plan or, where such a plan has not been adopted, within two miles of a public airport or public use airport, would the project result in a safety hazard or excessive noise for people residing or working in the project area?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: The Project is not located within an airport land use plan or, where such a plan has not been adopted, within two miles of a public airport or public use airport (County of San Diego 2011, Figure M-1). However, based on the FAA's Notice Criteria Tool on the FAA website (FAA 2018), the Project site is in proximity to a navigation facility which may impact the assurance of navigation signal reception. Thus, the appropriate filing with the FAA is required in order to ensure that the Project is in compliance with the FAA, in accordance with Part 77.9 of the Code of Federal Regulations. This topic will be further addressed in the DEIR.

e) Impair implementation of or physically interfere with an adopted emergency response plan or emergency evacuation plan?

- ☐ Potentially Significant Impact
- ☒ Less than Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ No Impact

The following sections summarize the project's consistency with applicable emergency response plans or emergency evacuation plans.

i. OPERATIONAL AREA EMERGENCY PLAN AND MULTI-JURISDICTIONAL HAZARD MITIGATION PLAN:

Less-Than-Significant Impact: The Operational Area Emergency Plan (OES 2010) is a comprehensive emergency plan that defines responsibilities, establishes an emergency organization, defines lines of communications, and is designed to be part of the statewide Standardized Emergency Management System. The Operational Area Emergency Plan provides guidance for emergency planning and requires subsequent plans to be established by each jurisdiction that has responsibilities in a disaster situation. The Multi-Jurisdictional Hazard Mitigation Plan (OES and UDC 2017) includes an overview and discussion of the risk assessment process, hazards present in the jurisdiction, hazard profiles, and vulnerability assessments. The plan also identifies goals, objectives, and actions for each jurisdiction in the County of San Diego, including all cities and the County's unincorporated areas. The Project would not interfere with this plan because it would not prohibit subsequent plans from being established or prevent the goals and objectives of existing plans from being carried out.

ii. SAN DIEGO COUNTY NUCLEAR POWER STATION EMERGENCY RESPONSE PLAN

No Impact: The Project would not interfere with the San Diego County Nuclear Power Station Emergency Response Plan due to the location of the project and the specific requirements of the plan. The emergency plan for the San Onofre Nuclear Generating Station includes an emergency planning zone within a 10-mile radius. All land area within 10 miles of the station is not within the jurisdiction of the unincorporated County and, as such, a project in the unincorporated area is not expected to interfere with any response or evacuation.

iii. OIL SPILL CONTINGENCY ELEMENT

No Impact: The Project is not located along the coastal zone or coastline; therefore, it would not interfere with the Oil Spill Contingency Element.

iv. EMERGENCY WATER CONTINGENCIES ANNEX AND ENERGY SHORTAGE RESPONSE PLAN

No Impact: The Project would not alter a major water or energy supply infrastructure, such as the California Aqueduct; therefore, it would not interfere with the Emergency Water Contingencies Annex and Energy Shortage Response Plan.

v. DAM EVACUATION PLAN

No Impact: The Project is not located within a dam inundation zone; therefore, it would not interfere with the Dam Evacuation Plan.

f) Expose people or structures, either directly or indirectly, to a significant risk of loss, injury or death involving wildland fires?

☒ Potentially Significant Impact	☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated	☐ No Impact

Potentially Significant Impact: The Project site is located in a "very high" Fire Hazard Severity Zone as determined by the California Department of Forestry and Fire Protection. A fire protection plan (FPP), per County requirements, will be prepared for the private land portions of the Project. The FPP will describe how the portion of the Project on private land will comply with requirements related to emergency access, water supply, and fire suppression design measures in consideration of the high concentration of electrical equipment that would be present on the Project site. The FPP, per County requirements, will identify and address any direct and/or cumulative impacts resulting from the project regarding fire hazards. Coordination with the Tribe and Campo Fire is underway for the portion of the Campo Wind Project on the Reservation. This issue will be discussed in the DEIR.

g) Propose a use, or place residents adjacent to an existing or reasonably foreseeable use that would substantially increase current or future resident's exposure to vectors, including mosquitoes, rats or flies, which are capable of transmitting significant public health diseases or nuisances?

☐ Potentially Significant Impact	☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated	☒ No Impact

No Impact: The Project does not involve or support uses that allow water to stand for a period of 72 hours (3 days) or more (e.g., artificial lakes, agricultural irrigation ponds). Also, the Project does not involve or support uses that would produce or collect animal waste, such as equestrian facilities, agricultural operations (e.g., chicken coops, dairies), solid waste facilities, or other similar uses. Therefore, the Project would not substantially increase current or future residents' exposure to vectors, including mosquitoes, rats, or flies.

X. HYDROLOGY AND WATER QUALITY -- Would the project:

a) Violate any water quality standards or waste discharge requirements, or otherwise substantially degrade surface or groundwater quality?

☒	Potentially Significant Impact	☐	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Potentially Significant Impact: A Minor Stormwater Management Plan will be prepared for the portions of the Project on private land which is intended to meet the permit requirements of the San Diego Regional Water Quality Control Board. The Minor Stormwater Management Plan will incorporate several Best Management Practices to provide water quality treatment consistent with the Regional Permit's standards. This issue will be addressed in the DEIR.

b) Is the project tributary to an already impaired water body, as listed on the Clean Water Act Section 303(d) list? If so, could the project result in an increase in any pollutant for which the water body is already impaired?

☐	Potentially Significant Impact	☒	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Potentially Significant Impact: According to the Clean Water Act Section 303(d) list, the nearest impaired water body is Cottonwood Creek approximately 11 miles west of the Project site, and outside the watershed of the Project site (County of San Diego 2011, Figure C-3; County of San Diego 2014). The nearest water body to the portions of the Project on Reservation is also Cottonwood Creek. Therefore, it is unlikely that any pollutants that might be generated by the project would contribute to this impaired water body. For the private land portion of the Project, a Minor Stormwater Management Plan will be prepared for the project that will address all necessary BMPs to ensure that potential pollutants will be reduced in any runoff to the maximum extent practicable so as not to impact receiving waters. Although impacts are anticipated to be less than significant, this topic will be further discussed in the DEIR.

c) Could the Project cause or contribute to an exceedance of applicable surface or groundwater receiving water quality objectives or degradation of beneficial uses?

☒	Potentially Significant Impact	☐	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Potentially Significant Impact: A Minor Stormwater Management Plan will be prepared for the private land portion of the Project that will address all necessary BMPs to prevent significant impacts to water quality and ensure potential pollutants will be reduced in any runoff to the maximum extent practicable so as not to impact receiving waters. Water quality will be further discussed in the DEIR.

d) Substantially decrease groundwater supplies or interfere substantially with groundwater recharge such that the project may impede sustainable groundwater management of the basin.

☒	Potentially Significant Impact	☐	Less than Significant Impact

☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: Water may be required for operation of the Project and would be required during construction. Water would be sourced from either on-site groundwater wells, if sufficient yield can be demonstrated, and/or non-potable water from local water purveyors such as Jacumba Community Services District or Padre Dam Municipal Water District. This issue will be addressed in the DEIR.

e) Substantially alter the existing drainage pattern of the site or area, including through the alteration of the course of a stream or river, or through the addition of impervious surface, in a manner which would:

i. Result in substantial erosion or siltation on- or off-site?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: The Project would include improvements which may impede or redirect flood flows. Roads would be located away from drainage bottoms, steep slopes, and erodible soils if practicable, and would be designed to maintain current surface water runoff patterns and prevent erosion. Soil erosion would be controlled at culvert outlets with appropriate structures. If road grade and/or runoff patterns result in added erosion, control measures would be installed to minimize the added erosion. Although impacts are anticipated to be less than significant, this issue will be addressed in the DEIR.

ii. Substantially increase the rate or amount of surface water in a manner which would result in flooding on- or off-site?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: The Project would include improvements which may impede or redirect flood flows. Roads would be located away from drainage bottoms, steep slopes, and erodible soils if practicable, and would be designed to maintain current surface water runoff patterns and prevent flooding. This issue will be addressed in the DEIR.

iii. Create or contribute runoff water which would exceed the capacity of existing or planned storm water drainage systems or provide substantial additional sources of polluted runoff?

☒ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☐ No Impact

Potentially Significant Impact: A Minor Stormwater Management Plan and a Drainage Study will be prepared for the private land portion of the Project that will evaluate all potential drainage facilities and will ensure that adequate drainage facilities are included in the project design. No substantial additional sources of polluted runoff are anticipated to occur as a result of the Project beyond those discussed in responses a) through c) above. A Minor Stormwater Management Plan will be prepared for the Project that will address all necessary BMPs to ensure that potential pollutants will be reduced in any runoff to the maximum extent practicable so as not to significantly impact water quality. This issue will be discussed in the DEIR.

iv. Impede or redirect flood flows?

☒	Potentially Significant Impact	☐	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Potentially Significant Impact: The Project would include improvements which may impede or redirect flood flows. The applicant is required to provide a Drainage Study for the private land portion of the Project indicating runoff quantities and conditions before and after development of the project, including analysis of existing and proposed drainage facility capacity and lines of inundation by the 100-year flood. In addition, the applicant will also provide preliminary grading plans showing drainage patterns, improvements to storm drain system, inlets, points of entry into natural drainage channels, energy dissipaters, and any other applicable drainage features. This issue will be addressed in the DEIR.

f) In flood hazard, tsunami, or seiche zones, risk release of pollutants due to project inundation?

☒	Potentially Significant Impact	☐	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☒	No Impact

No Impact: The Project site is not identified as being within a 100-year flood hazard area; however, the applicant is required to provide a Drainage Study indicating runoff quantities and conditions before and after development of the project, including analysis of existing and proposed drainage facility capacity and lines of inundation by the 100-year flood. In addition, the applicant will also provide preliminary grading plans showing drainage patterns, improvements to storm drain system, inlets, points of entry into natural drainage channels, energy dissipaters, and any other applicable drainage features. This issue will be addressed in the DEIR. The Project site is not located along the shoreline of a lake or reservoir; therefore, it could not be inundated by a seiche. The Project site is located more than 1 mile from the coast; therefore, in the event of a tsunami, it would not be inundated.

g) Conflict with or obstruct implementation of a water quality control plan or sustainable groundwater management plan?

☒	Potentially Significant Impact	☐	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Potentially Significant Impact: The Project would include improvements which may impact water quality. The Project also proposes to either use existing groundwater wells or import water for construction. The DEIR will analyze this issue.

XI. LAND USE AND PLANNING — Would the project:

a) Physically divide an established community?

☐	Potentially Significant Impact	☒	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Less than Significant Impact: The proposed Project would not disrupt or physically divide the surrounding area. Typical projects that have the potential to physically divide an established community would be stadiums, freeways, railroads, etc., none of which are being proposed. Therefore, impacts would be less than significant.

b) Cause a significant environmental impact due to a conflict with any land use plan, policy, or regulation adopted for the purpose of avoiding or mitigating an environmental effect?

☒	Potentially Significant Impact	☐	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Potentially Significant Impact: The private lands portion of the Project is subject to the General Plan Rural Lands Regional Category and contains lands within the Rural Lands 80 (RL-80) Land Use Designation. The Project is also subject to the policies of the Boulevard Subregional Plan and Mountain Empire Subregional Plan. The properties are zoned S92. The proposed use can only be allowed with the approval of an MUP on the Project site. The portion of the project on the Reservation is not subject to the County's land use or planning jurisdiction. The DEIR will analyze the Project with regard to applicable land use plans and policies and determine if there are any conflicts. This topic will be further addressed in the EIR.

XII. MINERAL RESOURCES — Would the project:

a) Result in the loss of availability of a known mineral resource that would be of value to the region and the residents of the state?

☐	Potentially Significant Impact	☒	Less than Significant Impact
☐	Less Than Significant With Mitigation Incorporated	☐	No Impact

Less-Than-Significant Impact: The lands within the Project site have not been classified by the California Department of Conservation – Division of Mines and Geology (Update of Mineral Land Classification: Aggregate Materials in the Western San Diego Production-Consumption Region, 1997). The Project site may contain mineral resource deposits suitable for crushed rock. However, due to the expensive mining and processing of crushed rock combined with transportation costs, this currently restricts crushed rock operations to urbanized areas within the Western San Diego Consumption Region of the County. Therefore, no potentially significant loss of availability of a known mineral resource of value to the region and the residents of the state would occur as a result of this project. Moreover, if the resources are not considered significant mineral deposits, loss of these resources cannot contribute to a potentially significant cumulative impact.

b) Result in the loss of availability of a locally-important mineral resource recovery site delineated on a local general plan, specific plan or other land use plan?

- ☐ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ Less than Significant Impact
- ☒ No Impact

No Impact: The Project site is not located on a mineral resource recovery site delineated in the General Plan for private lands portion, or other land use plan. Therefore, the Project would not result in the loss of availability of locally important mineral resource(s).

<u>XIII. NOISE</u> — Would the project result in:

a) Generation of a substantial temporary or permanent increase in ambient noise levels in the vicinity of the project in excess of standards established in the local general plan or noise ordinance, or applicable standards of other agencies?

- ☒ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ Less than Significant Impact
- ☐ No Impact

Potentially Significant Impact: The Project may produce temporary or periodic increases in ambient noise levels, principally during construction. A Noise Analysis Report will be prepared for the Project that will evaluate noise-generating sources of the project for conformance with the County Noise Ordinance and General Plan (where applicable), and in comparison with existing noise levels on the Project site. Analysis will include the potential for temporary or periodic increases in ambient noise levels in the Project vicinity. The Project also has the potential to result in a permanent increase in ambient noise levels in the vicinity of the Project. A Noise Analysis Report will be prepared for the Project that will evaluate permanent noise generating sources of the Project for conformance with the County Noise Ordinance and General Plan (where applicable), and in comparison with existing noise levels in on the Project site. This issue will be addressed in the DEIR.

b) Generation of excessive groundborne vibration or groundborne noise levels?

- ☒ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ Less than Significant Impact
- ☐ No Impact

Potentially Significant Impact: The Project may produce groundborne vibration or groundborne noise levels during construction of the Project. A Noise Analysis Report will be prepared that will evaluate noise generating sources for conformance with the County Noise Ordinance and General Plan (where applicable), and in comparison with existing noise levels on the Project site. Analysis will include the potential for groundborne vibration and groundborne vibration noise levels during the construction phase of the Project. This issue will be addressed in the DEIR.

c) For a project located within the vicinity of a private airstrip or an airport land use plan or, where such a plan has not been adopted, within two miles of a public airport or public use airport, would the project expose people residing or working in the project area to excessive noise levels?

☐ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☒ No Impact

No Impact: The Project is not located within a 1-mile vicinity of a private airstrip. The Project is not located within the vicinity of an airport land use plan or within two miles of a public airport where a plan has not been adopted (County of San Diego 2007, Figure M-1). Therefore, the Project would not expose people working or residing in the area to excessive noise levels.

XIV. POPULATION AND HOUSING — Would the project:

a) Induce substantial unplanned population growth in an area, either directly (for example, by proposing new homes and businesses) or indirectly (for example, through extension of roads or other infrastructure)?

☐ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☒ No Impact

No Impact: The Project proposes new renewable energy infrastructure. This physical change would not induce substantial population growth in the area because there would be no extension of water, sewer, or roadways into previously unserved areas, and no regulatory changes are proposed that would allow increased population growth.

b) Displace substantial numbers of existing people or housing, necessitating the construction of replacement housing elsewhere?

☐ Potentially Significant Impact ☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated ☒ No Impact

No Impact: No homes or people would be displaced necessitating the construction of homes elsewhere. No impact would result.

XV. PUBLIC SERVICES — Would the project:

a) Would the project result in substantial adverse physical impacts associated with the provision of new or physically altered governmental facilities, need for new or physically altered governmental facilities, the construction of which could cause significant environmental impacts, in order to maintain acceptable service ratios, response times or other performance service ratios, response times or other performance objectives for any of the public services:

i. Fire protection?
ii. Police protection?
iii. Schools?
iv. Parks?
v. Other public facilities?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: The Project does not include residential use and is not expected to significantly alter the need for additional schools, parks, or police protection. However, regarding fire protection, a Fire Protection Plan will be prepared that will address measures to reduce fire risk in the area for the portions of the Project on private lands and evaluate the adequacy of existing emergency service facilities in relation to the determined fire risk. Coordination with the Tribe and Campo Fire is underway for the Campo Wind Project to address fire risk. Fire protection will be addressed in the DEIR.

XVI. RECREATION — Would the project:

a) Would the project increase the use of existing neighborhood and regional parks or other recreational facilities such that substantial physical deterioration of the facility would occur or be accelerated?

☐ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☒ No Impact

No Impact: The Project does not involve any residential use, including, but not limited to, a residential subdivision, mobile home park, or construction for a single-family residence that may increase the use of existing neighborhood and regional parks or other recreational facilities in the vicinity.

b) Does the project include recreational facilities or require the construction or expansion of recreational facilities, which might have an adverse physical effect on the environment?

☐ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☒ No Impact

No Impact: The Project does not include recreational facilities or require the construction or expansion of recreational facilities. Therefore, the construction or expansion of recreational facilities cannot have an adverse physical effect on the environment.

XVII. TRANSPORTATION — Would the project:

a) Conflict with a program plan, ordinance or policy addressing the circulation system, including transit, roadway, bicycle and pedestrian facilities?

☒ Potentially Significant Impact	☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated	☐ No Impact

Potentially Significant Impact: The Project would require a Traffic Impact Analysis to determine if the project could conflict with any performance measures establishing measures of effectiveness of the circulation system. A Traffic Control Plan would also be prepared prior to the start of construction to reduce impacts to off-site traffic flow and would address transportation activities, such as the delivery of project components. The Project will be analyzed to determine if there are any conflicts with a program plan, ordinance or policy addressing the circulation system. Project implementation will not result in the construction of any road improvements or new road design features that would interfere with the provision of public transit, bicycle, or pedestrian facilities. The issue of roadway facilities will be addressed in the DEIR.

b) Would the Project conflict or be inconsistent with CEQA Guidelines section 15064.3, subdivision (b)(1)?

☒ Potentially Significant Impact	☐ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated	☐ No Impact

Potentially Significant Impact: The Project proposes new renewable energy infrastructure. Consistency with CEQA Guidelines section 15064.3 subdivision (b)(1) will be addressed in the DEIR.

c) Substantially increase hazards due to a geometric design feature (e.g., sharp curves or dangerous intersections) or incompatible uses (e.g., farm equipment)?

☐ Potentially Significant Impact	☒ Less than Significant Impact
☐ Less Than Significant With Mitigation Incorporated	☐ No Impact

Less than Significant Impact: The Project would use the existing network of permanent roads to access the Project site, where feasible. In addition to the existing roads, new access roads would be constructed to provide access to the improvements. New permanent access road layout would incorporate applicable standards regarding internal road design and circulation, particularly those provisions related to emergency vehicle access. Therefore, the Project would not substantially increase hazards. This topic will not be further addressed in the DEIR.

d) Result in inadequate emergency access?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: It is not anticipated that the Project would result in inadequate emergency access. A Fire Protection Plan will be prepared for the Project that will describe how the Project portions on private lands will comply with requirements related to emergency access, water supply, and fire suppression design measures. Additionally, new permanent access road layout would incorporate applicable standards regarding internal road design and circulation, particularly those provisions related to emergency vehicle access. Adequate emergency access will be required of the Project. This issue will be addressed in the DEIR.

XVIII. TRIBAL CULTURAL RESOURCES — Would the project:

a) Cause a substantial adverse change in the significance of a tribal cultural resource, as defined in Public Resources Code §21074 as either a site, feature, place, or cultural landscape that is geographically defined in terms of the size and scope of the landscape, sacred place, or object with cultural value to a California Native American tribe, and that is:

i. Listed or eligible for listing in the California Register of Historical Resources, or in a local register of Historical Resources as defined in Public Resources Code §5020.1(k), or

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: Consultation will be conducted with the California Native American tribes that request consultation. Where applicable, the DEIR will analyze whether the proposed Project will cause a substantial adverse change in the significance of a tribal cultural resource that is listed or eligible for listing in the California Register of Historical Resources or in a local register of Historical Resources.

ii. A resource determined by the lead agency, in its discretion and supported by substantial evidence, to be significant pursuant to criteria set forth in subdivision (c) of Public Resources Code §5024.1. In applying the criteria set forth in subdivision (c) of Public Resources Code §5024.1, the Lead Agency shall consider the significance of the resource to a California Native American tribe.

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: Consultation will be conducted with the California Native American tribes that request consultation. Where applicable, the DEIR will analyze whether the proposed Project will cause a substantial adverse change in the significance of a tribal cultural resource as determined by the lead agency.

<u>XIX. UTILITIES AND SERVICE SYSTEMS</u> — Would the project:

a) Require or result in the relocation or construction of new or expanded water, wastewater treatment or storm water drainage, electric power, natural gas, or telecommunications facilities, construction or relocation of which could cause significant environmental effects?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: The Project proposes new renewable energy generation infrastructure. The 230 kV gen-tie line would carry wind energy from a proposed wind energy project on the Reservation to a proposed substation/switchyard adjacent to the Sunrise Powerlink. No relocation or construction of new water or wastewater treatment facilities are proposed. The Project would require appropriately sized and designed stormwater drainage facilities for the project to operate safely and efficiently. Any environmental impacts from the construction of drainage facilities would be evaluated with other appropriate technical reports such as drainage, biological, or cultural resources. This topic will be addressed further in the DEIR.

b) Have sufficient water supplies available to serve the project and reasonably foreseeable future development during normal, dry and multiple dry years?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: Minimal water supply may be needed for the operation of the Project. During construction water is expected to be required for dust suppression and concrete mixing in particular. Water would be sourced from either on-site groundwater wells, if sufficient yield can be demonstrated, and/or non-potable water from local water purveyors such as Jacumba Community Services District or Padre Dam Municipal Water District. This issue will be addressed in the DEIR.

c) Result in a determination by the wastewater treatment provider, which serves or may serve the project that it has adequate capacity to serve the project’s projected demand in addition to the provider’s existing commitments?

☐ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☒ Less than Significant Impact
☐ No Impact

Less than Significant Impact: During construction, portable toilets, as needed, would be provided for on-site sewage handling, and would be pumped and cleaned regularly by the construction contractor. The O&M building would likely include a septic system on the Reservation, not within County jurisdiction.

d) Generate solid waste in excess of State or local standards, or in excess of the capacity of local infrastructure, or otherwise impair the attainment of solid waste reduction goals?

☐ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☒ Less than Significant Impact
☐ No Impact

Less than Significant Impact: Construction of the Project would generate construction wastes that would be recycled to the extent possible. The waste generated by construction that would be sent to local landfills is not anticipated to overwhelm the remaining capacity of local landfill facilities such that these facilities would not be able to serve existing demand. In addition, area landfills have sufficient capacity to accommodate the minor volume of waste that may be generated during operation of the Project. Total waste sent to local landfills during construction is not anticipated to be substantial. Therefore, sufficient solid waste capacity exists to accommodate the Project's solid waste disposal needs and impacts would be less than significant.

e) Comply with federal, state, and local management and reduction statutes and regulations related to solid waste?

☐ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☒ Less than Significant Impact
☐ No Impact

Less than Significant Impact: The Project would be required to comply with applicable federal, state, and local statutes and regulations related to solid waste and recycling as applicable. Furthermore, the County's General Plan goals and policies related to solid waste disposal would ensure compliance with all applicable laws and regulations for the private land portion of the Project. Therefore, impacts associated with solid waste disposal would be less than significant.

XX. WILDFIRE — If located in or near state responsibility areas or land classified as very high fire hazard severity zones, would the project:

a) Substantially impair an adopted emergency response plan or emergency evacuation plan?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: A portion of the Project site is located in a "very high" Fire Hazard Severity Zone as determined by the California Department of Forestry and Fire Protection. A fire protection plan (FPP), per County requirements, will be prepared for the portion of the Project on private lands that will describe how the project will comply with requirements related to emergency access and response, water supply, and fire suppression design measures in consideration of the equipment that would be present on the Project site. Coordination with the Tribe and Campo Fire is underway regarding the Campo Wind Project. This issue will be addressed in the DEIR.

b) Due to slope, prevailing winds, and other factors, exacerbate wildfire risks, and thereby expose project occupants to, pollutant concentrations from a wildfire or the uncontrolled spread of a wildfire?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

Potentially Significant Impact: A portion of the Project site is located in a "very high" Fire Hazard Severity Zone as determined by the California Department of Forestry and Fire Protection. The Project may potentially exacerbate wildfire risks. An FPP will be prepared for the portion of the Project on private lands that will describe how that portion of the Project will comply with requirements related to emergency access and response, water supply, and fire suppression design measures in consideration of the equipment that would be present on the Project site. The Boulder Brush facilities portion of the Project would be unmanned facilities; however, there are rural residences in the surrounding area. This issue will be addressed in the DEIR.

c) Require the installation or maintenance of associated infrastructure (such as roads, fuel breaks, emergency water sources, power lines, or other utilities) that may exacerbate fire risk or that result in temporary or ongoing impacts to the environment?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

A portion of the Project site is located in a "very high" Fire Hazard Severity Zone as determined by the California Department of Forestry and Fire Protection. A FPP will be prepared for the portion of Project on private lands that will describe how that portion of the Project will comply with requirements related to emergency access and response, water supply, and fire suppression design measures in consideration of the equipment that would be present on the Project site. This issue will be addressed in the DEIR.

d) Expose people or structures to significant risks, including downslope or downstream flooding or landslides, as a result of runoff, post-fire slope instability, or drainage changes?

☒ Potentially Significant Impact
☐ Less Than Significant With Mitigation Incorporated
☐ Less than Significant Impact
☐ No Impact

The Project proposes new renewable energy generation infrastructure. This issue will be addressed in the DEIR.

XXI. MANDATORY FINDINGS OF SIGNIFICANCE:

a) Does the project have the potential to substantially degrade the quality of the environment, substantially reduce the habitat of a fish or wildlife species, cause a fish or wildlife population to drop below self-sustaining levels, threaten to eliminate a plant or animal community, substantially reduce the number or restrict the range of a rare or endangered plant or animal or eliminate important examples of the major periods of California history or prehistory?

- ☒ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ Less than Significant Impact
- ☐ No Impact

Potentially Significant Impact: As discussed in Sections IV and V, the Project has the potential to significantly impact biological and/or cultural resources and these issues will be further addressed in the DEIR.

b) Does the project have impacts that are individually limited, but cumulatively considerable? ("Cumulatively considerable" means that the incremental effects of a project are considerable when viewed in connection with the effects of past projects, the effects of other current projects, and the effects of probable future projects)?

- ☒ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ Less than Significant Impact
- ☐ No Impact

Potentially Significant Impact: The Project has the potential to incrementally contribute to cumulatively significant impacts. Potentially significant cumulative effects could occur related to Aesthetics, Air Quality, Biological Resources, Cultural Resources, Hydrology and Water Quality, Noise, Land Use Planning, Public Services (Fire Service), Transportation, Tribal Cultural Resources, and Wildfire. Therefore, cumulative impacts associated with the Project will be analyzed in the DEIR.

c) Does the project have environmental effects, which will cause substantial adverse effects on human beings, either directly or indirectly?

- ☒ Potentially Significant Impact
- ☐ Less Than Significant With Mitigation Incorporated
- ☐ Less than Significant Impact
- ☐ No Impact

Potentially Significant Impact: The Project has the potential to result in adverse effects on human beings directly, and indirectly. Potential impacts will be addressed in the DEIR.

XXII. REFERENCES USED IN THE COMPLETION OF THE INITIAL STUDY CHECKLIST

All references to federal, state, and local regulations are available on the Internet. For federal regulations refer to http://www4.law.cornell.edu/uscode/. For state regulations refer to www.leginfo.ca.gov. For County regulations refer to www.amlegal.com. All other references are available upon request.

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14 Code of Federal Regulations Part 77.9. Construction or alteration requiring notice.

40 Code of Federal Regulations 355. Emergency Planning and Notification.

Campo Wind Project with Boulder Brush Facilities
Public Comments to Notice of Preparation Matrix

#	Comment Letter Cite	Comments / Concerns	Considered in EIR or Planning Documents	Applicable EIR Section	Date Dated or Received
Federal Agencies					
1	Steve Quinn, Native American Heritage Commission	AB 52 Consultation Request	Yes	Tribal Cultural	3/6/2019
2	U.S. Fish and Wildlife	Biological Surveys to determine federally listed species locations	Yes	Biological Resources	8/28/2018
State Agencies					
1	Melina Pereira, CalTrans	Vehicle Permitting	Yes	Transportation	2/13/2019
2	Melina Pereira, CalTrans	Traffic Impact Study, Right of Way	Yes	Transportation	3/6/2019
3	State Clearing House OPR	NOP Acknowledgement	No	N/A	2/15/2019
Organizations					
1	Donna Tisdale, Backcountry Against Dumps; Courtesy of the Law Office of Stephan C. Volker	Scoping Comments of Backcountry Against Dumps and Donna Tisdale on the Proposed Boulder Brush Gen-Tie Line and Switchyard Facilities for the Campo Wind Project - Incomplete Project Application, Violation of County Zoning Code, EIR Provisions, Wildlife Impacts, Noise Impacts, GHG Impacts, Hydrological Impacts, Magnetic Field Radiation Impacts, Wildfire Impacts, Agricultural Impacts, Aesthetic Impacts, Compliance with CPUC General Order 131-D.	Yes	Biological Resources, Noise, GHG, Hydrology and Water Quality, Land Use and Planning, Wildfires, Agriculture, Aesthetics	3/18/2019
2	Donna Tisdale, Backcountry Against Dumps	Formal Opposition Letter referencing studies regarding disadvantages of wind turbines, includes formal oppositions to project, bird impacts	Yes	Health and Hazards, Noise, Biological Resources, Recreation	3/18/2019
3	Law Offices of Stephan C. Volker	Violation of Zoning Codes, Bird Impacts, Adequate Water Supplies, Wildfire Risks, Emergency Response Times, Shadow Flicker,	Yes	Aesthetics, Biological Resources, Hazards, Noise, Agriculture, GHG, Hydrology, Land Use and Planning, Public Services	2/21/2019
4	San Diego County Archaeological Society, INC	DEIR distribution review request	Yes	Cultural Resources	3/14/2019

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Community Planning Groups					
1	Boulevard Community Planning Group	Violation of zoning codes, lighting issues, groundwater concerns, fire protection, interference with cell towers	Yes	Aesthetics, Biological Resources, Hazards, Noise, Agriculture, Hydrology, Land Use and Planning, Paleontological Resources, Public Services, Utilities	3/18/2019
2	Campo Lake Morena Community Planning Group	Informal Email to Bronwyn Brown: Inclusion of Soil Carbons, Cumulative Impacts, Transmission Losses	Yes	Energy, Geology, GHG, Other CEQA Considerations	3/14/2019
Individuals					
1	Abdoul Diallo	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	Yes	Hazards, Noise	2/28/2019
2	Adam Anderson	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
3	Al Delalot	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
4	Alex Fernandes	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/18/2019
5	Alex Valequez	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/18/2019
6	Andrew Degroot	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
7	Andy DeGroot	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	No	N/A	2/28/2019
8	Anthony Ponhot	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
9	Anthony Ralphs	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities – Environmental concern of border wall and wind turbines	No	N/A	2/28/2019
10	April Zapor	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/18/2019
11	Barbara Kennerly	Informal Opposition Email to Bronwyn Brown: Electromagnetic Interference, Emergency Medical Response Times	Yes	Public Services	3/14/2019
12	Barrance Zaron	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	2/28/2019

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13	Barrance Zoyan	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
14	Ben Good	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	No	N/A	2/28/2019
15	Benjamin Good	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
16	Benjamin Good.	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	2/28/2019
17	Betty Chase	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/8/2019
18	Bill Davis	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
19	Borrance Zoyan	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	No	N/A	2/28/2019
20	Bruce Herbert	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
21	Bud Chase	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/8/2019
22	Byron Polen	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
23	Carmen Villade	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	Yes	Aesthetics, Biological Resources, Hazards, Noise, Hydrology	2/28/2019
24	Carmen Villeda	Public EIR Scoping Meeting – Comment Sheet	Yes	Biological Resources, Hazards, Hydrology	3/2/2019
25	Carmen Villeda	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	2/28/2019
26	Carmen Villeda	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
27	Casey Espinosa	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	2/28/2019

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28	Charles B. Good	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	2/28/2019
29	Charles Good	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
30	Charles Townsend	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/7/2019
31	Charles Townsend	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
32	Charlie Good	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities – Condemnation of Properties	Yes	Land Use and Planning	2/28/2019
33	Cheryl DeLozier	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/6//2019
34	Christina Cole	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/18/2019
35	Christopher Zapor	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/18/2019
36	Clifford Caldwell	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
37	Clifford Caldwell	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	Yes	N/A	2/28/2019
38	Clifford Caldwell and Concepcion Caldwell	Informal Opposition Email to Donna Tisdale regarding opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Lin, Substation Facilities, and Height Limit Waver	No	N/A	2/7/2019
39	Cole Dotson	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
40	Cole Dotson	Informal Opposition Email to Bronwyn Brown	No	N/A	3/13/2019
41	Concepcion Caldwell	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
42	Danica Walker	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/10/2019
43	Danica Walker	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/10/2019
44	David Cooper	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	2/28/2019

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45	David Cooper	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
46	David Wilson	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/7/2019
47	David Wilson	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/7/2019
48	Deanne Martino	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/10/2019
49	Debbie Moran	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/20/2019
50	Diana Harde	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
51	Don Bonfiglio	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
52	Donna Tisdale	Scoping Comments of Backcountry Against Dumps and Donna Tisdale on the Proposed Boulder Brush Gen-Tie Line and Switchyard Facilities for the Campo Wind Project - Incomplete Project Application, Violation of County Zoning Code, EIR Provisions, Wildlife Impacts, Noise Impacts, GHG Impacts, Hydrological Impacts, Magnetic Field Radiation Impacts, Wildfire Impacts, Agricultural Impacts, Aesthetic Impacts, Compliance with CPUC General Order 131-D.	Yes	Aesthetics, Air Quality, Biological Resources, Hazards, Noise, Agriculture, Hydrology, Land Use and Planning	
53	Donna Tisdale	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/18/2019
54	Donna Tisdale	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
55	Donna Tisdale	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	
56	Donna Tisdale	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities – In Opposition	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
57	Dustin Walker	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/16/2019
58	Dustin Walker	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/10/2019
59	Ed Tisdale	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019

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60	Erin Kayser	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
61	Gregg Curtis	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	Yes		2/28/2019
62	Heather Skains	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/11/2019
63	Heather Skains	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/11/2019
64	Jacob Troutman	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/18/2019
65	Janet Silva	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
66	Jason Fordyer	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/16/2019
67	Jeffrey G Morrison	Informal Opposition Email to Donna Tisdale regarding opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Lin, Substation Facilities, and Height Limit Waver	No	N/A	2/7/2019
68	Jeffrey McKernan	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
69	Jeffrey McKernan	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/17/2019
70	Jeffrey Morrison	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/8/2019
71	Jeffrey Morrison	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/8/2019
72	Jennifer Schwab	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/20/2019
73	Karen Mcyntyre	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
74	Kenneth Daubach	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
75	Kim Peterson	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
76	Lance Morrow	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/10/2019

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77	Lance Morrow	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
78	Lance Morrow	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines, Note: Open Space and Green Energy Concerns, Wildlife Concerns	Yes	Biological Resources, Hazards, Noise, Energy	3/10/2019
79	Larry Johnson	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
80	Laura Felton	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/20/2019
81	Laura McKernan	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
82	Laura McKernan	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/17/2019
83	Len Mauris	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
84	Leslie Mauris	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	2/28/2019
85	Leslie Mauris	Informal Email to Bronwyn Brown: Information Requests	Yes	Aesthetics, Public Services Utilities	
86	Leslie Wilson	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/78/2019
87	Leslie Wilson	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/7/2019
88	Linda Shannon	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/20/2019
89	Linda Shannon	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
90	Linda Shannon	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/14/2019
91	Lydia Adams	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/18/2019
92	Mandy McClain	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
93	Marie Morgan	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/9/2019
94	Marie Morgan	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/10/2019

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95	Mary Anne Oppenheimer	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/20/2019
96	Matthew K. Peter	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/118/2019
97	Melanie Ponhot	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
98	Michael Strand	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	2/28/2019
99	Michele Strand	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	Yes		2/28/2019
100	Michelle Chapman	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
101	Monica Albair	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
102	Murphy Smith	Informal Opposition Email to Bronwyn Brown: Intrinsic Value of Land, Mountainous Views, Wildlife Concerns, Health Effects, Environmental Injustice	Yes	Aesthetics, Biological Resources, Hazards	3/18/2019
103	Nancy Good	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	2/28/2019
104	Nancy Good	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
105	Pamela Guy	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
106	Pamela Guy	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/2/2019
107	Quentin Schwab	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/20/2019
108	Rett Lawrence	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
109	Richard Blaisdell	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/5/2019
110	Ricky Guy	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/7/2019
111	Ricky Guy	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
112	Robbin Washer	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/6//2019

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113	Robert and Marie Morgan	Informal Opposition Email to Bronwyn Brown: Scenic Landscape Concerns, Height Concerns, Proximity to Homes	Yes	Aesthetics	3/4/2019
114	Robert Morgan	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/8/2019
115	Robert Morgan	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/8/2019
116	Roberto Maupin	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
117	Ryan Peterson	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
118	Scott Haselton	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
119	Sharon Burton	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/20/2019
120	Sharon Burton	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/6//2019
121	Sharon Burton	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards, Noise	3/6/2019
122	Sheryl Hayter	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
123	Stanley Adams	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/18/2019
124	Steven Redman	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	See in Sections Biological Resources, 2.2 of EIR	3/18/2019
125	Tamara D Morrison	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	See in Sections Biological Resources, 2.2 of EIR	3/8/2019
126	Tamara Morrison	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines, Note: Traffic Concerns	Yes	Hazards, Noise, Transportation	3/8/2019
127	Tammy Daubach	Informal Opposition Email to Bronwyn Brown: Wildfire Risks, Alternative Projects, Firefighter Trainings, Cell Phone Issues, Road Damage, Military Flight Patterns, Wildlife Concerns	Yes	Biological Resources, Utilities	3/4/2019
128	Tammy Daubach	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
129	Tammy Daubach	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	Yes	Hazards, Energy, Traffic, Biology	2/28/2019

#	Comment Letter Cite	Comments / Concerns	Considered in EIR or Planning Documents	Applicable EIR Section	Date Dated or Received
130	Tammy Townsend	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/7/2019
131	Tammy Townsend	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
132	Teresa DeGroot	Petition to Oppose Terra-Gen's 90 New 586 Ft Tall 4 MW Turbines and New High-Voltage Line Planned for About 4,500 Acres of Campo Reservation Land in Boulevard, CA.	Yes	Aesthetics, Biological Resources, Hazards, Noise, Geology, Hydrology	2/28/2019
133	Teresa DeGroot	Speaker Slip: Public Scoping Meeting for NOP of an EIR for Boulder Brush Facilities	No	N/A	2/28/2019
134	Teri Lederman	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/20/2019
135	Tracey Martino	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/10/2019
136	Tracy Tisdale	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/17/2019
137	Valerie Morrow	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/10/2019
138	Valerie Morrow	2019 Wind Turbine Neighbor Survey: Addressing Health and Safety Issues from Existing Turbines	Yes	Hazards and Nosie	3/10/2019
139	Vicky Walker	Informal Email to Bronwyn Brown: Information Requests	No	N/A	2/1/2019
140	Walter Henders	Formal Opposition Letter Formal Opposition Letter- Opposition to Terra-Gen's Proposed Boulder Brush Gen-Tie Line, Campo Wind, and Torrey Wind Projects	Yes	Biological Resources, Air Quality	3/16/2019
141	William Largo	Public EIR Scoping Meeting – Comment Sheet	Yes	Aesthetics, Biological Resources	3/3/2019
142	William Largo	Boulder Brush Essay – Hazards and Health, Tribal Cultural Artifacts, Wildlife Concerns	Yes	Hazards and Health, Tribal Cultural, Biological Resources	3/1/2019

BACKCOUNRY AGAINST DUMPS
PO BOX 1275, BOULEVARD, CA 91905

DATE: March 18, 2019

TO: Bronwyn Brown, PDS Project Manager via Bronwyn.brown@sdcounty.ca.gov

FROM: Donna Tisdale, Chair, President; 619-766-4170; tisdale.donna@gmail.com;

RE: BOULDER BRUSH GEN-TIE LINE AND SWITCHYARD FACILITIES FOR CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019E-ER-19-16-001: NOTICE OF PREPARATION & INITIAL STUDY

Our Board of Directors voted unanimously to authorize me to submit these comments in opposition to Terra-Gen's proposed Boulder Brush Gen-tie, Campo Wind, and related Torrey Wind. They are all one big project.

We hereby fully incorporate the comments submitted 3-18-19 on behalf of the Boulevard Planning Group, and the Volker Law Firm.

While electricity generation via wind turbines *may have* global benefits, these are accompanied by substantial local externalities and environmental costs, primarily borne by rural communities like Boulevard that are close to wind turbines.

Below is a chronology put together by a group based in Australia that follows this issue very closely: ***"Three- decades of wind industry deception – a chronology of a global conspiracy of silence and subterfuge***".[1]

The information below summarizes all the information they have gathered and posted online:
July 1, 1979

2MW MOD-1 Turbine installed[2]

To trial industrial-level wind energy generation in the US, the 5th operational wind turbine is installed near Boone, North Carolina.

September 1, 1979

First complaints received from a dozen families within a 3km radius of turbine[3]

Much to everyone's surprise, complaints were made by some residents (see dots on image for location). The annoyance was described as an intermittent "thumping" sound accompanied by vibrations. .. A "feeling" or "presence" was described, felt rather than heard, accompanied by sensations of uneasiness

[1] https://stopthesethings.com/2015/02/22/three-decades-of-wind-industry-deception-a-chronology-of-a-global-conspiracy-of-silence-and-subterfuge/

[2] https://stopthesethings.files.wordpress.com/2013/07/kelley-et-al-1985.pdf
[3] https://stopthesethings.com/2013/07/20/what-wind-swindlers-always-knew/

and personal disturbance. .. The "sounds" were louder and more annoying inside the affected homes. .. Some rattling of loose objects occurred. In one or two severe situations, structural vibrations were sufficient to cause loose dust to fall from high ceilings, which created an additional nuisance.

October 1, 1979 —
January 1, 1981

Wind turbine operation creates enormous sound pressure waves[4]

Many calloborators, including NASA and SERI fully investigated acoustic, seismic and atmospheric aspects using turbine operational information and data recordings in a series of field experiments (the NASA research). This image from the field studies shows the sound pressure caused by rotating blades passing the tower.

March 1, 1981

Pressure waves from wind turbines react with structure of houses[5]

(Figure 7.2; Kelley et al., 1985)NASA's first inside-home testing of turbine noise show sound pressure waves interacting with structures in affected houses. The dynamic (acoustic) pressure field within a residential room is controlled by (1) changes in the shape of the room caused by a diaphragm action from internal and external pressure changes (loadings); (2) higher mode resonances in the walls and floors; (3) cavity oscillations (Helmholtz-type resonances) from an air volume moving in and out of the room through an opening such as a door or window; and (4) the resonant modes of the air volume itself. The ranges of these various resonances are plotted and the factors controlling structural mode damping are added (Figure 7-2).

Householders are exposed to Low Frequency Noise (LFN) from wind turbines while indoors[6]

Stephens D.G., Shepherd, K.P., Hubbard H.H. and Grosveld, F.W. (1982) Guide to the evaluation of human exposure to noise from large wind turbines. NASA Technical Memorandum 83288NASA's Guide to the evaluation of human exposure to noise from large turbines - 'Receiver exposure' includes noise evaluation inside homes.

March 2, 1982

Closed windows and doors do not protect occupants from LFN[7]

(Fig C-10; Stephens et al., 1982Further NASA research showed that even with windows shut, houses do not stop LFN sound energy. Measured levels inside the home are significantly higher than predicted within the LFN range. The house acts like a drum for LFN.

[4] https://stopthesethings.com/2013/07/20/what-wind-swindlers-always-knew/
[5] http://stopthesethings.com/2013/07/20/what-wind-swindlers-always-knew/
[6] https://stopthesethings.files.wordpress.com/2015/01/nasa-guide-to-evaluating-turbine-noise-hubbard-et-al-1982.pdf
[7] https://stopthesethings.files.wordpress.com/2015/01/nasa-guide-to-evaluating-turbine-noise-hubbard-et-al-1982.pdf

March 3, 1982

Turbine redesign from downwind to upwind does not fix LFN problem[8]

(Fig A1, A2 and A3; Stephens et al., 1982)The position of the turbine was thought to contribute to the problem. The MOD-1 wind turbine was a downwind turbine. The acoustics of upwind turbines were investigated. A change in configuration of the turbine did change the noise profile, however, as the blades still must pass a tower, LFN sound pressure emissions remain high.

NASA research on human impacts provided to wind industry[9]

Hubbard, H. H. (1982) Noise induced House Vibrations and Human Perception. Noise Control Engineering Journal Sept-Oct 19(2),49-55.Wind industry is provided with research through this summary article in the Noise Control Engineering Journal. It describes noise-induced house responses, including frequencies, mode shapes, acceleration levels and outside-to-inside noise reductions. The role of house vibrations in reactions to environmental noise is defined and some human perception criteria are reviewed.

November 1, 1984

Noise inside homes worse than outside[10]

Hubbard, H.H., & Shepherd, K.P. (1984) Response measurements for two building structures excited by noise from a large horizontal axis wind turbine generator. NASA Contractor Report 172482.More NASA research shows that house structure excitation from wind turbine operation is similar to the sonic boom created by jet aircraft pssing overhead. Interior noise can be greater than outside noise. Many people complain that wind turbines sound like a jet that never lands - this is why. There is an overlap between the peak acceleration level (vibration measure) and peak sound pressure levels within two structures that had been excited by commercial jets, helicopters and wind turbines.

January 3, 1985

Hypothesis for infrasound-induced motion sickness[11]

Nussbaum, D.S. & Reinis, S. (1985) Some individual differences in human response to infrasound. UTAIS Report N. 282It was known that not every one responded to infrasound in the same way and studies were commenced to determine the possible 'transducers' for infrasound in the human body and explore how they might differ between individuals. People who suffer from infrasound were found to be measurably different to people who did not. The resulting hypothesis proposes the differences are related to anatomical differences (diameter of inner ear), neural responsiveness as well as processing of information in the brain (central nervous system). Clear parallels to motion sickness was made.

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[8] https://stopthesethings.files.wordpress.com/2015/01/nasa-guide-to-evaluating-turbine-noise-hubbard-et-al-1982.pdf
[9] https://stopthesethings.files.wordpress.com/2015/02/hubbard-1982-noise-induced-house-vibrations-airports.pdf
[10] https://stopthesethings.files.wordpress.com/2015/01/hubbard-and-shepherd-1985.pdf
[11] http://docs.wind-watch.org/Infrasound-1985-Nussbaum-Reinis.pdf

February 1, 1985

Major research on community annoyance from wind turbine released[12]

(Kelley et al, 1985)Extensive NASA research established the origin and possible amelioration of acoustic disturbances associated with the operation of the MOD-1 wind turbine. Results show that the source of this acoustic annoyance was the transient, unsteady aerodynamic lift imparted to the turbine blades as they passed through the lee wakes of the larqe, cylindrical tower supports. Nearby residents were annoyed by the LFN impulses propagated into the structures of the homes in which the complainants lived. The situation was aggravated further by a complex sound propagation process controlled by terrain and atmospheric focusing.

November 1, 1987

Laboratory simulation of wind turbine annoyance conducted[13]

(Figure 5) Kelley, N.D. (1987) A Proposed metric for assessing the potential of community annoyance from wind turbine low-frequency emissions. Windpower '87 Conference and Exhibition, October 5-8, 1987. San Francisco, CaliforniaKelley continued researching the annoyance from wind turbines in a 'laboratory situation'. A testing facility was constructed and furnished with a control room, listening room and speaker room. Subjects were exposed to LFN emission profiles similar to that detected in the MOD-1 turbine and asked to rate their annoyance.

November 2, 1987

Wind turbine annoyance measured[14]

(Table 2; Kelley, 1987Participants rated their perceptions in various LFN environments using this scale, recording noise, annoyance, vibration and pulsations.

November 3, 1987

Lab studies confirm dB(A) worst noise measure for predicting annoyance[15]

(Table 3; Kelley, 1987)Of all the noise filters tested, dB(A) was shown to be the worst of all at predicting annoyance from LFN

November 4, 1987

Wind industry told that dB(A) unsuitable to measure LFN emissions from wind turbines[16]

(Kelley,1987)Wind industry informed of how to predict annoyance from LFN emissions from wind turbines at Windpower '87 Conference. Kelley explains how to measure LFN emissions that annoy

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[12] https://stopthesethings.files.wordpress.com/2013/07/kelley-et-al-1985.pdf

[13] http://cdn.knightlab.com/libs/timeline/latest/embed/index.html?source=0Ak2bgr7C0nhPdGR3S1lEekU3T3p4ZDhUNDdRV2Y2ZkE&font=Bevan-PotanoSans&maptype=toner&lang=en&height=650

[14] https://stopthesethings.files.wordpress.com/2015/02/kelley-1987-wind-farm-low-frequency-noise-problem-identified.pdf

[15] https://stopthesethings.files.wordpress.com/2015/02/kelley-1987-wind-farm-low-frequency-noise-problem-identified.pdf

[16]

neighbours of wind farms. LFN can be intensified inside homes. The dB(A) filter cuts out all the LFN and is therfore unsuitable. G-weighted scales were better correlated with noise, annoyance, vibration and pulsations.

January 2, 1988

End of NASA research

This was essentially the end of almost a decade of NASA research into the unexpected annoyance of wind turbine operation on neighbours. It revealed the fundamental flaw - the turbines blades passing the tower, which generates huge pressure waves - LFN emissions. Depending on topography, weather and the location of houses and turbines, some LFN emissions were focussed and reacted with homes. The sensation from LFN emission generated many complaints. The levels were higher inside the homes than outside. LFN can not be detected when dB(A) filtes are applied. Susceptible people experience a range of symptoms including motion-sickness-like symptoms

January 1, 1995

Wind developers regroup and respond to NASA research, creating the Noise Working Group[17]

page i) ETSU-R-97 (1996) The Assessment and rating of noise from wind farms. Report from the working group on noise from wind farms. September 1996. MM dor the Department of Trade and IndustrySeven years have passed. In an attempt kick start the wind industry again, a group of mostly wind farm developers, calling themselves the Noise Working Group was establlished in the UK by the Department of Trade and Industry and through the Energy Technology Support Unit (ETSU - now called Future Energy Solutions). They met and created a set of procedures for measuring wind farm noise. Their aim was to promote the development of the wind industry, without the burden of dealing with community annoyance.

September 1, 1996

Noise Working Group produce ETSU-R-97 guidelines for assessing wind turbine noise[18]

ETSU-R-97 (1996)Noise standard document produced by the Noise Working Group makes it plain that its purpose is to create guidelines that will promote the development of the wind industry by not placing "unreasonable restrictions on wind farm development or adding unduly to the costs and administrative burdens on wind farm developers or local authorities."

ETSU deliberately excludes testing inside homes[19]

(3.11-3.12, Bowdler, 2005)Without any supportive evidence, a 10 dB(A) buffer is assumed to occur inside homes compared to outside. No need to take measurements inside just deduct this 10 dB(A) from outside noise level readings and say that this is equivalent to the inside noise level.

[17] http://www.hayesmckenzie.co.uk/downloads/ETSU%20Full%20copy%20%28Searchable%29.pdf
[18] http://www.hayesmckenzie.co.uk/downloads/ETSU%20Full%20copy%20%28Searchable%29.pdf
[19] https://stopthesethings.files.wordpress.com/2015/02/2005-july-bowdler-etsu-r-97_-why_-it_-is_-wrong.pdf

ETSU sets night time noise limit higher than day time limit[20]

(1.2, 4.1-4.2, Bowdler, 2005ETSU sets night time noise limit high of 43dB(A), while day time limit is 37-42 dB(A). Critics write "The conclusions of ETSU-R-97 are so badly argued as to be laughable in parts (the daytime standard is based on the principle that it does not matter if people cannot get to sleep on their patio so long as they can get to sleep in their bedrooms). It is the only standard where the permissible night time level is higher than the permissible day time level."

September 6, 1996

ETSU avoids measuring LFN from wind turbines[21]

(Cox, Unwin & Sherman, 2012, p53The sampling and filtering protocols in ETSU remove the dominant LFN component of the noise emissions from wind turbines

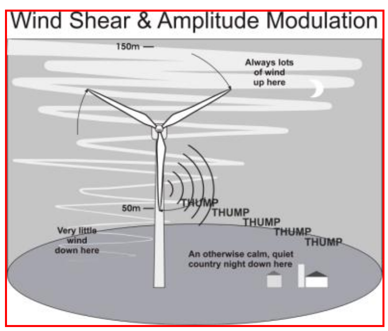
September 7, 1996

ETSU does not measure aerodynamic modulation[22]

Wind turbines emit highly intrusive LFN thumping noises (excess amplitude modulation) that are essentially filtered out and ignored by the measurement protocols recommended in the ETSU, thereby failing to protect residents from this annoyance. The noise is comparable to that of helicopters. Because of its LFN nature, the annoyance can be experienced at significant distances from turbines.

ETSU silent on wind shear and LFN propagation[23]

Bowdler, D. (2005). ETSU-R-97: Why it is wrong. New acoustics, Dunbartonshire, ScotlandWind shear occurs when wind speed at upper levels is higher than at lower elevations, which is common at night. This means there is more noise emitted and less masking of the noise at homes. Instead, the ETSU assumes as wind turbine noise increases, there will be a proportional increase in background noise due to increased wind speed.



[20] https://stopthesethings.files.wordpress.com/2015/02/2005-july-bowdler-etsu-r-97_-why_-it_-is_-wrong.pdf
[21] https://stopthesethings.files.wordpress.com/2015/02/2012-cox-unwin-sherman-where-etsu-silent.pdf
[22] https://stopthesethings.files.wordpress.com/2015/02/2010-hansen-report-hallett_wind_farm_assessment_hansen_version-6.pdf

[23] https://stopthesethings.files.wordpress.com/2015/02/2005-july-bowdler-etsu-r-97_-why_-it_-is_-wrong.pdf

October 1, 1996

ETSU falsely elevates background noise readings to hide noise produced by wind turbines[24]

Cox, R., Unwin, D. and Sherman, T. (2012) Wind turbine noise impact assessment - Where ETSU is silentUnder ETSU, background noise levels set the benchmark for turbine noise criteria. ETSU artificially elevated background levels by using techniques such as poor microphone shielding, limiting monitoring locations, sample size, sample time of day, sample duration, survey period, sample processing.

March 1, 2003

Australian 1st wind farm noise guidelines follow ETSU[25]

EPA (2003) Environmental noise guidelines: Wind farms. EPA, Adelaide, South AustraliaSouth Australian EPA release Environmental Noise Guidlines: Wind Farms. The allowable noise limit is set at 35 dB(A). Section 2.2 specifies that the noise criteria for a new wind farm development should not exceed 35 dB(A). The guidelines follow ETSU: use of dB(A) as the exclusive noise measure; deliberating excluding LFN and testing inside homes. In relation to LFN and infrsound it writes: "The EPA has consulted the working group and completed an extensive literature search but is not aware of infrasound being present at any modern wind farm site". The EPA had never carried out any field research to support that assertion.

Wind industry knows noise models inadequate[26]

Sloth, E., Neilsen, N, Kristensen, E., & Sondergaarg, B. (2004) Problems related to the use of existing noise measurement standards when predicting noise from wind turbines and wind farms. AUSWEA conference, AusWind, Launceston, Tasmania, 28-30 July 2004At an Australian Wind industry conference, AUSWEA, Eric Sloth from Vestas presented collaborative research findings (Vestas, Bonus, Delta - later named as Siemens) that confessed that their noise prediction models were inadequate and further research was required.

Australian wind industry increases turbine noise limit from 35 dB(A) to 40 dB(A)[27]

Evidence put forward by a wind farm developer (AGL) in a wind farm planning case (Hallett) in South AustraliaThis letter from the EPA confirms that the development manager from Wind Prospect was able to convince the SA EPA to up the allowable turbine noise limit from 35 dB(A) to 40 dB(A).

[24] https://stopthesethings.files.wordpress.com/2015/02/2012-cox-unwin-sherman-where-etsu-silent.pdf
[25] https://stopthesethings.files.wordpress.com/2015/02/sa-epa-guidelines-noise-from-windfarms-2003.pdf
[26] https://stopthesethings.files.wordpress.com/2015/02/sloth-auswea-2004conference.pdf
[27] https://stopthesethings.files.wordpress.com/2015/02/2007-letter-confirming-wind-developers-worked-with-epa-to-increase-35-to-40.pdf

July 1, 2009

Sixty years of WHO research shows sleep deprivation, caused by noise, is a serious adverse health effect[28]

World Health Organization (2009) Night Noise Guidelines for Europe. WHO, Regional Office for Europe, DenmarkThe WHO reviews the available evidence and concludes sleep deprivation can lead to consquences for health and well-being. They write: "Sleep is a biological necessity and disturbed sleep is associated with a number of adverse impacts on health.... (and) is viewed as a health problem in itself (environmental insomnia), (as) it also leads to further consequences for health and well-being"

July 1, 2009

New version of EPA guidelines - limit up to 40 dB(A)[29]

EPA (2009) Wind farms environmental noise guidelines. EPA, Adelaide, South AustraliaNew version of SA EPA Environmental Noise Guidlines: Wind Farms. For no other reason than wind industry lobbying, the allowable noise limit is increased from 35 dB(A) to 40 dB(A). The guidelines continue to follow ETSU: use of dB(A) as the exclusive noise measure; deliberating excluding LFN and testing inside homes. In relation to LFN and infrsound it continues to assert: "The EPA has consulted the working group and completed an extensive literature search but is not aware of infrasound being present at any modern wind farm site". The EPA had never carried out any field research to support that assertion.

July 3, 2009

Wind turbine syndrome described[30]

Dr. Nina Pierpont explains how turbine infrasound and LFN create the range of symptoms associated with Wind Turbine Syndrome. Case histories provided as supporting data.

January 1, 2011

Infrasound also generated by movement of the turbine tower[31]

Styles, P., Westwood, R. F., Toon, S. M., Buckingham, M. P., Marmo, B., & Carruthers, B. (2011). Monitoring and mitigation of LFN from wind turbines to protect comprehensive test ban seismic monitoring stations. 4th Annual Meeting on Wind turbine noice, Rome, Italy 12-14 April 2011.In a study to investigate and mitigate LFN and infrasound from wind turbines that interfere with seimic monitoring to detect nuclear detonations, it was shown that the wind turbine tower itself moves and this is another source of infrasound

June 29, 2011

Vestas knew that low frequency noise from larger turbines needed greater setbacks[32]

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[28] http://www.euro.who.int/__data/assets/pdf_file/0017/43316/E92845.pdf
[29] https://stopthesethings.files.wordpress.com/2015/06/47788_windfarms.pdf
[30]Pierpont, N. (2009). Wind turbine syndrome: A report on a natural experiment. Santa Fe, NM, USA: K-Selected Books
[31] https://stopthesethings.files.wordpress.com/2015/02/wtn2011_styles_final.pdf

Letter from Ditlev Engel, (CEO Vestas) to Danish Minister of the Environment, Karen Ellemann, Dated 29 June 2011This is a letter from the CEO of Vestas, lobbying the Danish government not to bring in significant noise regulations, admitting that low frequency noise from larger turbines will increase setback distances needed for neighbours.

Draft NSW guidelines for wind farms released for discussion[33]

Draft for consultation - NSW Planning Guidelines Wind farms: A resource for the community, applicants and consent authorities. New South Wales Department of Planning and Infrastructure. December 2011New guidelines for wind farm operation are drafted. Some LFN testing proposed and C-weighting used. Lower noise limits (drop from 40 to 35 dB(A) are proposed. 2km setback. No in home testing performed.

March 1, 2012

Vestas attempt to avoid LFN measurement[34]

Letter from Ken McAlpine (Director, Policy and Government Relations, Vestas Australian Wind Technology PTY LTD) to NSW Department of Planning Systems and Reform Re: Draft NSW Planning Guidelines: Wind Farms dated 14 March 2012Wind turbine manufacturer Vestas implores NSW government to remove any reference to LFN and exclude any testing; also ask for noise limits to stay at 40 dB(A).

August 1, 2013

Wind developers refuse to cooperate with noise impact studies[35]

Schomer, P., Erdreich J., Boyle, J., & Pamidighantam, P. (2013). A proposed theory to explain some adverse physiological effects of the infrasonic emissions at some wind farm sites. 5th International Conference on Wind Turbine Noise. Denver, Colorado. 28-30 August 2013Paul Schomer, George Hessler and Rob Rand investigates the Shirley Wisconsin wind farm acoustic annoyance and concludes "Most residents do not hear the wind-turbine sound; noise annoyance is not an issue. The issue is physiological responses that result from the very low-frequency infrasound and which appears to be triggering motion sickness in those who are susceptible to it." Schomer laments the difficulty of studying wind turbine annoyance when devlopers refuse to cooperate by allowing on-off testing.

September 1, 2014

Cones of wind turbine infrasound hypothesis and motion sickness[36]

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[32] https://stopthesethings.files.wordpress.com/2015/02/engel-ditlev-vestas-letter-to-danish-environment-minister-in-english.pdf
[33] https://stopthesethings.files.wordpress.com/2015/02/2011-nsw_wind_farm_guidelines_web_dec2011.pdf
[34] https://stopthesethings.files.wordpress.com/2015/02/2012-march-vestas.pdf
[35] http://stopthesethings.com/2013/09/28/sick-again-motion-sickness-sufferers-cop-it-worst-from-giant-fans/

[36] https://vimeo.com/103602357

Kevin Allan Dooley website http://www.kevindooleyinc.com/Kevin Dooley proposes that 'cones' of infrasound exposure from wind turbines is related to motion sickness symptoms.

Ontario Council enacts new by-law including infrasound from wind farms[37]

Corporation of the town of Plympton-Wyoming, By-law Number 62 of 2014 Being a by-law to provide for the regulation of wind turbine noise within the town of Plympton-Wyoming. Read a first and second 24th September 2014Under the bylaw, if a resident complains about infrasound, the municipality would hire an engineer qualified to take the measurements before laying a charge. If a company is found guilty – can range from $500 to $10,000 per offence and could exceed $100,000 if the offense continues. The municipality recoups the cost of the specialized testing under the bylaw

12:00 AM
October 1, 2014

US Wind farm declared 'Hazard to Human Health'[38]

The Brown County Board of Health declared the Shirley-Wisconsin wind farm a " … Human Health Hazard for all people (residents, workers, visitors, and sensitive passersby) who are exposed to Infrasound/Low Frequency Noise and other emissions potentially harmful to human health."

Cause and effect relationship established - Turbine LFN and human sensation of annoyance in homes[39]

Cooper, S. (2014). The results of an acoustic testing program Cape Bridgewater wind farm 44.5100R7:MSC. The Acoustic Group. Prepared for Energy Pacific (Vic) Pty Ltd.Comissioned by Pacific Hydro, and performed by Steven Cooper at Cape Bridgewater with 6 individuals who kept diaries of the sensations they were experiencing. Parallel in-home testing of turbine noise revealed wind turbine signature and its presense corellated with annoyance as recorded in participant diaries. A cause and effect relationship is undeniable.

November 1, 2014

Infrasonic wind turbine signature in homes[40]

Hansen, K., Zajamsek, B., & Hansen, C. (2014). Noise Monitoring in the Vicinity of the Waterloo Wind Farm. University of Adelaide.Private noise testing still was happening inside peoples homes because they were suffering. However this was happening without the co-operation of the wind turbine operators. They refuse to provide on-off testing to demonstrate that the turbines are causing the infrasonic pulses inside their homes or provide hub-height wind speed data to determine wind shear. One such study was underway at Waterloo South Australia when a cable fault allowed de facto on-off

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[37] https://stopthesethings.com/2014/10/13/world-first-ontario-council-includes-infrasound-in-wind-farm-noise-law/
[38] http://stopthesethings.com/2014/10/16/board-of-health-declares-wisconsin-wind-farm-a-human-health-hazard/
[39] http://stopthesethings.com/2015/01/23/steven-coopers-cape-bridgewater-wind-farm-study-the-beginning-of-the-end-for-the-wind-industry/
[40] **https://stopthesethings.files.wordpress.com/2015/01/hansen-waterloo-on-off-testing.pdf**

testing to be conducted. They demonstrate that the 'wind turbine signature' of the pulses created by the blades passing the tower is only evident when turbines are operational.

December 1, 2014

Evidence mounts that wind turbines impact on health[41]

21 peer reviewed papers on the adverse health effects of wind turbines

December 1, 2014

Sleep deprivation by wind turbine noise: a dose-response relationship identified[42]

Danish Experts: Sleep Deprivation the Most Common Adverse Health Effect Caused by Wind Turbine NoiseDanish study concludes that noise from wind turbines increases the risk of annoyance and disturbed sleep in exposed subjects in a dose-dependent relationship. The higher the dose or exposure to LFN and infrasound, the worse the disruption to sleep.

February 14, 2015

The story so far ...[43]

We have now come full circle - just as was found 30 years ago - the dB(A) noise filter is totally irrelevant, infrasound LFN is the cause of adverse heath effects and as this is not attenuated, but is often amplified by structures, in-home testing must be used to protect neighbours. Find out more, as the story continues to develop through the Waubra Foundation, a not-for-profit organisation that respresents the communities that have been adversely impacted by wind turbines.

# # #

There is much more to the story since February 2015, some of which is covered in these and other comments. There is never enough time or funds to defend our communities…

[41] http://stopthesethings.com/2014/12/17/21-peer-reviewed-articles-on-the-adverse-health-effects-of-wind-turbine-noise/
[42] http://stopthesethings.com/2014/12/24/danish-experts-sleep-deprivation-the-most-common-adverse-health-effect-caused-by-wind-turbine-noise/
[43] http://waubrafoundation.org.au/

BOULEVARD PLANNING GROUP

PO BOX 1272, BOULEVARD, CA 91905

DATE: March 18, 2019

TO: Bronwyn Brown, PDS Project Manager via Bronwyn.brown@sdcounty.ca.gov

FROM: Donna Tisdale, Chair, Boulevard Planning Group; as an individual: 619-766-4170; tisdale.donna@gmail.com; PO Box 1275, Boulevard, CA 91905

RE: BOULDER BRUSH GEN-TIE LINE AND SWITCHYARD FACILITIES FOR CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019E-ER-19-16-001: NOTICE OF PREPARATION & INITIAL STUDY

At our regular meeting held on March 7, 2019, our Group voted (5-0-0 with 2 absent-excused) to authorize the Chair to submit additional opposition comments on the NOP, following submittal of our previous project comments on 2-12-19. We hereby incorporate by reference all our previous comments submitted on this project, on Terra-Gen's Campo Wind project, and Terra-Gen's Torrey Wind / San Diego Wind project.

Some of these comments may repetitive. The goal is to get our concerns and real world on-the-ground experiences with industrial wind turbines across to decision makers. The impacts are very real with turbine-generated low-frequency noise and infrasound professionally documented here out to 11 miles or so from existing wind turbines in the 2-2.3 MW range. Proposed turbines are 4.2 MW.

Thank you for requiring a joint EIR/EIS. However, we repeat our position that all three Terra-Gen projects must be considered and analyzed in one joint CEQA/NEPA EIR/EIS as the one large project it is. They all use the same substation/switchyard facilities and a single 400 MW CAISO grid queue # 1429 listed as Mount Laguna Wind 2. Purposely piecemealing review of the whole of the project and all connected, direct, indirect actions/impacts is forbidden under CEQA and NEPA; it is also unethical and potentially negligent.

We are formally requesting that the County provide aerial photo maps of these projects showing the project components and all the homes and other occupied structures within at least a 3-5 mile radius, including those on private land and tribal land. The County previously honored a similar request for Enel Green Power's now terminated Jewel Valley Wind project proposed for Jewel Valley and McCain Valley that included the current Torrey Wind project site.

PDS LAND DEVELOPMENT CODE UPDATE

- In a PDS email alert sent on March 15, the following statement was made (emphasis added)*: "PDS is undertaking a comprehensive update of the LDC Update, which includes the County's Zoning Ordinance. The purpose of the LDC Update is to help implement the General Plan and Community Plans, and to advance the County's vision to be Healthy, Safe and Thriving.*"
- Boulevard and surrounding predominantly low-income rural communities ALSO deserve to benefit from the same vision to be Healthy, Safe, and Thriving.

- The growing web of Industrial wind, solar and related utility infrastructure represents just the opposite for our disproportionately impacted and overburdened communities.
- County agencies and decision makers should be protecting our residents instead of repeatedly throwing us under the renewable energy bus as collateral damage.

WIND ORDINANCE NOISE WAIVER & WAIVER OPTIONS MUST BE WITHDRAWN:

- **Boulevard is an unwilling host community!**
- Tule Wind's 57-2.3 MW turbines have been in operation since late 2017.
- PDS and a majority of the Board of Supervisors inexplicably, and in our opinion, negligently gave them a waiver of the C-weighted restrictions in the updated Wind Energy Ordinance.
- Neighbors are now significantly impacted by those 2.3 MW turbines, with no real response to complaints from Tule Wind, BLM, PDS, or elected officials.
- ***Currently, 24 of Torrey Wind's proposed 30 - 4.2 MW turbines are located in the Noise Waiver Area approved as part of the Wind Ordinance! This simply adds insult to injury for impacted residents.***
- Why repeat this huge error in judgment and violation of the Public Trust that has been placed in our government entities and decision makers?
- This undue burden must be lifted from our tax-paying residents. They are suffering through no fault of their own.

THE COUNTY MUST USE SOME OF TULE WIND'S REPORTED $3.5 MILLION/YEAR IN TAX PAYMENTS TO FUND INDEPENDENT NOISE AND ELECTROMAGNETIC INTERFERENCE MONITORING AND MITIGATION AT IMPACTED HOMES:

- Why did the County negligently authorize a noise waiver for Tule Wind? We warned what would happen.
- Where is the post-construction noise monitoring and enforcement?
- Iberdrola was very much aware of the falsity of their claims that there would be no noise issues with their Tule Wind turbines.
- Prior to approval, Iberdrola and their same noise specialist were already being sued by 60 neighbors of their Hardscrabble Wind project in New York State[1]. The impacts described in that lawsuit are eerily similar to what residents are dealing with locally and at other turbine-impacted communities.
- It is our understanding that at least some of the 60 Hardscrabble Wind neighbors have been bought out through confidential settlement agreements with Iberdrola/Avangrid.

2019 PUPLIC HEALTH POSITION STATEMENT ON HUMAN HEALTH EFFECTS OF WIND TURBINES

- Despite our misplaced optimism that our County would actually want to protect public health, the 2019 HHSA statement is just as inadequate and biased towards industry as the 2012 statement. It ignores the real world suffering that has already been and continues to be inflicted and updated research that does not fit the pro-wind industry's political agenda.

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[1] https://www.scribd.com/doc/114674283/Hardscrabble-Wind-lawsuit

- This statement is out-dated and relies mostly on government or industry funded information while ignoring relevant facts and peer-reviewed research that supports impacted residents.
- To date, the vast majority of government funded /industry information is produced without doing actual on-site field studies at turbine-impacted homes.
- March 2019: One example on government funding that promotes wind energy with no funds for protecting public health and safety –just making it faster and less expensive for industry (emphasis added): *The U.S. Department of Energy (DOE) has announced $6.2 million in funding for nine wind energy research projects*[2]. *The projects are focused on reducing environmental compliance costs and environmental impacts of onshore and offshore wind. Funded by the DOE's Office of Energy Efficiency and Renewable Energy's Wind Energy Technologies Office, the early-stage research projects will develop technology solutions to environmental siting and operational challenges to reduce wind project permitting time and costs, increase the certainty of project development outcomes, and provide more deployment options at reduced costs.*
- Overall, these actions appear to be an intentional effort to discredit impacted communities and to benefit the wind industry in support of an unsustainable political agenda.
- The 2019 statement fails to address more recent decisions from courts, boards of health, and other entities in the US and Australia that do find turbines to be nuisance that effects the health and well-being or residents.
- We expect better from our Public Health Officer and Director of Planning and Development Services who are supposed to be protecting the health and well being of all County residents, even those who are unlucky enough to live in a beautiful rural area targeted for industrial conversion as a renewable energy hub.
- PDS's 2019 online Community Planning and Sponsor Group Training document at page 140[3] states that ***the 2011 General Plan "…provides the foundation for decisions that will:…Protect the public from noise, natural, and manmade hazards".***
- The PDS website includes the following statement under the About Us header[4]***: "Department programs such as building plan review, building inspection, and code compliance help maintain public health and safety.***
- The HHSA website includes the following statement: ***"Public Health Services is dedicated to community wellness and health protection in San Diego County. Public Health Services works to prevent epidemics and the spread of disease, protect against environmental hazards****…"*[5]
- Nowhere does it say that the County's pronounced protections, above, DO ***NOT APPLY TO WIND TURBINE-IMPACTED NEIGHBORS AND COMMUNITIES.***
- PDS failed to timely honor our valid requests for the HHSA contact and that the updated public health position statement be included as part of the EIR/EIS review process for Campo Wind and Torrey Wind, and that a draft version be provided for comment prior to release.
- Who authored and approved this public health position statement? Was it PDS or HHSA?
- No one signed it. What are the author's credentials? Who approved it?

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[2] https://nawindpower.com/doe-funds-environmentally-focused-wind-research-projects?utm_medium=email&utm_source=LNH+03-15-2019&utm_campaign=NAW+Latest+News+Headlines

[3]Page 140 https://www.sandiegocounty.gov/content/dam/sdc/pds/Groups/Chair_Resources/CPSGAnnualTraining2019.pdf

[4] https://www.sandiegocounty.gov/content/sdc/pds/AboutUs.html

[5] https://www.sandiegocounty.gov/content/sdc/hhsa/programs/phs.html

- When a Public Records Act Request (PRA) was submitted to HHSA on this statement, Dr. Wooten responded right away that they were in receipt and would respond accordingly.
- Then, Sharon Ippolito PDS PRA coordinator, reached out (email 3-7-19) saying that Dr. Wooten had failed to include the original PRA request letter when she forwarded the email to PDS.
- ***Why is PDS involved in a PRA request to HHSA?***
- In another email (3-15-19), Ms. Ippolito attached a Notice of Extension of Time to Respond to Public Records Act Request, extending response time by 14 days to March 29th. That means the requested documents will not be produced prior to the March 18 the comment deadline for Boulder Brush/Campo Wind or the Statement's March 22nd presentation to the Planning Commission.
- *We know that this biased and inaccurate statement will be used as a bludgeon against our community by developer Terra-Gen, County entities, the Bureau of Indian Affairs, Campo tribal leadership and others in an effort to convince decision makers to approve Terra-Gen's Boulder Brush Gen-Tie and facilities, the 60-586' tall 4.2MW Campo Wind and 30- 4.2 MW Torrey Wind turbines. It is unconscionable*.
- **The statement summary's second bullet point unprofessionally and inadequately states that *while noise from wind turbines is not casually related to adverse health effects ,wind turbines may be a source of annoyance and that annoyance may cause stress that may be associated with certain reported health effects.***
- ***Noise impacts on health are well established*. Turbine-generated noise emission are just more complex and pulsing which makes it even worse for those who are impacted.**
- The legal definition of annoyance:
  Dissatisfaction, disturbance, grievance, hindrance, mischief, molestation, nuisance, provocation, trouble, umbrage[6].
- **From San Diego County's Wind Ordinance' revised DEIR**[7]
  - ***Excerpt-emphasis added*: "Although the reaction to noise would vary, it is clear that noise is a significant component of the environment, and excessively noisy conditions can affect an individual's health and well-being. The effects of noise are often only transitory, but adverse effects can be cumulative with prolonged or repeated** **exposure. The effects of noise on a community can be organized into six broad** ***categories: sleep disturbance, permanent hearing loss, human performance and behavior, social interaction of communication, extra-auditory health effects, and general annoyance."***
- **From San Diego County's CHAPTER 4. NOISE ABATEMENT AND CONTROL**:[8] (emphasis added)
  - ***SEC. 36.401. PURPOSE.***
  - ***" Disturbing, excessive or offensive noise interferes with a person's right to enjoy life and property and is detrimental to the public health and safety. Every person is entitled to an environment free of annoying and harmful noise. The purpose of this***

[6] Burton's Legal Thesaurus, 4E. Copyright © 2007 by William C. Burton. Used with permission of The Mc Graw-Hill Companies, Inc.

[7] Page 2.8.3 & 2.8.4: https://www.sandiegocounty.gov/pds/advance/POD10007DEIR.html
[8] https://www.sandiegocounty.gov/dplu/docs/NO-401.pdf

chapter is to regulate noise in the unincorporated area of the County to promote the public health, comfort and convenience of the County's inhabitants and its visitors. "

- ***Noise abatement and control should apply to all 'inhabitants'!***
- The final bullet point of the 2019 HHSA's statements Summary says, "*The weight of evidence suggests that, when sited properly, wind turbines are not related to adverse health effects."*
- ***WHAT IS PROPER SITING? HOW CAN THAT STATEMENT BE DEEMED VALID WHEN NO SITING RESTRICTIONS OR EVIDENCE THAT THEY ARE SAFE ARE EVEN MENTIONED OR CITED??***
- ***WHAT ARE THEY BASED ON? SELF-SERVING CONFLICTED INDUSTRY RECOMMENDATIONS OR REAL WORLD IMPACTS AND SETBACKS?***
- *We already have people impacted by turbines within at least a 5 mile or so radius. One property owner 3 miles from turbines has lost two tenants due to turbine noise and vibrations.*
- Based on our community's first-hand experience with wind turbine impacts since 2005, and hearing directly from those impacted at Boulevard Planning Group meetings, we strongly object to and denounce the 2019 statement as outdated, invalid, and negligent.
- *When actual field studies and/or hearings are conducted, the professionals involved have repeatedly exposed the high levels of wind turbine generated noise / vibrations and related sleep disruption and adverse health affects that generally discredit the government /industry positions of 'no impact'on those specific projects.*
- **Recent professional noise testing was conducted at 15 Boulevard area homes[9] by Richard Carman Ph.D, P.E. (40 years experience)[10] and Michael Amato (35 years experience) [11] with Wilson Ihrig, Accoustics, Noise & Vibrations**. They documented the presence of low-frequency noise, infrasound, and amplitude modulation within 8 miles from Tule Wind and Kumeyaay Wind based on current measurements. And Ocotillo Wind infrasound 11-12 miles away from Boulevard and Jacumba Hot Springs homes at levels as high as 66dB. The report also includes their 2013 report on measurements taken in 2012 prior to Tule Wind's construction. Their report is being submitted for the record by others.
- **Falmouth Massachusetts' two turbines are referenced in the statement:**
  - ***What is not referenced in the 2019 HHSA statement is the* Massachusetts Court of Appeal Decision[12] entered November 6, 2018, upholding an early judgment that The judgment declared that two wind turbines operated by the town were a nuisance and ordered that their operation cease and desist.**
  - **(excerpt): (emphasis added)** *Dr. George Woodwell and The Green Center, Inc. (proposed interveners) appeal from the denial of their motion to intervene in an action between the town of Falmouth (town) and the Falmouth zoning board of appeals (board) in which judgment had already entered. The town did not appeal from that judgment. The proposed interveners sought to defend the interests of the town by intervening for the*

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[9] Results of Ambient Noise Measurements of the Existing Kumeyaay Wind and Tule Wind Facilities In the Area of Boulevard of Boulevard and Jacumba Hot Springs Pertaining To The Proposed Torrey Wind and Campo Wind Turbine Facilities: 15 March 2019; submitted by Richard Carman, Ph.D, P.E; Michael A. Amato

[10] http://www.wilsonihrig.com/about-us/meet-our-team/richard-carman/

[11] http://www.wilsonihrig.com/about-us/meet-our-team/michael-amato/

[12] COMMONWEALTH OF MASSACHUSETTS APPEALS COURT 18-P-104 TOWN OF FALMOUTH vs. ZONING BOARD OF APPEALS OF FALMOUTH & others.1 MEMORANDUM AND ORDER PURSUANT TO RULE 1:28: Full document posted at: http://www.windaction.org/posts/49053-court-order-in-falmouth-appeal-denied#.XI2RrChKiUk

purpose of filing a motion for relief from judgment to modify the remedy pursuant to Mass. R. Civ. P. 60 (b), 365 Mass. 828 (1974). The judge denied the motion concluding that the interveners could not likely establish standing, and that the motion was untimely. We affirm.

  - **The underlying case: Superior Court Upholds ZBA's Order that the Town of Falmouth Cease and Desist the Operation of Two Wind Turbines**
  - ***The Decision*[13]*(emphasis added):*** *The Court upheld the ZBA's finding that the turbines constituted a nuisance, and ordered the Town to cease operating the turbines. The Court found, based on multiple studies that were presented as evidence, that the noise created by the turbines exceeded the allowable ambient noise levels under the Town Bylaw. The Court further found that the ZBA could apply the Town Bylaw regarding noise as adopted in 2013, even though the turbines were already operating at the time the Bylaw was adopted. Moreover, the Court held that the turbines constituted a nuisance regardless of whether they violated the noise Bylaw. The Court held that the noise generated by the turbines negatively affected the health and well-being of the Funfars, by, among other things, causing Mr. Funfar stress, anxiety, insomnia, and nausea. The Court also noted that other residents had registered similar complaints, lending further support to its order to shut down the turbines.*

- ***Turbine bombshell: A new investigation into Bald Hills Wind Farm noise complaints has found that neighbours' health concerns are legitimate; posted 9-11-18 by South Gippsland Sentinel-Times*** [14] ***(Australia)***
  - **Noise 'detrimental and unreasonable'**
  - THE investigation commissioned by the South Gippsland Shire Council, at a cost of $33,600, into Noise Complaint Notifications by residents living near the Bald Hills Wind Farm is complete. And two and a half years after they first made their grievances known, the report has found their complaints were fully justified.
    Described by the shire as "a highly experienced independent public health consultant", at his appointment in February this year, James C. Smith and Associates has found that "there is a nuisance caused by wind farm noise, in that, the noise is audible frequently within individual residences and this noise is adversely impacting on the personal comfort and wellbeing of individuals".
- **Dec 4, 2017: Australia's Administrative Appeals Tribunal (ATT) - Waubra Foundation vs ACNC:**
  - **Summary of the Effect of the Medical and Scientific Evidence (starting at paragraph 467 of the judgment, here are the key factual findings and conclusions on noise and health**[15] **(emphasis added):**
    - ***SUMMARY OF THE EFFECT OF THE MEDICAL AND SCIENTIFIC EVIDENCE***
    - *On our analysis, a number of propositions emerge from the medical and scientific evidence. Some of those propositions had unanimous support by the relevant experts, and others had the support of most.*

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13 https://www.lexology.com/library/detail.aspx?g=c7a2e6c7-18ce-469f-987c-00cc2844995d
14 https://sgst.com.au/2018/09/turbine-bombshell/
15 https://waubrafoundation.org.au/wp-content/uploads/2017/12/Decision-4-Dec-17.pdf

- *The propositions which we understand have unanimous support from the relevant experts or are not contested include the following:*
- *Wind turbines emit sound, some of which is audible, and some of which is inaudible (infrasound);*
- *There are numerous recorded instances of WTN exceeding 40 dB(A) (which is a recognized threshold for annoyance/sleep disturbance);*
- *There are also recorded instances of substantial increases in sound at particular frequencies when particular wind farms are operating compared with those at times when they are shut down. [Measurements undertaken at the Waterloo wind farm showed that "noise in the 50 Hz third-octave band was found to increase by as much as 30 dB when the wind farm was operational compared to when it was shut down" – Exhibit A51, p 2.]*
- *If it is present at high enough levels, low frequency sound and even infrasound may be audible;*
- *WTN is complex, highly variable and has unique characteristics;*
- *The amount and type of sound emitted by a wind farm at a given time and in a given location is influenced by many variables including topography, temperature, wind speed, the type of wind turbines, the extent to which they are maintained, the number of turbines, and their mode of operation;*
- *Wind farms potentially operate 24 hours a day, seven days a week;*
- *There are numerous examples of WTN giving rise to complaints of annoyance from nearby residents, both in Australia and overseas.*
  - *The propositions which are supported by the preponderance of relevant expert opinion, and which we accept on that basis, include the following:*
- *A significant proportion of the sound emitted by wind turbines is in the lower frequency range, i.e. below 20 Hz;*
- *The dB(A) weighting system is not designed to measure that sound, and is not an appropriate way of measuring it. It is even acknowledged in the International Standard, ISO 1996-1 that the A-weighting system alone is "not sufficient to assess sounds characterized by tonality, impulsiveness or strong low-frequency content" – Exhibit A29, T43/8; Section 6.1; "Acoustics – Description, measurement and assessment of environmental noise – Part 1: Basic quantities and assessment procedures", International Standard ISO (1996-1).*
- *The most accurate way of determining the level and type of sound present at a particular location is to measure the sound at that location;*
- *The best way of accurately measuring WTN at a particular location is through 'raw' unweighted measurements which are not averaged across time and are then subjected to detailed "narrow-band" analysis;*
- *When it is present, due to its particular characteristics, low frequency noise and infrasound can be greater indoors than outdoors at the same location, and can cause a building to vibrate, resulting in resonance;*

- *Humans are more sensitive to low frequency sound, and it can therefore cause greater annoyance than higher frequency sound;*
- *Even if it is not audible, low frequency noise and infrasound may have other effects on the human body, which are not mediated by hearing but also not fully understood. Those effects may include motion-sickness-like symptoms, vertigo, and tinnitus-like symptoms. However, the material before us does not include any study which has explored a possible connection between such symptoms and wind turbine emissions in a particular population.*
    - *We consider that the evidence justifies the following conclusions:*
- *The proposition that sound emissions from wind farms directly cause any adverse health effects which could be regarded as a "disease" for the purposes of the ACNC Act is not established;*
- *Nor, on the current evidence, is there any plausible basis for concluding that wind farm emissions may directly cause any disease;*
- *However, noise annoyance is a plausible pathway to disease. We note the World Health Organization has stated: "There is sufficient evidence from large-scale epidemiological studies linking the population's exposure to environmental noise with adverse health effects. Therefore, environmental noise should be considered not only as a cause of nuisance but also a concern for public health and environmental health"– Exhibit A4, T287/5709, citing "WHO. Burden of disease from environmental noise." World Health Organization; 2011 [viewed April 2013]; Available from: http://www.euro.who.int/en/what-we-publish/abstracts/burden-of-disease-from-environmental-noise.-quantification-of-healthy-life-years-lost-in-europe as referenced by Professor G Wittert in Exhibit 56 NHMRC Draft Information Paper: Evidence on Wind Farms and Human Health, "Expert Review: Comments in full", National Health and Medical Research Council, February 2015, Appendix 8; and Exhibit 4, T299/6308, Reference No. 40, WHO "Burden of disease from environmental noise". Bonn: World Health Organization European Centre for Environment and Health, 2011. Available from: http://www.euro.who.int/__data/assets/pdf_file/0008/136466/394888.pdf*
- *There is an established association between WTN annoyance and adverse health effects (eg. this was established by the Health Canada study);*
- *There is an established association between noise annoyance and some diseases, including hypertension and cardiovascular disease, possibly mediated in part by disturbed sleep and/or psychological stress/distress. This is also supported by much of the documentary material before us, including a Victorian Department of Health publication entitled "Wind farms, sound and health", Technical Information, at 7. How can noise affect our health? – Exhibit A4, T297/6232362.*
- *There are as yet no comprehensive studies which have combined objective health measurements with actual sound measurements in order to determine*

for a given population the relationships between the sound emissions of wind turbines, annoyance, and adverse health outcomes. Indeed there is as yet no study which has given rise to a soundly based understanding of the degree to which particular types or levels of wind turbine emissions give rise to annoyance, or what levels or types of emissions are associated with what level of annoyance in the population. Because it relied on calculated rather than actual sound measurements, and was limited to the A and C-weighted systems, the Health Canada study did not do this. # # #

- **Neighbors of San Diego Regional Airport get a night time curfew for flights between 11:30 pm and 6 am so they can sleep. They can also apply for other mitigation such as dual pane windows and other home improvements through the federally funded Quieter Home Program**[16].
- **Neighbors of freeways get sound walls to help reduce the impact**.
- ***Neighbors of wind turbines, where noise and vibrations trespass into their homes and properties, creating a nuisance and adverse health impacts, say the turbines sound like jets that never land.***
- Neighbors also say they feel like they live in an airport runway with the rows of flashing red lights on top of turbines that sound of jets flying over.
- Turbine neighbors get nothing other than denial of the impacts they are suffering, allegations that they would be OK with those impacts if they were paid for them, and other inconsiderate and rude rejections and allegations.
- This reaction from decision makers and those who get paid to reportedly protect the public health and safety is unjust and unfair.

ENVIRONMENTAL JUSTICE APPLIES IN THE BOULEVARD / CAMPO –MANZANITA-LA POSTA RESERVATION AREA. A MAJORITY OF OUR CLOVER FLAT ELEMENTARY STUDENTS RECEIVE FREE MEALS:

- *CEQA, at its heart simply demands that a government agency fully contemplate and disclose the foreseeable consequences of its actions and avoid unnecessary environmental risks*
- **California Office of Attorney General Office Health In all Policies Task Force has the following Goals created in 2010 by Executive Order S-04-10, *the Health in All Policies Task Force***[17] *is charged with identifying "priority programs, policies, and strategies to improve the health of Californians while advancing the goals of improving air and water quality, protecting natural resources and agricultural lands, increasing the availability of affordable housing, improving infrastructure systems, promoting public health, planning sustainable communities, and meeting the climate change goals." The Attorney General sits on the Task Force, along with officers of 18 other California state agencies, departments, and offices.*
- ***Their identified goals include the following*:**
    - ***All California residents live in safe, healthy, and affordable housing.***

[16] https://www.kpbs.org/news/2015/feb/26/free-windows-doors-installed-3000-homes-near-san-d/
[17] https://oag.ca.gov/environment/communities/policies

- *California's decision makers are informed about the health consequences of various policy options during the policy development process.*

- **Environmental Justice & Healthy Communities**[18] "Environmental Justice" is defined in California law as the fair treatment of people of all races, cultures, and incomes with respect to the development, adoption, implementation, and enforcement of environmental laws, regulations, and policies. (Cal. Gov. Code, § 65040.12, subd. (e).)

NEPA:

- **The Council on Environmental Quality's Guidance Under NEPA includes the following (excerpts):**
  - *Each Federal agency should analyze the environmental effects, including human health, economic, and social effects of Federal actions, including effects on minority populations, low-income populations, and Indian tribes, when such analysis is required by NEPA." l Mitigation measures identified as part of an environmental assessment (EA), a finding of no significant impact (FONSI), an environmental impact statement (EIS), or a record of decision (ROD), should, whenever feasible, address significant and adverse environmental effects of proposed federal actions on minority populations, low-income populations, and Indian tribes. '* l Each Federal agency must provide opportunities for effective community participation in the NEPA process, including identifying potential effects and mitigation measures in consultation with affected communities and improving the accessibility of public meetings, crucial documents, and notices. l3 l Review of NEPA compliance (such as EPA's review under $ 309 of the Clean Air Act) 9 Id. at 7632 (Section 5-5). lo Id. at 7632 (Section 5-5) 'I Memorandum from the President to the Heads of Departments and Agencies. Comprehensive Presidential Documents No. 279. (Feb. 11, 1994). '* Id. I3 Id. must ensure that the lead agency preparing NEPA analyses and documentation has appropriately analyzed environmental effects on minority populations, low-income populations, or Indian tribes, including human health, social, and economic effects.14*[19]

PROBABLE ENVIRONMENTAL EFFECTS:

- People and project effects on human health, social and economics, are part of the environment and must be analyzed, including potentially significant effects on health and safety, quality of life, use and enjoyment of property, property values, potential loss of life-time investments, increased fire insurance costs or loss of insurance due to approval of up to 90 more industrial wind turbines, 8.5 miles of 150' tall poles and wires, and related infrastructure, all of which represent individually and cumulatively significant increase in wild fire ignition sources and fire fighting impediments/hazards.
- Fire fighters will need to wait for a fire to burn out of the project area to avoid potential hazards, thereby allowing a fire to potentially increase in size of blow out of control.
- We are requesting that Terra-Gen and property owner GM Gabrich be required to offer **PROPERTY VALUE PROTECTION AGREEMENTS** to help mitigate the very real overall negative

[18] https://oag.ca.gov/environment/communities
[19] https://ceq.doe.gov/docs/ceq-regulations-and-guidance/regs/ej/justice.pdf

impacts their projects represent to our rural community and residents who have invested here to enjoy a quiet rural lifestyle.

- **NOP Page 2: Recreation should be included in the EIR** due to the fact that both tribal and private residents use areas impacted by Boulder Brush Gen-Tie, Campo Wind (Campo Reservation), and Torrey Wind for walking, hiking, horseback riding, wildlife viewing, photography, stargazing, and more. None of that will be the same if an additional 60-90 4.2 MW 586' tall industrial wind turbines and almost 80 new steel poles up to 150' tall with high voltage lines are authorized and alter what is here now, especially in areas south of I-8 to the US/Mexico border.
- **The Boulevard Planning Area Community Trails Map, approved by the Board of Supervisors on June 24, 2009**, includes proposed trails along the train tracks through the Campo Reservation, along Tierra Del Sol / Shockey Truck Trail along the southern edge of the Campo Reservation and in the Ribbonwood Road area where portions of Boulder Brush Gen-tie line, facilities, and Torrey Wind turbines are proposed, including roads. Construction and operation would represent significant and cumulatively significant impacts.

PROJECT LOCATION:

- It needs to be made clear to decision makers that the existing Kumeyaay Wind and Tule Wind projects are located on federal land and that Torrey Wind will be the first proposed solely on private absentee-owned ranch land. And that Ribbonwood Road is the sole access for all the homeowners who reside in that neighborhood north of I-8.
- Kumeyaay Wind was approved by the Bureau of Indian Affairs with just an EA, no EIS!
- Introduction of the 8.5 mile Gen-tie line with 150' tall steel poles and reflective wires will not be compatible with the impacted residential areas on private and tribal lands.
- For most area residents, the existing Southwest Powerlink along the US/Mexico Border and the Sunrise Powerlink north of I-8 near the base of the Lagunas are not visible, due to our rolling terrain with valleys and ridges. The same is true for some or all of existing wind turbines.
- These new structures are not compatible with the majority of current land uses and mostly undeveloped quiet rural area. Loss of amenity and quality of life is a huge issue.

CAMPO WIND TURBINES – APPROVAL, CONSTRUCTION, O & M

- The NOP states that the County has no jurisdiction over the turbines. We all know that the noise, vibrations, dust, electrical and light pollution emissions will not stay within the boundaries of the Campo Reservation.
- These impacts represent both public and private nuisances and should be formally acknowledged as the facts on the ground for those already impacted by existing turbines that are 2MW and 2.3 MW each.
- The impacts from the proposed 4.2 MW turbines can and will increase exponentially. It is a matter of physics that has been documented
    - **Low-frequency noise from large wind turbines Henrik Møllera) and Christian Sejer Pedersen Section of Acoustics, Aalborg University, Fredrik Bajers Vej 7-B5, DK-9220 Aalborg Ø, Denmark (Received 5 July 2010; accepted 20 December 2010)** VC 2011

Acoustical Society of America. [DOI: 10.1121/1.3543957] PACS number(s): 43.50.Rq, 43.28.Hr, 43.50.Cb, 43.50.Sr [ADP] Pages: 3727–3744[20]

- (excerpts -emphasis added) *" As wind turbines get larger, worries have emerged that the turbine noise would move down in frequency and that the low-frequency noise would cause annoyance for the neighbors. The noise emission from 48 wind turbines with nominal electric power up to 3.6 MW is analyzed and discussed. The relative amount of low-frequency noise is higher for large turbines (2.3–3.6 MW) than for small turbines (2 MW), and the difference is statistically significant. The difference can also be expressed as a downward shift of the spectrum of approximately one-third of an octave. A further shift of similar size is suggested for future turbines in the 10-MW range. Due to the air absorption, the higher low-frequency content becomes even more pronounced, when sound pressure levels in relevant neighbor distances are considered. Even when A-weighted levels are considered, a substantial part of the noise is at low frequencies, and for several of the investigated large turbines, the one-third-octave band with the highest level is at or below 250 Hz. It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbors".*
- ***"V. CONCLUSIONS The results confirm the hypothesis that the spectrum of wind turbine noise moves down in frequency with increasing turbine size. The relative amount of emitted low-frequency noise is higher for large turbines (2.3–3.6 MW) than for small turbines (2 MW). The difference is statistically significant for one-third-octave bands in the frequency range 63–250 Hz. The difference can also be expressed as a downward shift of the spectrum of approximately one third of an octave. A further shift of similar size is suggested for turbines in the 10-MW range".***

- Based on first-hand experience with existing Kumeyaay Wind, Tule Wind, and Ocotillo Wind, all located on federal land, we know that there is little to no response to complaints filed. This inexplicable behavior and lack of response is not only alarming, it borders on negligence
- Who will be responsible for responding to complaints from residents living under County jurisdiction?
- Enforceable limits/restrictions must be placed on noise, vibrations, low-frequency noise, infrasound, electrical and light pollution emissions generated by the proposed Campo Wind and Torrey Wind turbines.
- No new turbines should be allowed until a legitimate and independent Health Impact Assessment is conducted at homes impacted by the existing Kumeyaay Wind and Tule Wind turbines. A moratorium should be mandated.
- **Excerpt from 2012 electrical pollution measurements in 2013 report for homes impacted by Kumeyaay and Ocotillo Wind turbines[21]:**

[20] http://vbn.aau.dk/files/53111081/Low_frequency_noise_from_large_wind_turbines.pdf

[21] Pages4-5: Assessment of Power Quality and Electromagnetic Field (EMF) Exposure at Campo and Manzanita Reservation Residences near the Kumeyaay Wind Turbines, And Ocotillo-Area Residences near the Ocotillo Wind Energy Facility Wind Turbine Electric Generator Installation: Sal La Duca Indoor Environmental Consultant Environmental Assay Inc. www.emfrelief.com 908-454-3965

- **(Executive Summary & Findings- excerpts-emphasis added): "*All residences displayed electrical characteristics within their electrical systems that are foreign to their electrical devices and related consumption characteristics. That is, these characteristics were detectable even with no power in use within the residences investigated (main breaker open/off). By virtue of the Electric field availability from installed wiring, all of these uncommon electrical characteristics (whether with power on or off) became a component of chronic personal exposure. Some residents noted experiencing damaging interference with their electrical / electronic equipment. One individual remarked having to replace a well pump several times. High frequency harmonics or other frequencies using the electric system as a carrier were detected at this site.2 High frequencies perform no useful work, other than perhaps heating (precipitating equipment burnout), when they are conveyed to a device engineered for 60 Hz exclusively. Another noted repeated EMI to television reception. Again, a high frequency presence was identified at this site on the electric system, and due to the type of electrical connection, external EMI is brought indoors without reduction. Some tribal members described the onset of various health issues that seemed to coincide closely with a certain time lag from the installation of the turbines, such as numerous cancers including stomach, kidney and brain".***
- ***"Although the scope of testing was limited, preventing us from conclusively determining the ultimate source(s) and propagation pathway(s) of the measured EMI, the most likely sources appear to be the Kumeyaay wind turbines and associated electrical substation and power distribution facilities. The most likely pathways are through ground currents, via the aerial distribution primary, and through the air when in closest proximity to the turbines. This may be considered pollution in an otherwise 60-Hz only environment where it may interfere with various forms of sensitive electronics, or life forms whose sensitivity is heightened for whatever reason".***

BOULDER BRUSH GEN-TIE LINE AND FACILITIES: CONSTRUCTION AND O & M:

- The gen-tie should be buried underground to reduce a wide-variety of impacts to scenic vistas, people, wildlife, law enforcement , Homeland Security, military, and emergency services employees whose lives and /or jobs will be impeded one way or another by 150'tall poles and wires and related 90-586' tall turbines.
- If built overhead, it is obvious that the Boulder Brush Gen-tie line will cross Old Hwy 80 & I-8 between Live Oak Springs and the Golden Acorn Casino.
- This means those routes of travel will be closed for certain periods of time.
- The community needs to be notified of when those closures will take place. It is the right thing to do.

ROADS:

- Residents on the north end of Ribbonwood Road have reported project vehicles parked in a manner that has blocked their road on several occasions.

- It is good to see that paving the unpaved section of Ribbonwood Road is planned.
- However, if the project is approved over local objections, paving will not reduce the traffic impacts for Ribbonwood Road residents related to the individual project or potentially overlapping construction of Campo Wind, Boulder Brush Gen-tie line and facilities, Torrey Wind, and / or Rugged Solar. They all plan to use Ribbonwood Road.
- A real traffic plan and notices must be provided to residents along with direct notification when their only road will be closed or traffic will be delayed so they can plan their lives accordingly.
- Entrance to the project should be located in a manner that least impacts the residents that rely on that road where the entrance is proposed.
- Using Lost Valley Road from McCain Valley Road should be considered as an alternative.

SURROUNDING LAND USES & SETTING:

- Land uses on private land in the area are overwhelmingly rural residential. Turbines and utility scale electrical infrastructure are not compatible.

Other Public agencies whose approval is required should also include the following:

- **US Border Patrol Campo & Boulevard Substations & US Military:**
    - Any approval of 546' tall wind turbines and new 150' tall utility lines and wires can and probably will impede both aerial and ground operations and officer safety in our US/Mexico border zone.
    - The same is true for US military flight paths and training at the local La Posta SEAL training facility and between air bases in San Diego and Arizona.
    - Currently, it is our understanding that military craft are supposed to fly 400 feet from the ground or above, but they seem to fly over our area daily much lower than that.
    - Border Patrol craft seem to fly much lower than that, especially when they are pursuing or monitoring groups of migrants who illegally cross the border in the Boulevard/Campo area.

ENVIRONMENT FACTORS POTENTIALLY AFFECTED:

- Page 8: Recreation, Agriculture & Forest Resources (Oak forests), Population & Housing and Mineral Resources *should all be checked marked as potentially affected.*
- We do agree with those factors that are already marked as potentially significant.
- Noise impacts during operation, too! Post construction noise monitoring must be funded by developers and enforced by the County for those located within their jurisdiction.

I. AESTHETICS:

- We agree with the Potentially Significant determination.
- Visual pollution/ loss of amenity impacts to private properties and quality of life must also be addressed, not just designated scenic resources.
- Terra-Gen's proposed Campo and Torrey Wind turbines will be 586 feet tall and will be highly visible, due to their expansive footprint, to many residents in Boulevard, Campo and the Campo Manzanita and La Posta Reservations.

- The churning motion of turbines can and does have adverse health effects for those who have vertigo or other existing or exacerbated health impacts.
- The bright flashing red lights at night can and do disturb sleep for some of our turbine-impacted residents.
- Sleep disruption, especially chronic sleep disruption/deprivation is a known stressor and adverse health impact that can and does result in numerous other debilitating maladies.
- ***See the 2019 Wind Turbine Neighbor Survey forms that were filled out by impacted residents and submitted to Bronwyn Brown and others on March 17th*. They all listed numerous health effects and 14 of the 15 respondents said the turbines made them want to move.**

III. AIR QUALITY: KNOWN SENSITIVE RECEPTORS, "OTHER EMISSIONS", AND CHRONIC EXPOSURE

- **III-d @ page 15: The project will result in "other emissions" that must include electrical** pollution that has already been documented around local wind turbines and electrical infrastructure. These damaging emissions must be recognized and honestly analyzed.
- High Voltage lines and industrial wind turbines do generate electrical radiation pollution that moves through the air (air quality) and the ground[22].
- **The wind industry is aware of the need to discharge/divert dangerous rotor voltages and currents into the ground in order to protect bearings and other vulnerable components.**
- *However, that energy goes somewhere and many times, in addition to radiation through the air, electrical pollution shows up in the ground and in homes on non-participating properties resulting in electrical pollution and related health effects.*
    - **AGES WIND TURBINE GROUNDING: Dangerous Voltages and Currents Present on Wind Power Turbine Generators – Must be Discharged to Ground for Reliable Operation**[23]
    - **Excerpt (emphasis added):** "*…Bearings and other critical components frequently fail because of high shaft currents generated in the wind turbine nacelle. Reliable maintenance free protection from rotor shaft high voltages and currents will reduce maintenance costs and improve up-time for wind turbine owners and operators. Problem: Wind turbine generator stator windings and rotors are directly connected to the power grid. Unlike the stator, the rotor is connected to the same grid via a converter. The converter makes operation possible at variable rotor speeds while maintaining constant stator voltage and frequency outputs to the grid. This system introduces dangerous rotor shaft voltages, and due to the high frequency converter switching, the generators, gear boxes, and other critical components are exposed to dangerous high frequency shaft currents causing EDM (Electrical Discharge Machining). Solution: A new shaft grounding technology known as AEGIS WTG (Wind Turbine Shaft Grounding System) uses circumferential rings of conductive micro fibers to discharge these harmful currents to ground. The AEGIS WTG shaft grounding system was successfully tested and applied to a GE 1.5 MW generator. Up-tower voltages of 1200 volts peak were measured on the shaft of the turbine. After AEGIS WTG was installed, the voltage was reduced to 32 volts peak. Concurrently, 56 amps of high frequency shaft currents are being diverted*

[22] http://www.electricalpollution.com/windturbines.html

[23] http://file.seekpart.com/keywordpdf/2011/5/13/2011513133815310.pdf

through the AEGIS WTG shaft grounding ring. The AEGIS WTG, a grounded conductor ring, is placed between the stator winding and the rotor. Dangerous rotor shaft voltages are diverted to ground, protecting bearings and other vulnerable components…"

- **We remind you that high levels of electromagnetic fields (EMF) and electromagnetic interference (EMI) were documented in late 2012 at homes around existing Kumeyaay and Ocotillo Wind turbines, and were the subject of a 2013 report**.[24]
- **David Stetzer of Stetzer Eelectric wrote a letter about his experience with wind turbines and electrical pollution: (attached) (excerpt-emphasis added) "** *In conclusion, it is my opinion that the electric utility is dumping distorted, high frequency currents into the earth where it flows uncontrolled over the ground back to their sub-stations. The wind turbines are a major source of these high frequency transients that are on the electric utility's electrical grid and end up on the earth. The IEEE Standards Association's NESC Handbook, Seventh Edition, Rule 215B, "prohibits the use of the earth normally as the sole conductor for any part of a supply circuit. … (Objections to use of the earth as part of a supply circuit are made from both safety and service standpoints.)" These currents destroy the infrastructure by electrolysis. They also affect milk production in dairy cows as shown in published, scientific, peer-reviewed papers. EPRI, the electric utility's own research arm, reports levels as low as 18µA cause cancer in humans. Rule 215B in the NESC Handbook also says: The destructive nature of current flow through the earth endangers other facilities through electrolysis. When earth returns were used in some rural areas before the 1960's, they became notorious offenders in dairy areas because circulating currents often caused both step and touch potentials. In some cases, these have adversely affected milking operations by shocking the cattle when they were connected to the milking machines and have affected feeding (see Rule 92D – Current in Grounding Conductor). The grounding methods required by the NESC, including the use of a metallic neutral throughout each span of a multi-grounded wye system, reduced the opportunity for such occurrences. It should be noted that the measurements are a mere snapshot in time and will change continuously as electrical loads change on the system. They will only become worse as more non-linear loads are connected to the grid. The so called "Green" loads such as solar and wind generation will only amplify these problems due to their lack of filters and use of switch-mode power supplies and inverters."*
- **Sensitive Receptors:** We repeat our request for the County to produce aerial photo maps showing how many residences are located within at least 3 miles of the proposed Boulder Brush Gen-Tie and facilities, the Campo Wind and Torrey Wind turbines.
- Current residents in the area include children, elderly, those whose health has already been negatively impacted their health and their immune systems compromised.
- ***Exposure will take place not only during construction but during the life of the project.***
- ***Cancer cases:* There are also several suspicious cases of cancer around the Kumeyaay Wind turbines and infrastructure, SDG&E's Boulevard Substation and the Southwest Powerlink, including but not limited to: brain, stomach, kidney, polycythemia, esophagus, tumors, Leukemia, and K9 Leukemia.**

[24] Assessment of Power Quality and Electromagnetic Field (EMF) Exposure at Campo and Manzanita Reservation Residences near the Kumeyaay Wind Turbines, And Ocotillo-Area Residences near the Ocotillo Wind Energy Facility Wind Turbine Electric Generator Installation; by Sal La Duca, Environmental Assay Inc 2-13.

VI. ENERGY:

- Based on our first-hand experience with Kumeyaay Wind, Tule Wind and Ocotillo Wind, there are times when the wind is not blowing and the turbines are actually consuming energy for cooling or heating their equipment to prevent damage.
- Some residents have complained about the noise from this equipment. Sound and vibrations carry great distances out here, especially low-frequency noise.
- We have asked for but have never received information on just how much energy these projects consume from the grid when the wind is not blowing.

IX-g: VECTORS:

- **"No Impact' determination should be revised.**
- Ribbonwood Road residents have complained about an influx of rats, squirrels, and snakes after Tule Wind turbines started operation in late 2017. They believe the ground vibrations drove them away from the Tule Wind site and onto private properties.
- Rats, squirrels, and other ground dwellers are considered vectors that can carry ticks and fleas and related diseases including Lyme and co-infections, bubonic plague, and murine typhus.

X. HYDROLOGY AND WATER QUALITY:

- Local ground water concerns are well-known to PDS and Jim Bennett. They are no different for this project and potential use of groundwater that can impact existing residential wells.
- Terra-Gen's proposed Boulder Brush/Torrey Wind (formerly known as San Diego Wind) project site is significantly impacted by the boundaries of the 100 year flood limits as documented in their San Diego Wind MET Tower Plot Plan (Westwood 5-10-18) page 2, submitted to PDS.
- The main project entrance is planned at the bottom of the Tule Creek floodplain drainage that crosses Ribbonwood Road within those 100-year flood boundaries.
- Previously, Public Works required at least one property owner to put funds into an account to build an all-weather crossing in that area. It was never built.
- Terra-Gen should be required to build that all-weather crossing for their projects and for their neighbors.
- In addition, there is /was an old water conservation dam reportedly located on Manzanita Reservation that previously eroded and resulted in a flood of stinky water washing out Ribbonwood Road near the proposed entrance of the Boulder-Brush /Torrey Wind project site.

XII. MINERAL RESOURCES:

- The Boulder Brush Gen-Tie / Torrey Wind site is located in an alluvium filled valley along Tule Creek. Like other alluvium filled valleys, it is full of Decomposed Granite (DG)
- DG is a well known mineral that could be of high value, with limited regional sources.

XII NOISE:

- ***<u>Noise impacts on health and welfare are well known and well documented: Noise from wind turbines is generally more complex but no less harmful. Also see comments on 2019 HHSA statement above.</u>***

  - **According to the County's Wind Turbine Development Information page[25], "<u>The following Noise Abatement Verification needs to be made part of the plot plan and signed</u>"**

    - I, the property owner, understand that the wind turbine system(s) proposed at ______________________ must comply with the requirements of Title 3, Division 6, Chapter 4 (Noise Abatement And Control) of the San Diego County Code of Regulatory Ordinances.
    - If the wind turbine system(s) permitted and installed on my property exceed the noise limit requirements I understand that the County of San Diego will take enforcement action which may require the property owner to alter or remove the wind turbine system(s).
    - Signed,
    - ____________________________________ _________________
      Name (printed) Date
    - ____________________________________
      Signature

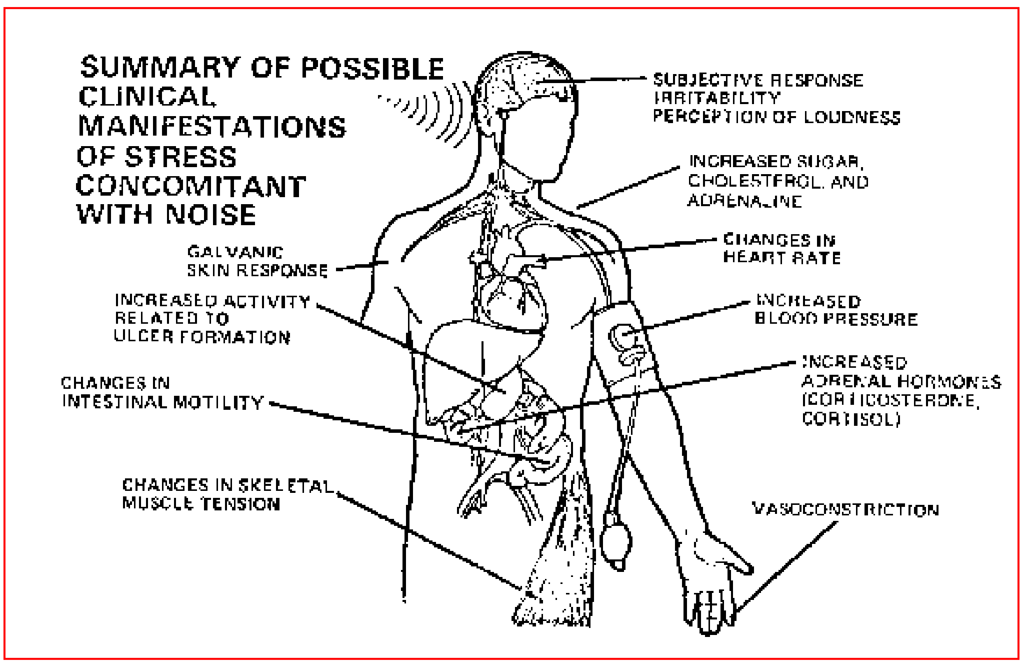
  - The **Noise Abatement Verification**, above, appears to indicate that the County is actually fully aware of the noise impacts from wind turbines.
  - **A new book has been published by Bruce Rapley, PhD: *<u>Conversations for a small planet; Volume 3 Biological Consequences of Low-Frequency Sound</u>***; published by Bouncing Koala Press in New Zealand 2018 (ISBN 978-473-46673-2)[26]
    - This peer-reviewed book is hereby incorporated fully by reference. A copy has been purchased and has been mailed to Bronwyn Brown at PDS for inclusion in the record for Terra-Gen'
    - Dr. Rapley is a consulting scientist with a PhD in Human Health and Cognition, an MPhil. in Technology and a BSc. in Biological Systems. His primary research interest is in environmental factors that affect living systems. Much of his earlier research focused on low-frequency magnetic fields and their effects on people and plants. Much of his pioneering research was conducted in this field which came to be known as bioelctromagnetics.
    - Combined with his research for his PhD in Human Health and Acoustics with the New Zealand Defence Force (NZDF), Dr. Rapley has a unique knowledge base and understanding of how sound in the environment can affect cognition (brain function –thinking processes) and physiological responses. ***That the human brain responds to subliminal sound is exemplified by the latest functional magnetic resonance imaging research from the German research team***

[25] https://www.sandiegocounty.gov/pds/windturb.html
[26] http://www.smart-technologies.co.nz/books.html

(Weichenberger et al. 2018[27]). They conclude that:
"Low-frequency sound (including infrasound) can, and does, affect the brain, at sound power levels below conscious perception".

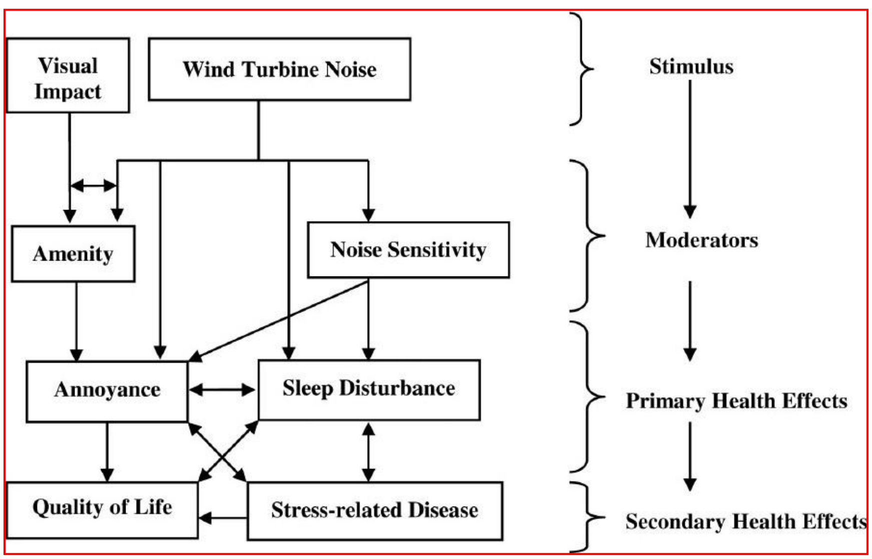
- The Weichenberger study is the first to demonstrate that infrasound near the hearing threshold may induce changes of neural activity across several brain regions, some of which are known to be involved in auditory processing, while others are regarded as key players in emotional and autonomic control. These findings allow the researchers to speculate on how continuous exposure to subliminal infrasound could exert a pathogenic influence on the organism, such as are observed in humans and animals living in close proximity to wind turbine installations. ***Of critical importance to the public debate regarding health effects of wind turbines is that the Weichenberger research negates the so-called Nocebo Effect***.

- **Sleep Disorders and Sleep Deprivation An Unmet Public Health Problem:** Editors: Harvey R Colten and Bruce M Altevogt. Institute of Medicine (US) Committee on Sleep Medicine and Research.Washington (DC): National Academies Press (US); 2006.ISBN-10: 0-309-10111-5; Bookshelf ID: NBK19960PMID: 20669438DOI: 10.17226/11617[28]
- **(excerpt) (emphasis added) "*The cumulative long-term effects of sleep deprivation and sleep disorders have been associated with a wide range of deleterious health consequences including an increased risk of hypertension, diabetes, obesity, depression, heart attack, and stroke. The Institute of Medicine (IOM) Committee on Sleep Medicine and Research concluded that although clinical activities and scientific opportunities in the field are expanding, awareness among the general public and health care professionals is low, given the magnitude of the burden*"**.



[27] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5389622/
[28] https://www.ncbi.nlm.nih.gov/books/NBK19960/

- **<u>The graphic above (Figure 3-1)</u> is from the USEPA back in NOISE EFFECTS HANDBOOK A Desk Reference to Health and Welfare Effects of Noise By Office of the Scientific Assistant Office of Noise Abatement and Control U.S. Environmental Protection Agency; Published by the National Association of Noise Control Officials, P. O. Box 2618, Fort Walton Beach, Florida 32549; October 1979, Revised July 1981; EPA500-9-82-106**[29]
    - **<u>Figure 3-1:</u> "Summary of possible clinical manifestations of stress concomitant with noise. Not only might there be harmful consequences to health during the state of alertness, but research also suggests effects may occur when the body is unaware or asleep**."
    - "Impulses from the brain activate centers of the autonomic nervous system which trigger a series of bodily reactions as part of a general stress response. Systems that may be affected include the glandular, cardiovascular, gastrointestinal, and musculoskelatal systems".
    - "It is possible that repeated or constant exposure to noise can contribute to deterioration in health. Whether or not environmental or industrial noise by itself can lead to chronic disturbances is hard to determine since there are so many other stresses to which people are exposed. (41) This research is difficult to conduct and little has been done in this area, but research is accumulating which suggests a relationship between long-term noise exposure and stress-related health effects, particularly those related to the cardiovascular system".
- **From Noise &Health A Bimonthly Inter-Disciplinary International Journal: Figure 1: (below)**[30]**A schematic representation of the relationship between wind turbines and health in a semi-rural setting.** The multiplicity of relationships emerges due to the variability in the response of individuals to noise.



[29] http://www.nonoise.org/library/handbook/handbook.htm#NONAUDITORY%20PHYSIOLOGICAL%20RESPO

[30] http://www.noiseandhealth.org/viewimage.asp?img=NoiseHealth_2011_13_54_333_85502_f4.jpg

Below: Figure 9. Model of direct and indirect noise effects[31]

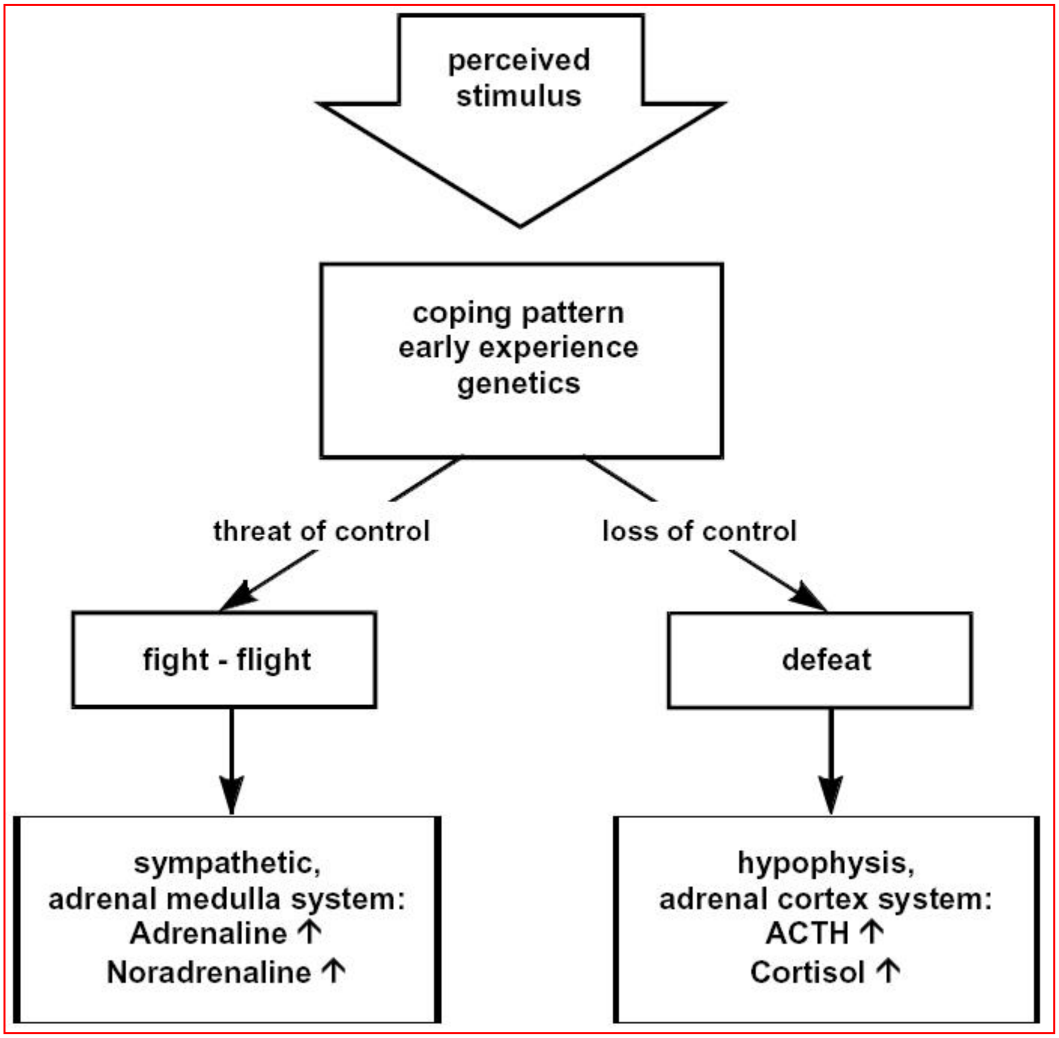


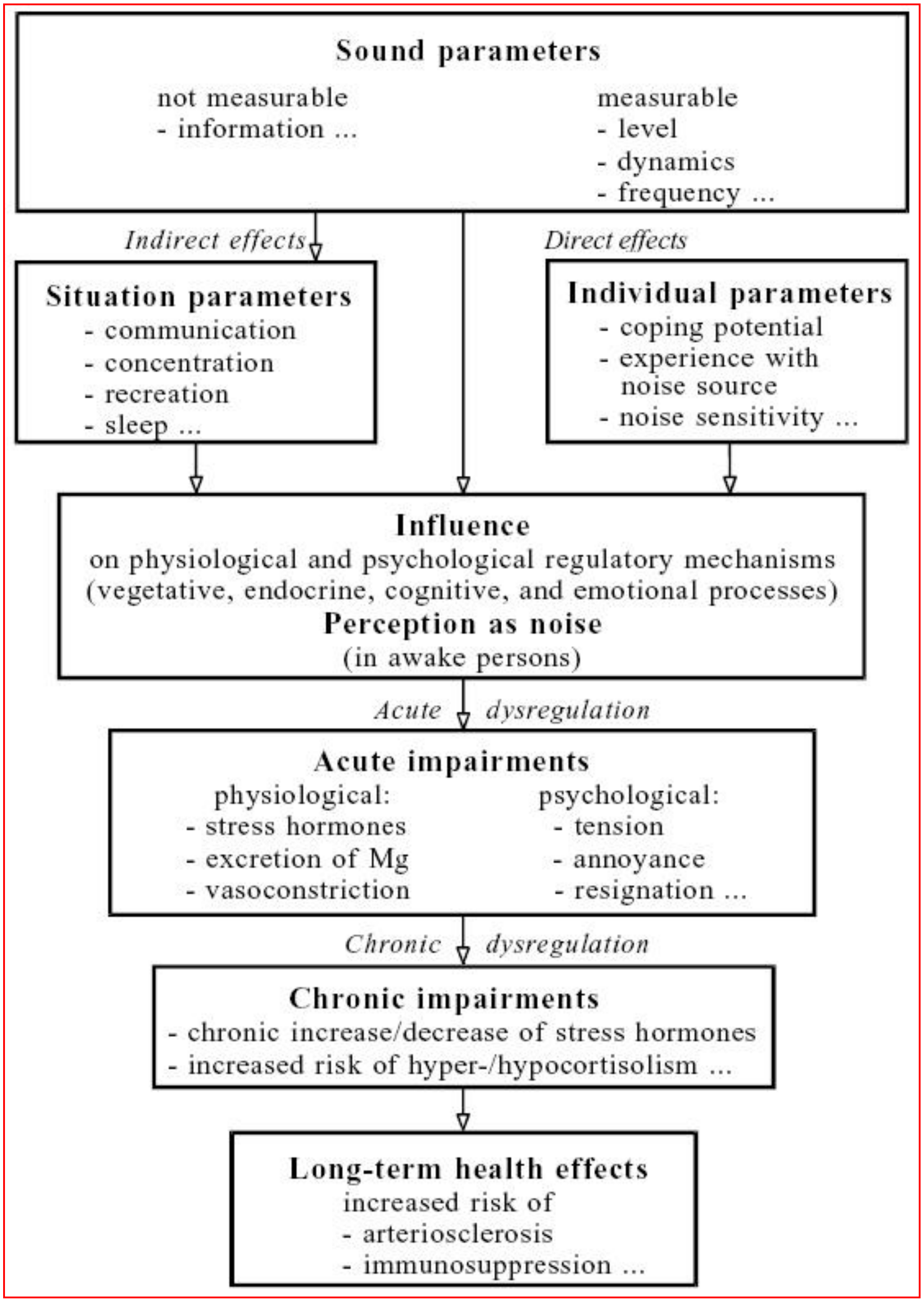
Figure 1. (below) The psychophysiological stress model (Henry and Stephens, 1977)[32]

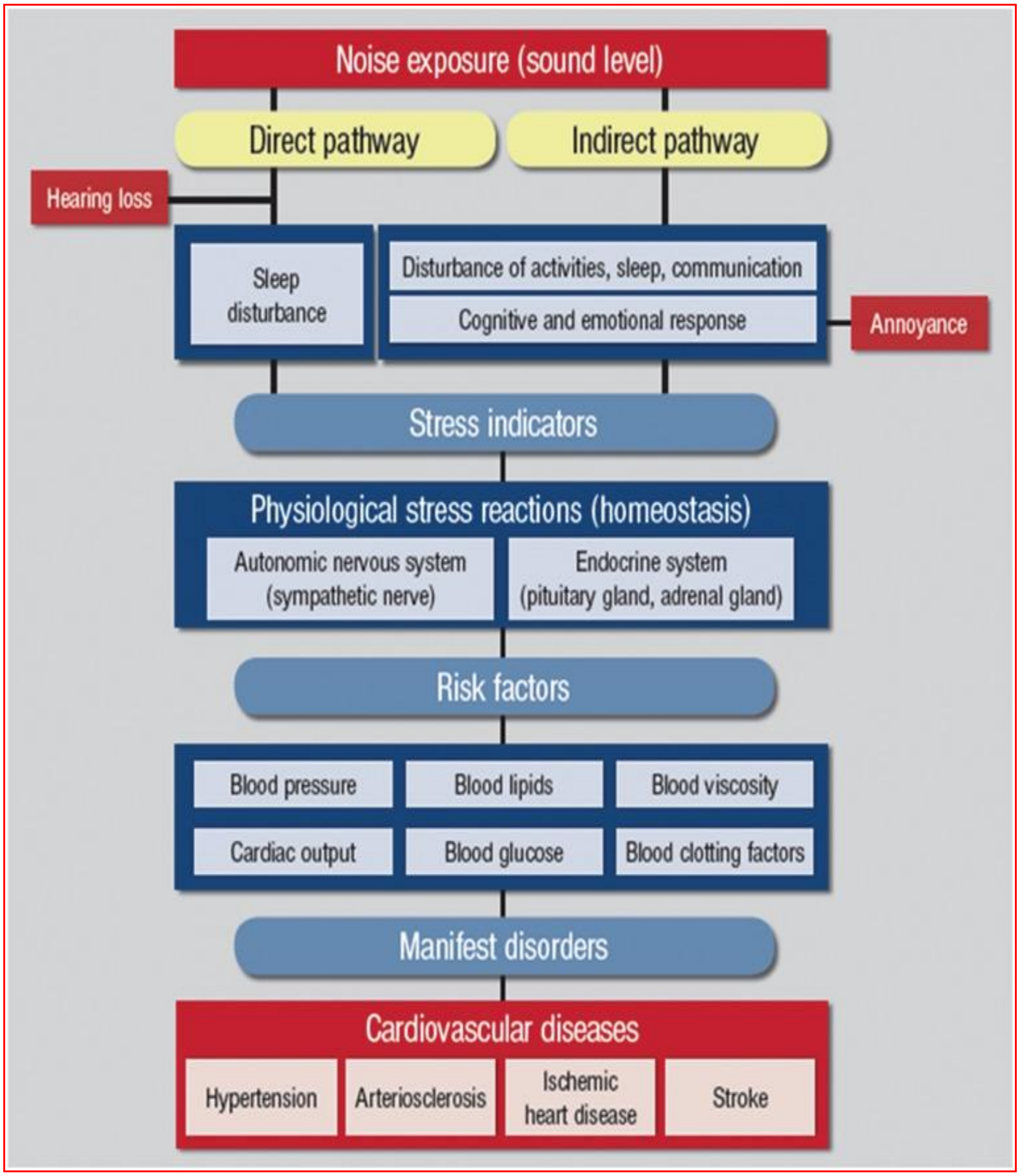
(Excerpt from Henry and Stephans, 1977)[33]: (emphasis added) "*It is generally accepted that noise has the potential to act as a non specific stressor. The stress concept was introduced into biological sciences by Selye (1956) and since then modified in various ways. We will use one of these modifications as a basis for the study of noise-induced endocrine reactions, the psychophysiological stress model of Henry and Stephens (1977). [Figure - 1] shows a simplified form of this model. A stimulus is perceived by our ears, eyes, nose or other senses and transmitted to the corresponding parts of the brain, where it is analysed.*"

[31] Ising H, Braun C. Acute and chronic endocrine effects of noise : Review of the research conducted at the Institute for water, soil and air hygiene. Noise Health [serial online] 2000 [cited 2019 Mar 13]; 2:7-24. Available from: http://www.noiseandhealth.org/text.asp?2000/2/7/7/31745

[32] http://www.noiseandhealth.org/viewimage.asp?img=NoiseHealth_2000_2_7_7_31745_1.jpg

[33] http://www.noiseandhealth.org/article.asp?issn=1463-1741;year=2000;volume=2;issue=7;spage=7;epage=24;aulast=Ising


Sound parameters
not measurable
- information ...
measurable
- level
- dynamics
- frequency ...
Indirect effects
Direct effects
Situation parameters
- communication
- concentration
- recreation
- sleep ...
Individual parameters
- coping potential
- experience with noise source
- noise sensitivity ...
Influence
on physiological and psychological regulatory mechanisms
(vegetative, endocrine, cognitive, and emotional processes)
Perception as noise
(in awake persons)
Acute dysregulation
Acute impairments
physiological:
- stress hormones
- excretion of Mg
- vasoconstriction
psychological:
- tension
- annoyance
- resignation ...
Chronic dysregulation
Chronic impairments
- chronic increase/decrease of stress hormones
- increased risk of hyper-/hypocortisolism ...
Long-term health effects
increased risk of
- arteriosclerosis
- immunosuppression ...



- **Graphic above was sourced from: Cardiovascular effects of environmental noise exposure[34]: Thomas Münzel,[1,*] Tommaso Gori,[1] Wolfgang Babisch,[2] and Mathias Basner[3]**
  - Published in European Heart 2014 Apr 1; 35(13): 829–836.
  - doi: 10.1093/eurheartj/ehu030; PMCID: PMC3971384; PMID: 24616334
    - **Abstract (emphasis added):** *The role of noise as an environmental pollutant and its impact on health are being increasingly recognized. Beyond its effects on the auditory system, noise causes annoyance and disturbs sleep, and it impairs cognitive performance. Furthermore, evidence from epidemiologic studies demonstrates that environmental noise is associated with an increased incidence of arterial hypertension, myocardial infarction, and stroke. Both observational and experimental studies indicate that in particular night-time*

[34] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3971384/

noise can cause disruptions of sleep structure, vegetative arousals (e.g. increases of blood pressure and heart rate) and increases in stress hormone levels and oxidative stress, which in turn may result in endothelial dysfunction and arterial hypertension. This review focuses on the cardiovascular consequences of environmental noise exposure and stresses the importance of noise mitigation strategies for public health".

- **Conclusion (emphasis added): "***Taken together, the present review provides evidence that noise not only causes annoyance, sleep disturbance, or reductions in quality of life, but also contributes to a higher prevalence of the most important cardiovascular risk factor arterial hypertension and the incidence of cardiovascular diseases. The evidence supporting such contention is based on an established rationale supported by experimental laboratory and observational field studies, and a number of epidemiological studies. Meta-analyses have been carried out to derive exposure–response relationships that can be used for quantitative health impact assessments.[91] Noise-induced sleep disturbance constitutes an important mechanism on the pathway from chronic noise exposure to the development of adverse health effects. The results call for more initiatives aimed at reducing environmental noise exposure levels to promote cardiovascular and public health. Recent studies indicate that people's attitude and awareness in particular towards aircraft noise has changed over the years.[92,93] Noise mitigation policies have to consider the medical implications of environmental noise exposure. Noise mitigation strategies to improve public health include noise reduction at the source, active noise control (e.g. noise-optimized take-off and approach procedures), optimized traffic operations (including traffic curfews), better infrastructural planning, better sound insulation in situations where other options are not feasible, and adequate limit values*".

- **South Australia Farmers Paid $1 Million to Host 19 Turbines Tell Senate they "Would Never Do it Again" due to "Unbearable" Sleep-Destroying Noise; posted June 15, 2015:**

Clive and Trina Gare's property.

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- Clive and Trina Gare are cattle graziers from South Australia's Mid-North with their home property situated between Hallett and Jamestown.
- Since October 2010, the Gares have played host to 19, 2.1MW Suzlon s88 turbines, which sit on a range of hills to the West of their stately homestead. Under their contract with AGL they receive around $200,000 a year; and have pocketed over $1 million since the deal began.
- The Gares gave evidence to the Senate Inquiry into wind power fraud during its Adelaide hearing: **COMMONWEALTH OF AUSTRALIA Proof Committee Hansard SENATESENATE SELECT COMMITTEE ON WIND TURBINES WEDNESDAY, 10 JUNE 2015**[35]

XIV. POPULATION AND HOUSING:

- b): The NO IMPACT should be changed to POTENTIALLY SIGNIFICANT. Introduction of up to 90 new 4.2 MW wind turbines into residential areas poses a real threat to the health, safety and well being of current or future residents.
- Well-known impacts from industrial wind turbines have resulted in the abandonment of homes impacted by various wind turbine projects around the world.
- ***Locally, 14 of 15 turbine-impacted residents already exposed to Kumeyaay Wind and Tule Wind turbines, who filled out a 2019 WIND TURBINE NEIGHBOR SURVEY between March 2nd and March 17th (surveys provided separately) responded YES, to the questions:*** *Do the turbines make you want to move?*
- The 14th resident responded to the same question with: NOT YET!
- At least one tribal member, near the Kumeyaay Wind turbines, has basically abandoned their home because of the turbines. They come home to check on the property and then leave again. They have reported much improved health since moving away from the turbines.
- Those same residents will be disproportionately impacted if and when any additional wind turbines are negligently approved and installed.

XV. PUBLIC SERVICES:

- **Fire Protection:** The whole of the project and all connected action projects, Campo Wind, Boulder Brush, and Torrey Wind, all need to be part of the Fire Protection Plan.
- Terra-Gen's projects should not be allowed to use Ribbonwood Road due to the fact that is a sole access route for local residents, some of whom have horses and other livestock that will need to be evacuated, too. It is also associated with Boulevard Trails and Pathways.
- In the event of a fire or other disaster, the presence of project related employees during construction and/or operation would only further exacerbate an already potentially deadly event. Think 2018 Camp Fire and residents trying to flee.

[35] https://stopthesethings.com/2015/06/15/sa-farmers-paid-1-million-to-host-19-turbines-tell-senate-they-would-never-do-it-again-due-to-unbearable-sleep-destroying-noise/

XVI. RECREATION:

- See previous comment on NOP above, regarding Boulevard Community Trails & Pathways that will be impacted by Terra-Gen projects: Campo Wind, Boulder Brush and Torrey Wind.

XVII. TRANSPORTATION:

- **c): sharp curves, dangerous intersections, and incompatible uses: This section should be marked 'Potentially Significant'**.
- Ribbonwood Road is a sole access route for area residents.
- The road is very narrow at points and there are sharp curves with no shoulders and hills with limited visibility. There are also some major boulders next to the road just south of Opalocka.
- The intersection of Ribbonwood Road and Opalacka is dangerous. It needs an all-way stop.
- Residents complained that during construction of Tule Wind their access to their homes on Ribbonwood Road was blocked for 20 minutes or so at a time.
- A better traffic plan and resident notification plan is needed.
- Secondary access route should be required.

XIX. UTILITIES & SERVICE SYSTEMS:

- **Communications should be included due to wind turbine interference with cell phone reception and more.**
- **Iberdrola , Tule Wind developer, participated in the research below and has received several complaints about cell phone interference from local residents.**
    - **Impact analysis of wind farms on telecommunication services:** D.de la Vega[a]I.Cascón[a]J.Cañizo[a]Y.Wu[b]D.Guerra[a]P.Angueira[a]; Renewable and Sustainable Energy Reviews; Volume 32, April 2014, Pages 84-99 [36]
    - **Abstract** Wind power is one of the fastest-growing technologies for renewable energy generation. Unfortunately, in the recent years some cases of degradation on certain telecommunication systems have arisen due to the presence of wind farms, and expensive and technically complex corrective measurements have been needed. This paper presents a comprehensive review on the impact of wind turbines on the telecommunication services. The paper describes the potential affections to several telecommunication services, the methodology to evaluate this impact, and mitigation measures to be taken in case of potential degradation, both preventive and corrective. The telecommunication services included in this review are those that have demonstrated to be more sensitive to nearby wind turbines: weather, air traffic control and marine radars, radio navigation systems, terrestrial television and fixed radio links. The methods described in the paper allow a thorough case-by-case analysis before the wind farm is installed, taking into account the particular features of each installation and the involved services. The prediction of the potential impact makes it possible to propose alternative solutions in order to assure the coexistence between the wind turbines and the telecommunication services.

[36] https://www.sciencedirect.com/science/article/pii/S1364032114000100

- **Conclusions:** This paper provides a comprehensive review about the potential impact of wind turbines on the telecommunications services. It summarizes the main effects than can be observed, as well as the methodology to follow in order to determine if a problem may occur, and possible corrective measurements.

- **d) Waste generation should be marked potentially significant related to hard to recycle turbine blades.**
  - In 2009, Kumeyaay Wind suffered a catastrophic failure where all the blades, nacelles, and other major components have to be replaced. The failure resulted in a lawsuit.
  - Over a decade later, some of the damaged blades are still sitting on the ground at the base of the turbines while others were disposed of at the Jacumba Garage east of Boulevard where they still sit on the ground. Was there disposal at Jacumba Garage legal?
  - Composite turbine blades are highly flammable and very difficult to recycle.
  - See: **Unsustainable Wind Turbine Blade Disposal Practices in the United States: A Case for Policy Intervention and Technological Innovation:** Katerin Ramirez-Tejeda1 , David A. Turcotte1 , and Sarah Pike DOI: 10.1177/1048291116676098; published in NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy[37]
  - **Conclusion** (excerpt-emphasis added): "*Finding better ways to manage the expected high number of blades in need of disposal is important in order to harvest wind energy in a truly sustainable manner. Better management would mean that economic and societal needs for clean energy are fulfilled without compromising the environment. None of the current methods allow for optimal wind turbine blade disposal. All of them carry potential economic, environmental, and occupational health concerns. Policy interventions such as allocation of more research funding to blade manufacturing and disposal, the provision of incentive mechanisms to recycling, and directives of producer responsibility could help overcome or minimize some of the challenges associated with disposing of wind turbine blades…*"

XX. WILDFIRE:

- b) We agree with the Potentially Significant determination.
- The Project, if approved over community objections, can only exacerbate wild fire risk.
- The Project has a high probability of actually igniting a wildfire through failure of a variety of components related to Project wind turbines, substation/switchyard, transformers, downed utility lines, impacts with utility lines, carelessly discarded cigarettes, vehicle fires, and more.
- Our previous comments included evidence of substation/transformer fires.
- Photos below were taken of the Kumeyaay Wind fire in December 2013:

[37] https://docs.wind-watch.org/ramireztejeda2016-bladedisposal.pdf

- **<u>The CalFire incident report #0025970, for the Kumeyaay Wind turbine fire,</u> documents the fact that burning debris was dropping from the tower and drifting downwind 100' to 800' into vegetation and that a vegetation fire was burning along the west end of the road next to tower 14. Infigen estimated $2 million in damage**.
- *<u>If approved and constructed over community opposition, Terra-Gen's Campo Wind and Torrey Wind projects should be required to be shut-off during so-called Utility Public Safety Power Shut-offs[38] when the Live Oak Springs / Boulevard area power is shut down.</u>*
- *SDG&E's November 11-16, 2018 De-energization Events report to CPUC[39], and other reports, should be taken into consideration as just one example of how many times /days the Boulevard area was without power, while the existing Kumeyaay and Tule Wind turbines were allowed to operate during high wind events.*

XXI. MANDATORY FINDINGS OF SIGNIFICANCE:

- ***c) We support the Potentially Significant determination and inclusion that "<u>The Project has the potential to result in adverse effects on human beings directly, and indirectly</u>".***

[38] https://www.sdge.com/wildfire-safety/public-safety-power-shutoffs

[39] http://cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/News_Room/NewsUpdates/2018/SDGE%20De-Energization%20Report%20(Nov%2011-16%202018%20RFW).pdf

SMALL SAMPLE OF LITIGATION RELATED TO ADVERSE WIND TURBINE IMPACTS:

- **1-1-19: West Virginia Record: Three lawsuits filed against New Creek Wind for negative health effects**[40]
  - *ELKINS — Three complaints were filed against New Creek Wind in federal court alleging negative effects on the health and well-being of several residents. New Creek Mountain Sportsman's Club; Helen Evans Swiger, Holly Evans Mick and Jill M. Evans; and Glendora Woods filed their lawsuits against New Creek Wind, Everpower Wind Holdings, Enbridge Holdings and Enbridge Inc. in the U.S. District Court for the Northern District of West Virginia at Elkins. Beginning in November 2016, the defendants' wind turbines have generated noises that have adversely affected the plaintiffs, according to the suits."Specifically, while the plaintiffs are outside on their property, they are confronted with irritating and unabated audible noise which significantly limits the use and enjoyment of their property and results in annoyance, along with other symptoms..." one of the complaints states. The plaintiffs claim the wind turbines are a nuisance and that the defendants were negligent. The plaintiffs are seeking compensatory and punitive damages in excess of $75,000 each. They are represented by Henry E. Woods III of Wood Law Office in Charleston.*
- Not in our backyard **A Current Affair – Victoria Martin King,1 November 2018;** Not In Anyone's Backyard: Angry Neighbours Launch $Million Lawsuit Against Wind Farm Developer & Council[41]
  - Sick and tired of soul-destroying wind turbine noise, a group of Victorian farmers have launched a class-action seeking $millions in damages. Their targets are the wind power outfit responsible and the Council that rubberstamped its development application, and which is responsible under Victoria's Public Health and Wellbeing Act to remedy the noise nuisance created.
- **Wind company admits nuisance damage to neighbours; published 1-5-17 by Paul Mooney in the Irish Farmers Journal[42]- High Court to determine compensation for seven families in April hearing (emphasis added)**
  - *"A Co Cork based wind energy company has accepted in the High Court that its wind farm has caused nuisance damage to seven neighbouring families. The High Court has now set aside ten days in April 2017 to determine what if any damages should be paid by the company to the families. The Farmers Journal understands that the cases taken by the families claim that the wind farm caused them nuisance as a result of excessive noise. The wind company is Enercon Wind Farm Services Ireland Ltd and it formally admitted liability to the Court. The damages hearing for the seven cases have been consolidated by the High Court on the basis that the cases are related. It will start on Tuesday 25 April. Pressure group Wind Aware Ireland claimed this week that the outcome of the case could be a watershed for existing and planned wind farms and investor confidence. "It is expected that more cases*

[40] U.S. District Court for the Northern District of West Virginia Case numbers: 2:18-cv-00111, 2:18-cv-00112, 2:18-cv-00113;

https://wvrecord.com/stories/511692267-three-lawsuits-filed-against-new-creek-wind-for-negative-health-effects

[41] https://stopthesethings.com/2018/11/14/not-in-anyones-backyard-angry-neighbours-launch-million-lawsuit-against-wind-farm-developer-council/

[42] https://www.farmersjournal.ie/wind-company-admits-nuisance-damage-to-neighbours-246465

will now follow," spokesperson Paula Byrne said in a statement. It is alleged that a number of families had to abandon their homes because of the severity of the noise from the wind farm."

- **One Lawsuit Settled, But No Truce in Wind Energy Debate**[43] **By Jack Spencer published in Michigan Capitol Confidential 1-3-15:**
  - *A lawsuit in which residents living near the Lake Winds wind plant south of Ludington claimed the facility was making people sick has been settled out of court. Cary Shineldecker, one of the plaintiffs in the case, isn't allowed to discuss details of the settlement, but is still allowed to talk about the alleged negative health effects that can be suffered by those who live near such facilities."What I think is different about this settlement is that, although the details of the settlement are confidential, I'm not gagged from speaking out about the problems with wind energy," Shineldecker said. "I think everything we've done here has helped the community and residents. For too long, supporters of wind energy have been able to silence and discredit those who have to live with the effects of it*.

- **Court waits on wind farms' response to suit By FERNANDO DEL VALLE Valley Morning Star | Posted: Wednesday, January 29, 2014 12:45 pm** fdelvalle@valleystar.com (Texas)(emphasis added)
  - *RAYMONDVILLE — Two wind farms have until next week to answer a lawsuit in which residents accuse wind turbines of creating noise, devaluing property and posing possible health risks, federal court records show. Records show U.S. District Judge Hilda Tagle requested that Duke Energy and E.ON Climate & Renewables North America and other defendants answer accusations by Feb. 6.The companies requested Dec. 27 that the lawsuit originally filed Nov. 27 in 197th State District Court here be moved to federal court. Twenty-three residents including Willacy County Commissioner Noe Loya and Precinct 3 Justice of the Peace Juan Silva Jr. filed the lawsuit, arguing the companies built wind turbines on their properties that created "nuisances."Elon Hasson, spokesman for E.ON in Chicago, said the company was reviewing the lawsuit. "We develop all of our wind farms in a safe, state-of-the-art and responsible manner," Hasson said in an email. "We believe these claims will be shown to have no validity."Tammie McGee, spokeswoman for Duke in Charlotte, N.C., declined comment but added the plaintiffs consented to the placement of turbines on their properties. The companies built "hundreds" of wind turbines that stand 467-feet high and weigh 7 tons on the properties of plaintiffs who received or will receive money and tax benefits that will exceed $50 million, the lawsuit states. The lawsuit states the companies "carelessly and negligently failed to adequately disclose the true nature and effects that the wind turbines would have on the community, including the plaintiffs' homes."The companies told residents that the wind turbines "would not be noisy, would not adversely impact neighboring houses and there would not be any potential health risks," the lawsuit states. But the wind turbines create noise, reduce property values, interfere with television, telephone, satellite and Internet reception and destroy "scenic countryside," the lawsuit states. The lawsuit states the wind turbines create "acoustic pressure pulsations that affect peoples' health."Some*

[43] https://www.michigancapitolconfidential.com/20951

residents were "even forced to abandon their homes," the lawsuit states. The lawsuit states "permanent and irreparable harm will be caused to the area" because the companies and county did not plan to remove the turbines when their approximately 20-year lifespan expires. Loya "can no longer enjoy sitting outside because of the loud noise," the lawsuit states. "The turbines also cause noise both inside and outside of the home, disturbing the peace and making it difficult to enjoy living there. (Loya) also experiences problems with his television reception. The wind turbines have also had a negative impact on the value of the property, among other losses," the lawsuit states. The lawsuits states Silva "has difficulty sleeping, cannot have his windows open (and) cannot enjoy the sound of nature, due to loud noise from wind turbines."

- **The Secret, Silent Wind Power Peril (Part I: The General Problem) (Master Resource 2-6-17)**[44]
  - **Helen Schwiesow Parker, PhD**, is a Licensed Clinical Psychologist and a Past Clinical Supervisory Faculty member at the University of Virginia Medical School. Her career includes practical experience in the fields of autism, sensory perception, memory and learning, attention deficit and anxiety disorders, including panic disorder and PTSD.
    - **(Excerpt –emphasis added)** *The primary pathway of turbine assault on human health and wellbeing is no mystery. The Israeli army has used low-frequency sound pulse as high-tech crowd control for years. Low-frequency noise at high intensities creates discrepancies in the brain, producing disorientation in the body: "The knees buckle, the brain aches, the stomach turns. And suddenly, nobody feels like protesting anymore.… It has no adverse effects, unless someone is exposed to the sound for hours and hours." But indeed, thousands of IWT neighbors around the world are subjected night and day, some now for decades, to these sub-audible (slowly vibrating) sound waves sent out as turbine blades spin past the shaft, setting up vibrations within body cavities: ears, eye sockets, skull, lungs, and belly. People are made nauseous and confused, with blurred vision, vertigo, headaches, tachycardia, heightened blood pressure, pain and ringing in the ears, difficulties with memory and concentration, anxiety, depression, irritability, and panic attacks arising when awake or asleep. "The effects of the turbines run from annoyance with the audible sound and shadow flicker to downright anguish from panic attacks which can feel like a death/dying episode of extreme pain. These are brought on by first a bit of nausea and upset stomach, extreme light headedness, and then the bad part: constriction and wringing of my insides. Sometimes I try to hang by a doorframe, other times I just lie on the ground if I can't make it to the house. It is truly an inner body disturbance."*

- **CUMULATIVE IMPACT PROJECTS:**
  - **The following projects should be analyzed as cumulative impact projects:**
    1. 252 MW Campo Wind (pending-ISO queue #1429)
    2. Boulder Brush Gen-tie & facilities 8.5 mile 230 kV gen-tie for Campo Wind (pending)
    3. 126 MW Torrey Wind (pending-ISO queue # 1429))

[44] https://www.masterresource.org/windpower-health-effects/secret-silent-wind-power-peril-1/

4. 55 MW Tule Wind Phase II (approved-pending)
5. 74 MW Rugged Solar (approved in 2015-pending)
6. 60 MW Boulevard Solar (formerly Soitec's Tierra Del Sol Solar) (approved in 2015-pending)
7. 100MW Boulevard Energy Storage (proposed)
8. 20MW Starlight Solar (Boulevard) (proposed-ISO queue #1432)
9. 90 MW Jacumba Valley Ranch (JVR) Solar (MUP pending-ISO queue # 1532))
10. 50 MW Kumeyaay Wind (existing-2005) (Campo Reservation) ($55 million)
11. 131 MW Tule Wind Phase I (existing-2017)
12. Tule Wind 138kV Gen-tie line to Boulevard Substation (existing-2017)
13. 155 MW Energia Sierra Juarez Wind (cross-border -existing-2015) ($300 million)
14. 20MW Jacumba Solar (existing- Aug 2017- ISO grid queue # 644A)
15. ECO Substation and 13.3 mile 138 kV line (existing- 2015)($435 million)
16. Boulevard Substation rebuild (existing-2015) (part of ECO Substation project)
17. 265 MW Ocotillo Wind (existing-2012) (just east of Jacumba & Boulevard)
18. 500 kV Sunrise Powerlink (existing-2012) ($1.9 billion)
19. 500 kV Southwest Powerlink (existing-1983)
20. Rough Acres Ranch MUP PDS2012-3300-12-02 (pending)

ALTERNATIVES:

- Any additional renewable energy projects should be installed in the already built urban and suburban areas including residential and commercial rooftops, (over 700 MW installed in SDG&E territory already), parking shade structures, reservoirs, closed landfills and other brownfields.
- The general predominantly low-income Boulevard area has already been disproportionately impacted with no justification to further impact those already suffering.
- If San Diego County's goal is to totally transform our beautiful area into a commercial industrial energy zone to benefit others then impacted and willing property owners should be bought out at a price that will allow them to replace what they have now in an area free of turbines and solar projects, and to cover increased property taxes , too.

Below is GE's biggest onshore wind turbine that dwarfs the barn and other buildings below it. A prototype for GE Renewable Energy's Cypress platform is now fully operational, producing power at a rated level of 5.3 MW in Wieringermeer, the Netherlands. The platform represents GE's largest onshore wind turbine in operation to date[45].

Please note the size of the barns and other buildings at base of this monster turbine. The height of this new turbine is not readily apparent. Is this what's next for Boulevard?? Would you want your family to live like this?

[45] https://nawindpower.com/ge-installs-prototype-of-its-biggest-onshore-wind-turbine?utm_medium=email&utm_source=LNH+03-15-2019&utm_campaign=NAW+Latest+News+Headlines

Thank you for consideration of these comments…Any errors or omissions are unintentional.

Attachment: Stetzer Electric WT EMF letter

DEPARTMENT OF TRANSPORTATION
DISTRICT 11
4050 TAYLOR STREET, MS-240
SAN DIEGO, CA 92110
PHONE (619) 688-6075
FAX (619) 688-4299
TTY 711
www.dot.ca.gov

Making Conservation a California Way of Life.

February 13, 2019

11-SD-8
PM 64.16
Boulder Brush Gen-Tie Line & Substation Facilities
Major Use Permit # PDS2018-MUP-19-002

Ms. Bronwyn Brown
Land Use/Environmental Planner
County of San Diego
Planning and Development Services
5510 Overland Avenue, Suite 310
San Diego, CA 92123

Dear Ms. Brown:

Thank you for including the California Department of Transportation (Caltrans) in the review process for the Major Use Permit (MUP) for the Boulder Brush Gen-Tie Line & Substation Facilities located near Interstate 8 (I-8) at Ribbonwood Road, near Boulevard. The mission of Caltrans is to provide a safe, sustainable, integrated and efficient transportation system to enhance California's economy and livability. The Local Development-Intergovernmental Review (LD-IGR) Program reviews land use projects and plans to ensure consistency with our mission and state planning priorities.

Caltrans has the following comments:

Traffic Control Plan/Hauling

The California Department of Transportation (Caltrans) has discretionary authority with respect to highways under its jurisdiction and may, upon application and if good cause appears, issue a special permit to operate or move a vehicle or combination of vehicles or special mobile equipment of a size or weight of vehicle or load exceeding the maximum limitations specified in the California Vehicle Code. The Caltrans Transportation Permits Issuance Branch is responsible for the issuance of these special transportation permits for oversize/overweight vehicles on the State Highway System. Additional information is provided online at:
http://www.dot.ca.gov/trafficops/permits/index.html

A Traffic Control Plan is to be submitted to Caltrans District 11, including the interchanges at I-8/Ribbonwood Road, at least 30 days prior to the start of any construction. Traffic shall not be unreasonably delayed. The plan shall also outline suggested detours to use during closures, including routes and signage.

Potential impacts to the highway facilities (I-8) and traveling public from the detour, demolition and other construction activities should be discussed and addressed before work begins.

If you have any questions, please contact Mark McCumsey at (619) 688-6802 or by email at mark.mccumsey@dot.ca.gov.

Sincerely,

Melina Pereira

MELINA PEREIRA, Acting Branch Chief
Local Development and Intergovernmental Review Branch

STATE OF CALIFORNIA—CALIFORNIA STATE TRANSPORTATION AGENCY Gavin Newsom, Governor

DEPARTMENT OF TRANSPORTATION
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Making Conservation a California Way of Life.

March 6, 2019

11-SD/IMP-I-8
PM 66.7
Boulder Brush Gen-tie Line and Switchyard Facilities for the Campo Wind Project
NOP SCH#2019029094

Ms. Bronwyn Brown
San Diego County
5510 Overland Ave., Suite 310
San Diego, CA 92123

Dear Ms. Brown

Thank you for including the California Department of Transportation (Caltrans) in the environmental review process for the Notice of Preparation for the Boulder Brush Gen-tie Line and Switchyard Facilities for the Campo Wind Project located near Interstate 8 (I-8) between Ribbonwood Drive and McCain Valley Road. The mission of Caltrans is to provide a safe, sustainable, integrated and efficient transportation system to enhance California's economy and livability. The Local Development-Intergovernmental Review (LD-IGR) Program reviews land use projects and plans to ensure consistency with our mission and state planning priorities.

Caltrans has the following comments:

Please include comments from our previous letter dated on February 13, 2019 when preparing your Draft Environmental Impact Report (DEIR).

<u>Traffic Impact Study</u>
A traffic impact study (TIS) is necessary to determine this proposed project's near-term and long-term impacts to the State facilities – existing and proposed – and to propose appropriate mitigation measures.

- The geographic area examined in the TIS should also include, at a minimum, all regionally significant arterial system segments and intersections, including State highway facilities where the project will add over 50 to 100+ peak hour trips.
- In addition, the TIS could also consider implementing vehicles miles traveled (VMT) analysis into their modeling projections.
- Any increase in goods movement operations and its impacts to State highway facilities should be addressed in the TIS.
- The data used in the TIS should not be more than 2 years old.

- Please provide Synchro Version 10 files.

Right-of-Way

Any work performed within Caltrans' right-of-way (R/W) will require discretionary review and approval by Caltrans and an encroachment permit will be required for any work within the Caltrans' R/W prior to construction. As part of the encroachment permit process, the applicant must provide an approved final environmental document including the California Environmental Quality Act (CEQA) determination addressing any environmental impacts within the Caltrans' R/W, and any corresponding technical studies.

If a highway closure plan is needed as part of the encroachment permit, it should be submitted to Caltrans at least 30 days prior to initiating installation of the crossings. No work shall begin in Caltrans' Right of Way (R/W) until an encroachment permit is approved.

Please see Chapter 600 of the Encroachment Permits Manual for requirements regarding utilities and state R/W: http://www.dot.ca.gov/trafficops/ep/manual.html

Please see Chapter 17 of the Plan Preparation Manual for requirements regarding utilities and state R/W: http://www.dot.ca.gov/design/cadd/manuals/ppm.html

Early coordinate with Caltrans is recommended. If you have any questions, please contact Charlie Lecourtois, of the Caltrans Development Review Branch, at (619) 688-6705 or Trent Clark, of the Developmental Review Branch, at (619) 688-3140 or by e-mail sent to trent.clark@dot.ca.gov.

Sincerely,

Melina Pereira

MELINA PEREIRA, Acting Branch Chief
Local Development and Intergovernmental Review Branch

Enclosure

From: Billie Jo Jannen, Chairman
Campo Lake Morena Community Planning Group

To: Project Manager Bronwyn Brown
San Diego County Planning and Development Services

March 14, 2019

Re; **Boulder Brush Gen-Tie Line & Substation Facilities: PDS2019-MUP-19-002; ER 19-16-001 Notice of Preparation**

Dear Ms. Brown:

Our planning group voted unanimously to endorse and support the Boulevard Planning Group's comments in opposition to Boulder Brush Gen-Tie line, Substation Facilities and height limit waiver, with the following additional comments:

We disagree with staff's characterization of greenhouse gas emissions (VIII. GREENHOUSE GAS EMISSIONS, p. 21) as a "less than significant impact." In fact, tons of carbon will be released permanently from soil and plants that currently sequester it, and county assessments continue to snub sensible quantification of those releases.

1. **Soil carbon releases need to be quantified**. According to research on carbon sequestration in arid biomes, soil sequestration – and not surface vegetation – is the greater part of local greenhouse gas-holding capacity.

According to the Food and Agriculture Organization of the United Nations: "In dryland environments, soil organic carbon in the first 100 cm soil amounts to about 4 tons/hectare." http://www.fao.org/3/y5738e/y5738e07.htm#TopOfPage

Subsoil biological agents – mostly bacteria – sequester this carbon and are permanently destroyed when the soil is disturbed. https://phys.org/news/2014-04-arid-areas-absorb-unexpected-amounts.html.

According to the 2014 study *Spatial Distribution of Soil Organic Carbon and Its Influencing Factors in Desert Grasslands of the Hexi Corridor, Northwest China*, arid regions worldwide contain 40 times more carbon than what has been released due to human activity, adding, "soils in these regions are fragile and may experience degradation, desertification, wind erosion, and overgrazing. Small changes in soil conditions can modify the original balance of soil carbon cycle, increase the C loss from soil, and release more greenhouse gases into the atmosphere. Therefore, SOC storage in the desert-grassland ecosystem is a critical component of global C cycle and has a considerable effect on reducing the rate of enrichment of atmospheric CO_2."
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3986398/

Unimpaired natural systems will not only hold the carbon they have, but will hold even more as atmospheric CO2 increases, making them an irreplaceable GHG-buffering resource. www.currentscience.ac.in/Volumes/106/10/1357.pdf

If planners are serious about greenhouse gas reduction, it is unforgivable that this has been ignored in project applications in San Diego County. Staff has informed us several times over the past three years that the science of soil sequestration is too new a concept to allow project carbon releases to be included in local GHG calculations.

We reject this reasoning. Wildland and agricultural scientists have been studying soil sequestration **for over 30 years**, and work has become intensive in recent years. Methods of physical measurement and quantification have been refined and there is not a single reason – other than simple disinclination -- for county staff to neglect consulting with these experts. Some of these researchers are located right here in San Diego County. At what point is the science "old" enough to be used for practical purposes?

2. **The sequestration losses of this project would not be necessary without the construction of the Campo and Torrey wind turbine projects**. *These impacts are all cumulative*, so the Boulder Brush EIR should present ALL of the GG releases coming from this cluster of interdependent projects, and so should the Torrey Wind EIR.

3. **The EIR should include transmission losses in its benefit calculations**. When generation is located miles from the majority of end users, it adds millions to the cost of providing electricity to those users. Excess generation is required to replace long-distance transmission losses, and this should also be quantified in any accounting of CO2 from a remote source. Explanation and calculations for transmission and distribution losses can be found on several websites. http://electrical-engineering-portal.com/total-losses-in-power-distribution-and-transmission-lines-1
https://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3

4. **Please use efficiency capacity and known production numbers** from local wind projects, rather than nameplate capacity, to provide estimates of what the new projects will provide. **Wind projects will never produce to nameplate capacity**. The public is given the impression that it's receiving (for example) 10 megawatts, when in reality, it's getting 3, and the other 7 are coming from a fossil fuel peaker plant. These projections are used to justify the destruction and expense of energy projects and should be done honestly. https://www.eia.gov/tools/faqs/faq.cfm?id=101&t=3
www.eia.gov/totalenergy/data/annual/pdf/sec17.pdf

In summary: Please do a full and correct greenhouse gas assessment to determine how much carbon will be released cumulatively by these three related projects. Please include plant/soil carbon releases, the carbon cost of metals and rare earths mining and smelting, product fabrication and transport, concrete mixing, construction, maintenance, transmission losses and decommissioning.

Sincerely

Billie Jo Jannen
(619) 415-6298

County of San Diego

MARK WARDLAW
DIRECTOR

PLANNING & DEVELOPMENT SERVICES
5510 OVERLAND AVENUE, SUITE 310, SAN DIEGO, CA 92123
(858) 694-2962 • Fax (858) 694-2555
www.sdcounty.ca.gov/pds

KATHLEEN A. FLANNERY
ASSISTANT DIRECTOR

BOULDER BRUSH FACILITIES
MAJOR USE PERMIT (PDS2019-MUP-19-002)

FEBURARY 28, 2019 EIR PUBLIC SCOPING MEETING - COMMENT SHEET

To whom this concerns, I William Largo oppose to the Boulder Brush facilities, sunrise Power link and any other Developments related, Due to the damage that is caused during and after the development it affects the land by destroying hundreds of acres; it deprives the water source and it affects the eco-system of wild life. In addision this development does not benefit our Community, it does not bring us Jobs and doesnt benifit our interest instead it brings a conflict of interest. This development is going to ruin our mountainous views and it'll devalue the land of home owners within a few hundred mile radius if you have any concernment you'll See our Community does not approve of this.

Submit by Mail, Fax or Email. Comments must be received no later than March 18, 2019 at 4:00 p.m.

Bronwyn Brown, Project Manager
County of San Diego
Planning and Development Services
5510 Overland Ave., Suite 310
San Diego, CA 92123

Email: bronwyn.brown@sdcounty.ca.gov

FAX: (858) 694-2555

Phone: (858) 495-5516

William F. Largo 3/3/19
Commenter Signature, Date

William F. Largo
Print Name

P.O BOX 1176
Address

Boulevard CA, 91905
City, State, Zip Code

Boulder Brush Essay

3/1/2019

To whom this may concern, I am writing this letter on behalf of the new generation that's native to east county area. I have lived here since 1998 and had experienced the outcome of the wind-turbines since day one.

Therefore I am against the wind-turbine project there is a lot of conflict and destruction that comes with these wind turbines. For example, they are affecting the air space to the birds like the hawks, owls, blue jays and the ravens and bats that are known to fly into these turbines due to the electric magnetic field that these turbines put out, also to mention their eco-system. During the process of installing of these obstructions the native plant life is being destroyed do to the amount of water that's being used for building and safety procedures which in return depletes the water sources and rips the land raw from its natural plant life that the wild life has inhibited it is affecting the road runner, wild kangaroo mice the raccoons, rabbits the coyotes, mountain lions, bob- cats A.K.A lynx, Deer and the rams which are located in areas starting from Inko-pa mountain through McCain valley and the mountainous areas where wind-turbines are located the list goes on but these wind-turbines affect a major part of these animals eco-system and the natural springs that are linked with numerous other natural springs in the area which happen to already be affected due to expansion of population and the rural construction sites that are taking place in San-Diego.

In addition no one has thought to take into consideration the artifacts that have been left behind by the Kumeyaay natives that once roamed these lands freely there are petroglyphs in these mountains and remains of pottery left behind that are not normally heard of but as a native these are found to be sacred and not spoken of leaving the grounds remained left alone.

Despite from that there are a lot of concernment towards the health of those who live near or within the radius of these wind-turbines it has been documented that industrial-scale wind turbines, now approaching within 600 ft. with a blade span as large as a 747 airplane, do generate audible mechanical and aerodynamic noise, low- frequency noise, vibrations and generally inaudible infrasound can cause chronic sleep disruption, panic-attacks and other adverse stress response impacts on people and other living things within a radius of several miles. I for one have been experiencing these symptoms I experience waking up on a consecutive day at 2-3 in the morning and occasions nausea in the mornings what first came to my mind was what could be causing this then I thought perhaps it's the wind turbines due to the electric magnetic field it puts out while in service, sure thing I found facts that do support wind turbines that create these affects. So I come to a conclusion that these are affecting the health of those within its radius and it's affecting the wild life as well and all the native artifacts left behind on these lands.

X William E [signature]

County of San Diego

MARK WARDLAW
DIRECTOR

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Email: bronwyn.brown@sdcounty.ca.gov

FAX: (858) 694-2555

Phone: (858) 495-5516

William F. Largo 3/3/19
Commenter Signature, Date

William F. Largo
Print Name

P.O BOX 1176
Address

Boulevard CA, 91905
City, State, Zip Code

Boulder Brush Essay

3/1/2019

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X

NATIVE AMERICAN HERITAGE COMMISSION
Cultural and Environmental Department
1550 Harbor Blvd., Suite 100
West Sacramento, CA 95691 Phone (916) 373-3710
Email: nahc@nahc.ca.gov
Website: http://www.nahc.ca.gov
Twitter: @CA_NAHC

March 6, 2019

Bronwyn Brown
San Diego County
5510 Overland Ave., Suite 310
San Diego, CA 92123

RE: SCH# 2019029094 Boulder Brush Gen-tie Line and Switchyard Facilities for the Campo Wind Project, San Diego County

Dear Ms. Brown:

The Native American Heritage Commission (NAHC) has received the Notice of Preparation (NOP), Draft Environmental Impact Report (DEIR) or Early Consultation for the project referenced above. The California Environmental Quality Act (CEQA) (Pub. Resources Code §21000 et seq.), specifically Public Resources Code §21084.1, states that a project that may cause a substantial adverse change in the significance of a historical resource, is a project that may have a significant effect on the environment. (Pub. Resources Code § 21084.1; Cal. Code Regs., tit.14, §15064.5 (b) (CEQA Guidelines §15064.5 (b)). If there is substantial evidence, in light of the whole record before a lead agency, that a project may have a significant effect on the environment, an Environmental Impact Report (EIR) shall be prepared. (Pub. Resources Code §21080 (d); Cal. Code Regs., tit. 14, § 5064 subd.(a)(1) (CEQA Guidelines §15064 (a)(1)). In order to determine whether a project will cause a substantial adverse change in the significance of a historical resource, a lead agency will need to determine whether there are historical resources within the area of potential effect (APE).

CEQA was amended significantly in 2014. Assembly Bill 52 (Gatto, Chapter 532, Statutes of 2014) (AB 52) amended CEQA to create a separate category of cultural resources, "tribal cultural resources" (Pub. Resources Code §21074) and provides that a project with an effect that may cause a substantial adverse change in the significance of a tribal cultural resource is a project that may have a significant effect on the environment. (Pub. Resources Code §21084.2). Public agencies shall, when feasible, avoid damaging effects to any tribal cultural resource. (Pub. Resources Code §21084.3 (a)). **AB 52 applies to any project for which a notice of preparation, a notice of negative declaration, or a mitigated negative declaration is filed on or after July 1, 2015.** If your project involves the adoption of or amendment to a general plan or a specific plan, or the designation or proposed designation of open space, on or after March 1, 2005, it may also be subject to Senate Bill 18 (Burton, Chapter 905, Statutes of 2004) (SB 18). **Both SB 18 and AB 52 have tribal consultation requirements**. If your project is also subject to the federal National Environmental Policy Act (42 U.S.C. § 4321 et seq.) (NEPA), the tribal consultation requirements of Section 106 of the National Historic Preservation Act of 1966 (154 U.S.C. 300101, 36 C.F.R. §800 et seq.) may also apply.

The NAHC recommends consultation with California Native American tribes that are traditionally and culturally affiliated with the geographic area of your proposed project as early as possible in order to avoid inadvertent discoveries of Native American human remains and best protect tribal cultural resources. Below is a brief summary of portions of AB 52 and SB 18 as well as the NAHC's recommendations for conducting cultural resources assessments.

Consult your legal counsel about compliance with AB 52 and SB 18 as well as compliance with any other applicable laws.

AB 52

AB 52 has added to CEQA the additional requirements listed below, along with many other requirements:

1. Fourteen Day Period to Provide Notice of Completion of an Application/Decision to Undertake a Project: Within fourteen (14) days of determining that an application for a project is complete or of a decision by a public agency to undertake a project, a lead agency shall provide formal notification to a designated contact of, or tribal representative of, traditionally and culturally affiliated California Native American tribes that have requested notice, to be accomplished by at least one written notice that includes:
    a. A brief description of the project.
    b. The lead agency contact information.
    c. Notification that the California Native American tribe has 30 days to request consultation. (Pub. Resources Code §21080.3.1 (d)).
    d. A "California Native American tribe" is defined as a Native American tribe located in California that is on the contact list maintained by the NAHC for the purposes of Chapter 905 of Statutes of 2004 (SB 18). (Pub. Resources Code §21073).

2. Begin Consultation Within 30 Days of Receiving a Tribe's Request for Consultation and Before Releasing a Negative Declaration, Mitigated Negative Declaration, or Environmental Impact Report: A lead agency shall begin the consultation process within 30 days of receiving a request for consultation from a California Native American tribe that is traditionally and culturally affiliated with the geographic area of the proposed project. (Pub. Resources Code §21080.3.1, subds. (d) and (e)) and prior to the release of a negative declaration, mitigated negative declaration or Environmental Impact Report. (Pub. Resources Code §21080.3.1(b)).
    a. For purposes of AB 52, "consultation shall have the same meaning as provided in Gov. Code §65352.4 (SB 18). (Pub. Resources Code §21080.3.1 (b)).

3. Mandatory Topics of Consultation If Requested by a Tribe: The following topics of consultation, if a tribe requests to discuss them, are mandatory topics of consultation:
    a. Alternatives to the project.
    b. Recommended mitigation measures.
    c. Significant effects. (Pub. Resources Code §21080.3.2 (a)).

4. Discretionary Topics of Consultation: The following topics are discretionary topics of consultation:
    a. Type of environmental review necessary.
    b. Significance of the tribal cultural resources.
    c. Significance of the project's impacts on tribal cultural resources.
    d. If necessary, project alternatives or appropriate measures for preservation or mitigation that the tribe may recommend to the lead agency. (Pub. Resources Code §21080.3.2 (a)).

5. Confidentiality of Information Submitted by a Tribe During the Environmental Review Process: With some exceptions, any information, including but not limited to, the location, description, and use of tribal cultural resources submitted by a California Native American tribe during the environmental review process shall not be included in the environmental document or otherwise disclosed by the lead agency or any other public agency to the public, consistent with Government Code §6254 (r) and §6254.10. Any information submitted by a California Native American tribe during the consultation or environmental review process shall be published in a confidential appendix to the environmental document unless the tribe that provided the information consents, in writing, to the disclosure of some or all of the information to the public. (Pub. Resources Code §21082.3 (c)(1)).

6. Discussion of Impacts to Tribal Cultural Resources in the Environmental Document: If a project may have a significant impact on a tribal cultural resource, the lead agency's environmental document shall discuss both of the following:
    a. Whether the proposed project has a significant impact on an identified tribal cultural resource.
    b. Whether feasible alternatives or mitigation measures, including those measures that may be agreed to pursuant to Public Resources Code §21082.3, subdivision (a), avoid or substantially lessen the impact on the identified tribal cultural resource. (Pub. Resources Code §21082.3 (b)).

7. Conclusion of Consultation: Consultation with a tribe shall be considered concluded when either of the following occurs:
   a. The parties agree to measures to mitigate or avoid a significant effect, if a significant effect exists, on a tribal cultural resource; or
   b. A party, acting in good faith and after reasonable effort, concludes that mutual agreement cannot be reached. (Pub. Resources Code §21080.3.2 (b)).

8. Recommending Mitigation Measures Agreed Upon in Consultation in the Environmental Document: Any mitigation measures agreed upon in the consultation conducted pursuant to Public Resources Code §21080.3.2 shall be recommended for inclusion in the environmental document and in an adopted mitigation monitoring and reporting program, if determined to avoid or lessen the impact pursuant to Public Resources Code §21082.3, subdivision (b), paragraph 2, and shall be fully enforceable. (Pub. Resources Code §21082.3 (a)).

9. Required Consideration of Feasible Mitigation: If mitigation measures recommended by the staff of the lead agency as a result of the consultation process are not included in the environmental document or if there are no agreed upon mitigation measures at the conclusion of consultation, or if consultation does not occur, and if substantial evidence demonstrates that a project will cause a significant effect to a tribal cultural resource, the lead agency shall consider feasible mitigation pursuant to Public Resources Code §21084.3 (b). (Pub. Resources Code §21082.3 (e)).

10. Examples of Mitigation Measures That, If Feasible, May Be Considered to Avoid or Minimize Significant Adverse Impacts to Tribal Cultural Resources:
    a. Avoidance and preservation of the resources in place, including, but not limited to:
       i. Planning and construction to avoid the resources and protect the cultural and natural context.
       ii. Planning greenspace, parks, or other open space, to incorporate the resources with culturally appropriate protection and management criteria.
    b. Treating the resource with culturally appropriate dignity, taking into account the tribal cultural values and meaning of the resource, including, but not limited to, the following:
       i. Protecting the cultural character and integrity of the resource.
       ii. Protecting the traditional use of the resource.
       iii. Protecting the confidentiality of the resource.
    c. Permanent conservation easements or other interests in real property, with culturally appropriate management criteria for the purposes of preserving or utilizing the resources or places.
    d. Protecting the resource. (Pub. Resource Code §21084.3 (b)).
    e. Please note that a federally recognized California Native American tribe or a non-federally recognized California Native American tribe that is on the contact list maintained by the NAHC to protect a California prehistoric, archaeological, cultural, spiritual, or ceremonial place may acquire and hold conservation easements if the conservation easement is voluntarily conveyed. (Civ. Code §815.3 (c)).
    f. Please note that it is the policy of the state that Native American remains and associated grave artifacts shall be repatriated. (Pub. Resources Code §5097.991).

11. Prerequisites for Certifying an Environmental Impact Report or Adopting a Mitigated Negative Declaration or Negative Declaration with a Significant Impact on an Identified Tribal Cultural Resource: An Environmental Impact Report may not be certified, nor may a mitigated negative declaration or a negative declaration be adopted unless one of the following occurs:
    a. The consultation process between the tribes and the lead agency has occurred as provided in Public Resources Code §21080.3.1 and §21080.3.2 and concluded pursuant to Public Resources Code §21080.3.2.
    b. The tribe that requested consultation failed to provide comments to the lead agency or otherwise failed to engage in the consultation process.
    c. The lead agency provided notice of the project to the tribe in compliance with Public Resources Code §21080.3.1 (d) and the tribe failed to request consultation within 30 days. (Pub. Resources Code §21082.3 (d)).

The NAHC's PowerPoint presentation titled, "Tribal Consultation Under AB 52: Requirements and Best Practices" may be found online at: http://nahc.ca.gov/wp-content/uploads/2015/10/AB52TribalConsultation_CalEPAPDF.pdf

SB 18

SB 18 applies to local governments and requires local governments to contact, provide notice to, refer plans to, and consult with tribes prior to the adoption or amendment of a general plan or a specific plan, or the designation of open space. (Gov. Code §65352.3). Local governments should consult the Governor's Office of Planning and Research's "Tribal Consultation Guidelines," which can be found online at: https://www.opr.ca.gov/docs/09_14_05_Updated_Guidelines_922.pdf

Some of SB 18's provisions include:

1. Tribal Consultation: If a local government considers a proposal to adopt or amend a general plan or a specific plan, or to designate open space it is required to contact the appropriate tribes identified by the NAHC by requesting a "Tribal Consultation List." If a tribe, once contacted, requests consultation the local government must consult with the tribe on the plan proposal. **A tribe has 90 days from the date of receipt of notification to request consultation unless a shorter timeframe has been agreed to by the tribe.** (Gov. Code §65352.3 (a)(2)).
2. No Statutory Time Limit on SB 18 Tribal Consultation. There is no statutory time limit on SB 18 tribal consultation.
3. Confidentiality: Consistent with the guidelines developed and adopted by the Office of Planning and Research pursuant to Gov. Code §65040.2, the city or county shall protect the confidentiality of the information concerning the specific identity, location, character, and use of places, features and objects described in Public Resources Code §5097.9 and §5097.993 that are within the city's or county's jurisdiction. (Gov. Code §65352.3 (b)).
4. Conclusion of SB 18 Tribal Consultation: Consultation should be concluded at the point in which:
   a. The parties to the consultation come to a mutual agreement concerning the appropriate measures for preservation or mitigation; or
   b. Either the local government or the tribe, acting in good faith and after reasonable effort, concludes that mutual agreement cannot be reached concerning the appropriate measures of preservation or mitigation. (Tribal Consultation Guidelines, Governor's Office of Planning and Research (2005) at p. 18).

Agencies should be aware that neither AB 52 nor SB 18 precludes agencies from initiating tribal consultation with tribes that are traditionally and culturally affiliated with their jurisdictions before the timeframes provided in AB 52 and SB 18. For that reason, we urge you to continue to request Native American Tribal Contact Lists and "Sacred Lands File" searches from the NAHC. The request forms can be found online at: http://nahc.ca.gov/resources/forms/

NAHC Recommendations for Cultural Resources Assessments

To adequately assess the existence and significance of tribal cultural resources and plan for avoidance, preservation in place, or barring both, mitigation of project-related impacts to tribal cultural resources, the NAHC recommends the following actions:

1. Contact the appropriate regional California Historical Research Information System (CHRIS) Center (http://ohp.parks.ca.gov/?page_id=1068) for an archaeological records search. The records search will determine:
   a. If part or all of the APE has been previously surveyed for cultural resources.
   b. If any known cultural resources have already been recorded on or adjacent to the APE.
   c. If the probability is low, moderate, or high that cultural resources are located in the APE.
   d. If a survey is required to determine whether previously unrecorded cultural resources are present.

2. If an archaeological inventory survey is required, the final stage is the preparation of a professional report detailing the findings and recommendations of the records search and field survey.
   a. The final report containing site forms, site significance, and mitigation measures should be submitted immediately to the planning department. All information regarding site locations, Native American human remains, and associated funerary objects should be in a separate confidential addendum and not be made available for public disclosure.
   b. The final written report should be submitted within 3 months after work has been completed to the appropriate regional CHRIS center.

3. Contact the NAHC for:
   a. A Sacred Lands File search. Remember that tribes do not always record their sacred sites in the Sacred Lands File, nor are they required to do so. A Sacred Lands File search is not a substitute for consultation with tribes that are traditionally and culturally affiliated with the geographic area of the project's APE.
   b. A Native American Tribal Consultation List of appropriate tribes for consultation concerning the project site and to assist in planning for avoidance, preservation in place, or, failing both, mitigation measures.

4. Remember that the lack of surface evidence of archaeological resources (including tribal cultural resources) does not preclude their subsurface existence.
   a. Lead agencies should include in their mitigation and monitoring reporting program plan provisions for the identification and evaluation of inadvertently discovered archaeological resources per Cal. Code Regs., tit. 14, §15064.5(f) (CEQA Guidelines §15064.5(f)). In areas of identified archaeological sensitivity, a certified archaeologist and a culturally affiliated Native American with knowledge of cultural resources should monitor all ground-disturbing activities.
   b. Lead agencies should include in their mitigation and monitoring reporting program plans provisions for the disposition of recovered cultural items that are not burial associated in consultation with culturally affiliated Native Americans.
   c. Lead agencies should include in their mitigation and monitoring reporting program plans provisions for the treatment and disposition of inadvertently discovered Native American human remains. Health and Safety Code §7050.5, Public Resources Code §5097.98, and Cal. Code Regs., tit. 14, §15064.5, subdivisions (d) and (e) (CEQA Guidelines §15064.5, subds. (d) and (e)) address the processes to be followed in the event of an inadvertent discovery of any Native American human remains and associated grave goods in a location other than a dedicated cemetery.

If you have any questions or need additional information, please contact me at my email address: Steven.Quinn@nahc.ca.gov.

Sincerely,

Nancy Gonzalez
for
Steven Quinn
Associate Governmental Program Analyst

cc: State Clearinghouse

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-20-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Sharon Burton name
2808 Ribbonwood Rd. Boulevard, Ca address
Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

This letter confirms my formal opposition to Terra-Gen's proposed Boulder Brush Gen-tie line and switchyard facilities, and their connected Campo Wind and Torrey Wind projects. *These destructive projects are not needed. Renewable energy can and should be generated on individual rooftops and in the cities where the majority of energy is consumed. Our rural communities, quality of life, and property values are not energy sacrifice zones!*

The predominantly low-income Boulevard / Jacumba area is already disproportionately impacted by the existing 129 industrial wind turbines at Kumeyaay Wind, Iberdrola's Tule Wind, Energia Sierra Juarez Wind, SDG&E's Sunrise Powerlink, Southwest Powerlink, ECO Substation, Boulevard Substation and 138kV line, and Jacumba Solar; AND the proposed Campo Wind, Torrey Wind, Rugged Solar (Rough Acres Ranch-Ribbonwood Road), Boulevard Solar (Tierra Del Sol) , Boulevard Energy Storage (Tule Jim) , Jacumba Valley Ranch (JVR) solar (Ketchum Ranch), Starlight Solar (Empire Ranch, Jewel Valley), and potentially others that have not yet been announced. These projects represent a host of damages and little to no local benefits.

Wind, solar, and related energy infrastructure projects generate noise and electrical pollution that can harm people, pets, livestock, and wildlife for miles around. And they are UGLY!

Instead of producing industry-biased reports wrongfully denying real-world adverse impacts, San Diego County should fund independent noise and electrical pollution testing and conduct Health Impact Assessments for those who are already suffering from previous negligent approvals allowing wind turbines and other energy infrastructure far too close to homes and other occupied structures. ***We deserve equal protection under the law! NO MORE TURBINES!***

(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/20/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Mary Anne Oppenheimer name
39544 Clements St. Boulevard CA 91905 address
619-760-7878 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/20/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Teri Lederman name
1563 Starship St., Jacumba, CA address
619-766-4636 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

This letter confirms my formal opposition to Terra-Gen's proposed Boulder Brush Gen-tie line and switchyard facilities, and their connected Campo Wind and Torrey Wind projects. *These destructive projects are not needed. Renewable energy can and should be generated on individual rooftops and in the cities where the majority of energy is consumed. Our rural communities, quality of life, and property values are not energy sacrifice zones!*

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DATE: 3-20-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Linda Shannon name
P.O. Box 1527 address
Boulevard, Ca 91905 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-20-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Debbie Moran name
39545 Clements St. Boulevard address
(619) 733-4788 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3/20/2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Quentin Schwab name

2246 Tierra Heights Rd
Boulevard CA 91905 address

619-577-9698 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-20-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

LAURA FELTEN name
2669 RIBBONWOOD RD., BOULEVARD CA 91905 address
lmfelten58@hotmail.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3/20/2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Jennifer Schwab name
2246 Tierra Heights Rd Boulevard CA 91905 address
619-889-1434 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 2-28-2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Pamela Guy name
2975 Ribbonwood RD P.O. BOX 1192 Boulevard address
guypam@yahoo.com 619-755-9413 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 2-28-2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Casey Espinosa name
2975 Ribbonwood RD Boulevard address
cowgrlguy@yahoo.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 2-28-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Nancy Good name
PO Box 1165 - Boulevard, CA address/
619-743-1517 or nancyKgood@gmail.com phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 2-28-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

CHARLES B. GOOD name
37649 OLD HWY 80 address
760 822 1657 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 2-25-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

[illegible] name
P.O. Box 1452 address
Boulevard CA 91905 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 2-23-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Leslie Harris name
2945 Ribbonwood Rd #2 address
619 733-9486 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 2-28-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
BARRANCE ZAKAN name
P O Box 776, Alpine 91903 address
flemightyg@gmx.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 2/28/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Benjamin P Good name BENJAMIN GOOD
35252 old Hwy 80 address
Pine Valley CA 91962 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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The predominantly low-income Boulevard / Jacumba area is already disproportionately impacted by the existing 129 industrial wind turbines at Kumeyaay Wind, Iberdrola's Tule Wind, Energia Sierra Juarez Wind, SDG&E's Sunrise Powerlink, Southwest Powerlink, ECO Substation, Boulevard Substation and 138kV line, and Jacumba Solar; AND the proposed Campo Wind, Torrey Wind, Rugged Solar (Rough Acres Ranch-Ribbonwood Road), Boulevard Solar (Tierra Del Sol) , Boulevard Energy Storage (Tule Jim) , Jacumba Valley Ranch (JVR) solar (Ketchum Ranch), Starlight Solar (Empire Ranch, Jewel Valley), and potentially others that have not yet been announced. These projects represent a host of damages and little to no local benefits.

Wind, solar, and related energy infrastructure projects generate noise and electrical pollution that can harm people, pets, livestock, and wildlife for miles around. And they are UGLY!

Instead of producing industry-biased reports wrongfully denying real-world adverse impacts, San Diego County should fund independent noise and electrical pollution testing and conduct Health Impact Assessments for those who are already suffering from previous negligent approvals allowing wind turbines and other energy infrastructure far too close to homes and other occupied structures. ***We deserve equal protection under the law! NO MORE TURBINES!***

(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 2-28-2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

DAVID COOPER name
38402 PIONEER LN address
619 993 9135 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

This letter confirms my formal opposition to Terra-Gen's proposed Boulder Brush Gen-tie line and switchyard facilities, and their connected Campo Wind and Torrey Wind projects. *These destructive projects are not needed. Renewable energy can and should be generated on individual rooftops and in the cities where the majority of energy is consumed. Our rural communities, quality of life, and property values are not energy sacrifice zones!*

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3.18.19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Michele Strand name
PO Box 1424 Blvd address
michelestrand@yahoo.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

This letter confirms my formal opposition to Terra-Gen's proposed Boulder Brush Gen-tie line and switchyard facilities, and their connected Campo Wind and Torrey Wind projects. *These destructive projects are not needed. Renewable energy can and should be generated on individual rooftops and in the cities where the majority of energy is consumed. Our rural communities, quality of life, and property values are not energy sacrifice zones!*

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-5-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Richard Blaisdell name
2981 La Posta Circle
Pine Valley CA 91962 address
rbrestor@gmail.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

This letter confirms my formal opposition to Terra-Gen's proposed Boulder Brush Gen-tie line and switchyard facilities, and their connected Campo Wind and Torrey Wind projects. *These destructive projects are not needed. Renewable energy can and should be generated on individual rooftops and in the cities where the majority of energy is consumed. Our rural communities, quality of life, and property values are not energy sacrifice zones!*

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(Comment letters are due by 4 PM March 18, 2019)

[signature]

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-6-2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Robbin Washer name
2948 Ribbonwood Road Boulevard address
619-766-4124
SGWasheR@YAhoo.Com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/6/2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Cheryl Delozier name
2948 Ribbonwood Road Boulevard address
619-766-4235
Cheryl.Delozier@Yahoo.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-6-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Sharon L. Burton name
2808 Ribbonwood Rd. Boulevard Ca. 91905 address
SLburton552@yahoo.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-7-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Ricky Guy name
2975 Ribbonwood Rd. address
858 997-6365 Phone # or email
ricky.Guy21@yahoo.com

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/7/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Tammy Townsend name
2273 Angel Dr. Boulevard CA 91905 address
619-729-3645 Tamuck2@gmail.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-7-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Charles Townsend name
2273 Angel Dr. Boulevard CA 91905 address
619-729-3198 / blvdchuck@gmail.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/7/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

DAVID WILSON name
2916 RIBBONWOOD RD BLVD CA address
~~619 993357~~ 619 993 3575 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/7/2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
LESLIE WILSON name
2916 Ribbonwood Rd Blvd CA 91905 address
WERQLES@NETZERO.COM Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/8/2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
JEFFREY MORRISON name
2920 RIBBONWOOD ROAD address BOULEVARD, CA 91905
619-701-4408 BLVCHIEF@YAHOO.COM Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/8/2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Tamara D. Morrison name
29120 Ribbonwood Rd Boulevard, CA address 91905
(619) 988-0367 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-8-2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Bud Chase name
2948 Ribbonwood Rd
Boulevard address
619-766-4235
Cheryl.DeLozier@yahoo.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

This letter confirms my formal opposition to Terra-Gen's proposed Boulder Brush Gen-tie line and switchyard facilities, and their connected Campo Wind and Torrey Wind projects. *These destructive projects are not needed. Renewable energy can and should be generated on individual rooftops and in the cities where the majority of energy is consumed. Our rural communities, quality of life, and property values are not energy sacrifice zones!*

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-08-2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

BETTY CHASE name

2948 ribbonwood RD Boulevard, CA address

619-766-4235 Cheryl.Delozier@yahoo.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

This letter confirms my formal opposition to Terra-Gen's proposed Boulder Brush Gen-tie line and switchyard facilities, and their connected Campo Wind and Torrey Wind projects. *These destructive projects are not needed. Renewable energy can and should be generated on individual rooftops and in the cities where the majority of energy is consumed. Our rural communities, quality of life, and property values are not energy sacrifice zones!*

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/8/2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Robert Morgan name

2912 Ribbonwood Rd address
Boulevard CA 91905
Smorgy@Hughes.NET Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-9-2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Marie J. Morgan name
2912 Ribbonwood Rd address
Boulevard, CA 91905
sMorgy@Hughes.Net Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/10/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave. Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Valerie Morrow Name
2910 Ribbonwood Rd Blvd. CA 91905 address
Valhound@gmail.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE. CAMPO WIND. AND TORREY WIND PROJECTS

DATE: 3/10/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave. Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Danica Walker Name
39211 Clements St. Address
858)663-1439 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/10/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave. Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

LANCE MORROW Name
2910 RIBBONWOOD RD BOULEVARD CA 91905 address
WEARARTTHOULM@AOL.COM Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002: PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: March 10-2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
DEANNE MARTINO name
2742 Ribbonwood Road
Boulevard address
619-766-9913 TDM2711@gmail.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/16/2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Tracey Martino name
2742 Ribbonwood Road Boulevard address
619-766-9913
Socaequestrian@Gmail.Com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-11-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Heather Skains name
2810 Ribbonwood Rd address Boulevard CA 91905
619-766-4203 hskains@yahoo.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/16/2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

JUSTIN WALKER name
39211 CLEMENTS ST BOULEVARD CA address
(619) 993-7968 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3/16/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

WALTER LEE HENDERSON name, Walt Henderson
38230 TIERRA REAL Rd address
760-212-3119 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-16-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Jason Fordyce name
PO Box 1045 boulevard CA address
619-766-3479 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-17-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

[signature] name DON BONFIGLIO

40123 Ribbonwood Rd address

Boulevard, CA 91905 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

This letter confirms my formal opposition to Terra-Gen's proposed Boulder Brush Gen-tie line and switchyard facilities, and their connected Campo Wind and Torrey Wind projects. *These destructive projects are not needed. Renewable energy can and should be generated on individual rooftops and in the cities where the majority of energy is consumed. Our rural communities, quality of life, and property values are not energy sacrifice zones!*

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Wind, solar, and related energy infrastructure projects generate noise and electrical pollution that can harm people, pets, livestock, and wildlife for miles around. And they are UGLY!

Instead of producing industry-biased reports wrongfully denying real-world adverse impacts, San Diego County should fund independent noise and electrical pollution testing and conduct Health Impact Assessments for those who are already suffering from previous negligent approvals allowing wind turbines and other energy infrastructure far too close to homes and other occupied structures. ***We deserve equal protection under the law! NO MORE TURBINES!***

(Comment letters are due by 4 PM March 18, 2019)

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-17-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Michelle Chapman name
40121 Ribbonwood Rd address
Boulevard, Ca 91905 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3/17/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123

FROM:

Monica Albair name
38228 Tierra Real Rd address
619-851-0115 mASLido@ msn.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3.17.19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
RETT LAWRENCE name
38345 OLD HWY 80 91905 address
JUSTRETT@YAHOO.COM Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3/17/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Melody E. Ponhot name
P.O. Box 1326 address
Boulevard, Ca 91905 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3/17/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Anthony W. Ponchot name
P. O. Box 1326 address
Boulevard, Ca 91905 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3.17.19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
JEFFREY A. McKERNAN name
37131 HWY 94 PO BOX 1209 BOULEVARD, CA. 91905 address
619.766.9185 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-17-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Laura McKernan name
Po Box 1209 (37131 Hwy 94) BLVD, CA 91905 address
(619) 766-9185 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-17-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Kim Patterson name
38230 Tierra Real Rd address
Kp3p1@yahoo.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-17-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Ryan Peterson name
38230 Tierra Real RD address
619-766-0078 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-17-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

DONNA TISDALE name

PO BX 1275, BOULEVARD 91905 address

619 766 4170 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-17-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
Ed Tisdale name
P. O. Box 1275 address
Boulevard Ca (619) 766-4170 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-17-2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Tracy Tisdale name

Po Box 961 address

Boulevard CA 91905 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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March 18, 2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM: Cole Dotson

38236 Tierra Real Rd

Boulevard, CA 91905

Cole.dotson@protonmail.com

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 3-18-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Alex Velazquez name

563 Broadway 33 address

El Cajon CA 92021 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

This letter confirms my formal opposition to Terra-Gen's proposed Boulder Brush Gen-tie line and switchyard facilities, and their connected Campo Wind and Torrey Wind projects. *These destructive projects are not needed. Renewable energy can and should be generated on individual rooftops and in the cities where the majority of energy is consumed. Our rural communities, quality of life, and property values are not energy sacrifice zones!*

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DATE: 3/18/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Jacob Trautman name
1234 Crystal Springs Dr address
Chula Vista CA 91915 / sellingemail619@gmail.com Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3/18/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Christopher Zapor name
38220 Highway 94 Boulevard, Ca. 91905 address
619-920-3815 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3/18/19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:
April Zapor name
38220 Highway 94 Boulevard, Ca. 91905 address
619-920-3027 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-19-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Lydia Adams name
PO Box 91931 Guatay CA address
619-573-1040 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-18-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Stanley Adams name
PO Box 91931 Grantey CA address
619-766-1010 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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DATE: 3-12-19

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Steven Redman name
7949 Wistful Vista St, Santee CA 92071 address
Steven.S.Redman@cbp.dhs.gov Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 2019MAR18

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Matthew K. Peter name
qlughpi@hotmail.com address
442 264 8320 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: 20190318

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

FERNANDES, ALEX name

22 Rivermeadows dr address

314-452-1241 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

San Diego County Archaeological Society, Inc.
Environmental Review Committee

14 March 2019

To: Ms. Bronwyn Brown
Department of Planning and Development Services
County of San Diego
5510 Overland Avenue, Suite 310
San Diego, California 92123

Subject: Notice of Preparation of a Draft Environmental Impact Report
Boulder Brush Gen-Tie Line and Switchyard Facilities
for the Campo Wind Project
PDS2019-MUP-19-002, Log No. PDS2019-ER-19-16-001

Dear Ms. Brown:

Thank you for the Notice of Preparation for the subject project, received by this Society last month.

We are pleased to note the inclusion of cultural resources in the list of subject areas to be addressed in the DEIR, and look forward to reviewing it during the upcoming public comment period. To that end, please include us in the distribution of the DEIR, and also provide us with a copy of the cultural resources technical report(s).

SDCAS appreciates being included in the County's environmental review process for this project.

Sincerely,

James W. Royle, Jr., Chairperson
Environmental Review Committee

cc: SDCAS President
File

P.O. Box 81106 San Diego, CA 92138-1106 (858) 538-0935

OPPOSITION TO TERRA-GEN'S PROPOSED BOULDER BRUSH GEN-TIE LINE, CAMPO WIND, AND TORREY WIND PROJECTS

DATE: March 14, 2019

TO: Bronwyn Brown, Planning & Development Services
5510 Overland Ave, Suite 310
San Diego, CA 92123
Bronwyn.brown@sdcounty.ca.gov

FROM:

Linda Shannon name
2587 Ribbonwood Rd. address (Tulle Mt. Rd - butts up to our property.)
Boulevard, ca. (619) 933-4880 Phone # or email

RE: BOULDER BRUSH GEN-TIE LINE & SWITCHYARD FACILITIES FOR THE CAMPO WIND PROJECT: PDS2019-MUP-19-002; PDS2019-ER-19-16-001

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(Comment letters are due by 4 PM March 18, 2019)

Hi Bronwyn

Dave and I find it Rude FOR you, and others who do not live here to do what you want. we have been here for 26 years, and enjoyed every moment, Except FOR all the crap you put in OUR area, with no concern about us. Our horse riding area is gone, because of you, we have been to all meetings, we have Sent our concerns, and you still do not listen to us. You can put all these turbins in your San Diego area, and in the Ocean. Sweeden & Norway have a better idea. Feel free to call me, or come to my 10 acres and talk to me. You should see what we are Really up against.

Hope To see you Soon

Linda

2019 WIND TURBINE NEIGHBOR SURVEY

I am a resident of the Boulevard area in rural Eastern San Diego County. In late 2005, the 25-2MW Gamesa turbines started operation at Kumeyaay Wind on the Campo Reservation. In late 2017, the 57-2.3 MW GE turbines started operation nearby, at Iberdrola's Tule Wind, with 52 of the 57 turbines installed on previously protected public BLM land in McCain Valley and 5 installed on private land owned by Hamann Company related entities. Now, Terra-Gen plans about 90 new 4.2 MW turbines on the Campo Reservation and private ranch land owned by GM Gabrych Family Limited Partnership.

***Since the existing wind turbines started operation, or since I moved into the area, I have noticed the following issues that either started or got worse for myself and/or my family members*:**

Symptoms and other issues/impacts are checked/circled below:

X noise / vibrations
X low rumbling, whooshing, grinding sounds
____sleep disruption / being startled awake
____chronic fatigue / loss of energy
____headache/migraines
____vertigo (spinning or moving sensation)
____nausea or stomach pain
X concentration/memory issues
____irritability, feeling on edge, or jittery
____unexplained panic attacks/anxiety
X ringing or buzzing in the ears
____pressure in chest
____sinus or breathing problems / asthma
____heart fluttering, racing, or heart attack
X increased blood pressure or blood sugar
____depression or unusual mood swings
____visual blurring or eye pain
____unexplained rashes
X joint and muscle pain
____cancer or benign tumors. Type of cancer?

____

____electrical interference at home /office
X disrupted TV, cell, satellite service
____increased static electricity
____blade shadow flicker / strobe effect
XXXX flashing night lights
X other issues not listed here

Symptoms seem worse when:

____inside home / office
X outside
X distracted by motion of turbines
____changes in air pressure / wind direction

Do symptoms get better or go away when you leave the area for days or weeks and then return when you get back?
____Yes X No

In your opinion, are existing turbines too close to homes /offices?
X Yes ____No

Do the turbines make you want to move?
X Yes ____No

Have you filed any complaints over the turbines?
X Yes ____ No

If yes, have you been contacted by San Diego County, BLM, Bureau of Indian Affairs, health officers, or wind turbine owners asking about or investigating your complaints: ____Yes ____No

If yes, was any help / investigations (noise/electrical/health) offered or provided?
____Yes X No

***I declare that this information is true to the best of my knowledge*:**

DATE: March 14, 2019

NAME: Linda Shannon

ADDRESS: 2587 Ribbonwood Rd
Boulevard, Ca.

PHONE / EMAIL (optional): 619) 933-4880

____Additional personal comments are on back of this page.

FROM : Murphy Smith

Paloma Way

Boulevard CA 91905

My name is Murphy Smith, and I am writing this to voice my opposition to the Campo Wind project and associated Terra-Gen power tie. Since 1999, my family has owned property which is about a mile outside the eastern border of the Campo Reservation. I spent my teenage years there and my brothers grew up there, so the land is sacred to us. I moved there again a few years ago in an effort to help maintain the property and keep it safe from fires and other threats; threats which now include the impending encroachment of hazardous industrial scale wind turbines.

Our property includes rolling hillsides and an immaculate view of the western horizon. This view is of the currently beautiful Campo Reservation and the surrounding mountains. From high points of our property we have a view to the North, which for about a decade now includes the wind turbines along Interstate 8. At night our northern horizon is a line of blinking red lights, which is now threatening to extend like a snake along our western horizon, surrounding our property along 180 degrees. What a change that would be from what it is now; a sky that on some nights you can still peer into the deepest, darkest black you have ever seen, glittering with stars barely dimmed by light pollution. Shame on anyone who presents the notion that replacing our stars with endlessly blinking red orbs signaling mass avian death is an acceptable or forgivable solution. Shame on San Diego County for killing the sky, the sky dwellers, and the stars.

The health effects of living in close proximity to these machines is still unknown, but communities like ours should not be used as testing beds to discover what they are, effectively turning us into guinea pigs. Many people recovering from illness move here to live in an environment which is nurturing and healing, away from the toxins of urban or suburban areas. My girlfriend Christina is one of those people suffering from many coexisting medical conditions. One of these is dysautonomia, which affects the autonomic and nervous system and makes one more sensitive to sensory disturbances. She has visited McCain Valley, another site nearby with many wind turbines, with me several times, and being close to the shadow flicker and repetitive noise affected her balance enough that she could not walk without holding on to me. I worry for residents here, many of which are elderly and have conditions which could be exacerbated by these industrial machines. The current research, much of which is biased by being wind-industry sourced, states that the effects are simply "annoyances". I would like to know where the line between an annoyance and a legitimate health issue lies. A tiny lump on your body is "annoying"- until it is diagnosed as cancer. Shame on San Diego County for not listening to its citizens when they were ill, allowing a tiny lump to become a growing cancer.

One of the most disturbing aspects of this project is the blatant environmental racism. At one time I did not oppose this project, as I generally support so-called green energy and also support the Campo tribe and their sovereignty. However, after talking to many members of the tribe who actually live on the reservation I was surprised to find out how many of them oppose the project, as it seems to be rolling over them without their support. The project seems to be only for the profit of the BIA and certain key higher-ups of the tribe, particularly tribal council members Michael Connolly Miskwish and Ralph Goff. What is absolutely appalling about this is how they are being targeted by harmful industrial energy developments which would not be allowed to take place in more affluent communities, much as they were targeted in the 1990s by industrial scale waste disposal companies, proving that these large corporations quite literally see the Campo reservation as a place to dump thieir trash. The difference this time is that now there is an opportunity for public utility companies like SDGE to make money from the projects as well, and city planners like Jim Whalen can't see the exploitation of the Campo tribe when his eyes are too full of dollar signs. Shame on San Diego County for joining the environmental racists. Shame on San Diego County for trying once again to dump its trash on the Campo Reservation.

This issue is no different from countless other examples of the social injustice of environmental racism such as the recent problems in Flint, Michigan or with the Dakota Access PipeLine and Standing Rock. When an economically underserved and culturally repressed community has resources that another community with more money and political strength wants, the latter community will stop at nothing to take those resources away. The same forces that fractured a great people and put them on land reservations, is now threatening to strip away that very same land. Shame on San Diego County, for once again taking land and life away from the Campo people, who owned the land long before.

I hope that it is clear in these comments the general view toward these projects shared by this community. This community will not stand still while being raped economically and environmentally. We will fight back. We will not trade the beauty of our natural world only to fatten the pockets of economic superpowers, while you lower our property values. We will not be deceived by the propaganda of red man versus white man, or of clean energy versus dirty energy, or of humanity versus nature, when the issue is really that of the haves versus the have-nots. San Diego County has taken a stance against its own citizens and the people of the reservation through the actions of County representatives like Jim Whalen, who has legally represented developers and who has a client list and track record which is an obvious conflict of interest; Jim Whalen, who helped develop the Multiple Species Conservation Program that U.S. District Court Judge Rudi Brewster ruled "would permit monumental destruction" of protected species. By choosing to rely on Whalen's counsel instead of true environmental lawyers, the County has shown the public its blatant disregard for environmental justice. Shame on San Diego County for choosing a position against its own citizens and the land which we call home.

Hopefully, mindful consideration of these and the countless other issues raised by the people concerning this project will be considered by the County, not just the insatiable greed of a few key players; perhaps then San Diego County will not have to bear the shame it is currently headed toward.

Thank you,

Murphy Smith

Gavin Newsom
Governor

STATE OF CALIFORNIA
Governor's Office of Planning and Research
State Clearinghouse and Planning Unit

Kate Gordon
Director

Notice of Preparation

February 15, 2019

To: Reviewing Agencies

Re: Boulder Brush Gen-tie Line and Switchyard Facilities for the Campo Wind Project
SCH# 2019029094

Attached for your review and comment is the Notice of Preparation (NOP) for the Boulder Brush Gen-tie Line and Switchyard Facilities for the Campo Wind Project draft Environmental Impact Report (EIR).

Responsible agencies must transmit their comments on the scope and content of the NOP, focusing on specific information related to their own statutory responsibility, within 30 days of receipt of the NOP from the Lead Agency. This is a courtesy notice provided by the State Clearinghouse with a reminder for you to comment in a timely manner. We encourage other agencies to also respond to this notice and express their concerns early in the environmental review process.

Please direct your comments to:

Bronwyn Brown
San Diego County
5510 Overland Ave., Suite 310
San Diego, CA 92123

with a copy to the State Clearinghouse in the Office of Planning and Research. Please refer to the SCH number noted above in all correspondence concerning this project.

If you have any questions about the environmental document review process, please call the State Clearinghouse at (916) 445-0613.

Sincerely,

Scott Morgan
Director, State Clearinghouse

Attachments
cc: Lead Agency

Document Details Report
State Clearinghouse Data Base

SCH# **2019029094**
Project Title Boulder Brush Gen-tie Line and Switchyard Facilities for the Campo Wind Project
Lead Agency San Diego County

Type **NOP** Notice of Preparation

Description Boulder Brush, LLC proposes an overhead (kV) gen-tie transmission line, a 500 kV substation, and a switchyard on private land under the jurisdiction of the County of San Diego. The development footprint of these facilities on private land totals approximately 200 acres. The Gen-tie would vary wind energy from the proposed Campo Wind Energy Project on the Campo Indian Reservation to the existing Sunrise Powerlink. The gen-tie line on private land would total approx. 3.5 miles in length, and include 32 steel poles at a maximum height of 150 feet. The applicant also proposes permanent and temporary access roads, temporary staging areas, and a temporary concrete batch plant. Although the majority of the Campo Wind Project is not within the County's jurisdiction and is not subject to the County's land use regulations, the project for CEQA purposes is considered to be all facilities required for the development of the Campo Wind Energy project.

Lead Agency Contact

Name Bronwyn Brown
Agency San Diego County
Phone (858) 495-5516 ***Fax***
email
Address 5510 Overland Ave., Suite 310
City San Diego ***State*** CA ***Zip*** 92123

Project Location

County San Diego
City
Region
Cross Streets McCain Valley Rd., and Ribbonwood Rd.
Lat / Long 32° 54' 56" N / 117° 1' 7" W
Parcel No. multiple
Township 16S ***Range*** 7E ***Section*** 36 ***Base***

Proximity to:

Highways
Airports
Railways
Waterways Tule Creek and unnamed drainages
Schools
Land Use Rural/ Rural Lands (RL-80)/ General Rural (S92)

Project Issues Aesthetic/Visual; Agricultural Land; Air Quality; Archaeologic-Historic; Biological Resources; Drainage/Absorption; Flood Plain/Flooding; Forest Land/Fire Hazard; Geologic/Seismic; Growth Inducing; Landuse; Minerals; Noise; Wetland/Riparian; Water Supply; Water Quality; Wildlife; Vegetation; Traffic/Circulation; Toxic/Hazardous; Solid Waste; Soil Erosion/Compaction/Grading; Public Services; Cumulative Effects

Reviewing Agencies Resources Agency; Department of Conservation; Cal Fire; Office of Historic Preservation; Department of Parks and Recreation; Department of Fish and Wildlife, Region 5; Office of Emergency Services, California; California Energy Commission; Native American Heritage Commission; Public Utilities Commission; Caltrans, District 11; Air Resources Board, Major Industrial Projects; State Water Resources Control Board, Division of Drinking Water; Department of Toxic Substances Control; Regional Water Quality Control Board, Region 9

P Distribution List County: San Diego SCH# 2019029094

rces Agency

sources Agency
dell Gayou

- [ ] **Dept. of Boating & Waterways**
  Denise Peterson
- [ ] **California Coastal Commission**
  Allyson Hitt
- [ ] **Colorado River Board**
  Elsa Contreras
- [ ] **Dept. of Conservation**
  Crina Chan
- [ ] **Cal Fire**
  Dan Foster
- [ ] **Central Valley Flood Protection Board**
  James Herota
- [ ] **Office of Historic Preservation**
  Ron Parsons

pt of Parks & Recreation
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- [ ] **S.F. Bay Conservation & Dev't. Comm.**
  Steve Goldbeck
- [ ] **Dept. of Water Resources**
  Resources Agency
  Nadell Gayou

sh and Game

- [ ] **Depart. of Fish & Wildlife**
  Scott Flint
  Environmental Services Division
- [ ] **Fish & Wildlife Region 1**
  Curt Babcock
- [ ] **Fish & Wildlife Region 1E**
  Laurie Harnsberger
- [ ] **Fish & Wildlife Region 2**
  Jeff Drongesen
- [ ] **Fish & Wildlife Region 3**
  Craig Weightman
- [ ] **Fish & Wildlife Region 4**
  Julie Vance
- [x] **Fish & Wildlife Region 5**
  Leslie Newton-Reed
  Habitat Conservation Program
- [ ] **Fish & Wildlife Region 6**
  Tiffany Ellis
  Habitat Conservation Program
- [ ] **Fish & Wildlife Region 6 I/M**
  Heidi Calvert
  Inyo/Mono, Habitat Conservation Program
- [ ] **Dept. of Fish & Wildlife M**
  William Paznokas
  Marine Region

Other Departments

- [ ] **California Department of Education**
  Lesley Taylor
- [x] **OES (Office of Emergency Services)**
  Monique Wilber
- [ ] **Food & Agriculture**
  Sandra Schubert
  Dept. of Food and Agriculture
- [ ] **Dept. of General Services**
  Cathy Buck
  Environmental Services Section
- [ ] **Housing & Comm. Dev.**
  CEQA Coordinator
  Housing Policy Division

Independent Commissions,Boards

- [ ] **Delta Protection Commission**
  Erik Vink
- [ ] **Delta Stewardship Council**
  Anthony Navasero
- [x] **California Energy Commission**
  Eric Knight
- [x] **Native American Heritage Comm.**
  Debbie Treadway
- [x] **Public Utilities Commission**
  Supervisor
- [ ] **Santa Monica Bay Restoration**
  Guangyu Wang
- [ ] **State Lands Commission**
  Jennifer Deleong
- [ ] **Tahoe Regional Planning Agency (TRPA)**
  Cherry Jacques

Cal State Transportation Agency CalSTA

- [ ] **Caltrans - Division of Aeronautics**
  Philip Crimmins
- [ ] **Caltrans – Planning HQ LD-IGR**
  Christian Bushong
- [ ] **California Highway Patrol**
  Suzann Ikeuchi
  Office of Special Projects

Dept. of Transportation

- [ ] **Caltrans, District 1**
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- [ ] **Caltrans, District 2**
  Marcelino Gonzalez
- [ ] **Caltrans, District 3**
  Susan Zanchi
- [ ] **Caltrans, District 4**
  Patricia Maurice
- [ ] **Caltrans, District 5**
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Cal EPA

Air Resources Board

- [ ] **Airport & Freight**
  Jack Wursten
  - [ ] **Transportation Projects**
    Nesamani Kalandiyur
  - [x] **Industrial/Energy Projects**
    Mike Tollstrup
- [ ] **California Department of Resources, Recycling & Recovery**
  Kevin Taylor/Jeff Esquivel
- [ ] **State Water Resources Control Board**
  Regional Programs Unit
  Division of Financial Assistance
- [x] **State Water Resources Control Board**
  Cindy Forbes – Asst Deputy
  Division of Drinking Water
- [ ] **State Water Resources Control Board**
  Div. Drinking Water #________
- [ ] **State Water Resources Control Board**
  Student Intern, 401 Water Quality Certification Unit
  Division of Water Quality
- [ ] **State Water Resouces Control Board**
  Phil Crader
  Division of Water Rights
- [x] **Dept. of Toxic Substances Control Reg. #________**
  CEQA Tracking Center
- [ ] **Department of Pesticide Regulation**
  CEQA Coordinator

Regional Water Quality Control Board (RWQCB)

- [ ] **RWQCB 1**
  Cathleen Hudson
  North Coast Region (1)
- [ ] **RWQCB 2**
  Environmental Document Coordinator
  San Francisco Bay Region (2)
- [ ] **RWQCB 3**
  Central Coast Region (3)
- [ ] **RWQCB 4**
  Teresa Rodgers
  Los Angeles Region (4)
- [ ] **RWQCB 5S**
  Central Valley Region (5)
  - [ ] **RWQCB 5F**
    Central Valley Region (5)
    Fresno Branch Office
  - [ ] **RWQCB 5R**
    Central Valley Region (5)
    Redding Branch Office
- [ ] **RWQCB 6**
  Lahontan Region (6)
  - [ ] **RWQCB 6V**
    Lahontan Region (6)
    Victorville Branch Office
- [ ] **RWQCB 7**
  Colorado River Basin Region (7)
- [ ] **RWQCB 8**
  Santa Ana Region (8)
- [x] **RWQCB 9**
  San Diego Region (9)
- [ ] **Other** ____________________
- [ ] ____________________
  Conservancy

Last Updated 5/22/18

Document Details Report
State Clearinghouse Data Base

Date Received 02/15/2019 ***Start of Review*** 02/15/2019 ***End of Review*** 03/18/2019

2019029094

Notice of Completion & Environmental Document Transmittal

Mail to: State Clearinghouse, P. O. Box 3044, Sacramento, CA 95812-3044 (916) 445-0613
For Hand Delivery/Street Address: 1400 Tenth Street, Sacramento, CA 95814

SCH # ____________

Project Title: Boulder Brush Gen-tie Line and Switchyard Facilities for the Campo Wind Project

Lead Agency: County of San Diego (Attn: Planning and Development Services) Contact Person: Bronwyn Brown
Mailing Address: 5510 Overland Avenue, Suite 310 Phone: (858) 495-5516
City: San Diego Zip: 92123 County: San Diego

Project Location: County: San Diego City/Nearest Community: Boulevard
Cross Streets: McCain Valley Road and Ribbonwood Road Zip Code: 91905
Lat. / Long.: 32 54' 56" N/117 1' 7" W Total Acres: see Project Description
Assessor's Parcel No.: 528-220-02 & -03, 529-050-01, Section: 36 Twp.: 16S Range: 07E Base: ______
529-060-01, 529-090-02, 529-100-01 thru 03, 529-120-01, 529-120-03, 529-130-01, 611-010-01, -02 and -03,
Within 2 Miles: State Hwy #: None Waterways: Tule Creek and unnamed drainages
Airports: None Railways: None Schools: None

Document Type:

CEQA: ☒ NOP ☐ Early Cons ☐ Neg Dec ☐ Mit Neg Dec ☐ Draft EIR ☐ Supplement/Subsequent EIR (Prior SCH No.) ______ Other ______

NEPA: ☐ NOI ☐ EA ☐ Draft EIS ☐ FONSI

Other: ☐ Joint Document ☐ Final Document ☐ Other ______

Governor's Office of Planning & Research
FEB 15 2019
STATE CLEARINGHOUSE

Local Action Type:

☐ General Plan Update ☐ General Plan Amendment ☐ General Plan Element ☐ Community Plan
☐ Specific Plan ☐ Master Plan ☐ Planned Unit Development ☐ Site Plan
☐ Rezone ☐ Prezone ☒ Use Permit (Major) ☐ Land Division (Subdivision, etc.)
☐ Annexation ☐ Redevelopment ☐ Coastal Permit ☐ Other ______

Development Type:

☐ Residential: ____ Acres ____
☐ Office: Sq.ft. ____ Acres ____ Employees ____
☐ Commercial: ____ Sq.ft. ____ Acres ____
☐ Industrial: Sq.ft. ____ Acres ____ Employees ____
☐ Educational ______
☐ Recreational ______
☐ Water Facilities: Type ______ MGD ______
☐ Transportation: Type ______
☐ Mining: ______ Employees
☒ Power: Type Wind MW ______
☐ Waste Treatment: Type ______ MGD ______
☐ Hazardous Waste: Type ______
☐ Other: ______

Project Issues Discussed in Document:

☒ Aesthetic/Visual
☒ Agricultural Land
☒ Air Quality
☒ Archeological/Historical
☒ Biological Resources
☐ Coastal Zone
☒ Drainage/Absorption
☐ Economic/Jobs
☐ Fiscal
☒ Floodplain/Flooding
☒ Forest Land/Fire Hazard
☒ Geologic/Seismic
☒ Greenhouse Gas Emissions
☒ Minerals
☒ Noise
☐ Population/Housing Balance
☒ Public Services/Facilities
☒ Cumulative Effects
☐ Recreation/Parks
☐ Schools/Universities
☐ Septic Systems
☐ Sewer Capacity
☒ Soil Erosion/Compaction/Grading
☒ Solid Waste
☒ Toxic/Hazardous
☒ Transportation
☒ Energy
☒ Vegetation
☒ Water Quality
☒ Water Supply/Groundwater
☒ Wetland/Riparian
☒ Wildlife
☒ Growth Inducing
☒ Land Use
☒ Tribal Cultural Res.
☒ Wildfire
☒ Other ______

Present Land Use/Zoning/General Plan Designation:

Regional Categories: Rural Land Use Designation: Rural Lands (RL-80)
Zoning: General Rural (S92)

Project Description: Boulder Brush, LLC proposes an overhead 230 kilovolt (kV) gen-tie transmission line, a 500 kV substation, and a switchyard on private land under the jurisdiction of the County of San Diego. The development footprint of these facilities on private land totals approximately 200 acres. The gen-tie line would carry wind energy from the proposed Campo Wind Energy Project on the Campo Indian Reservation to the existing Sunrise Powerlink. The gen-tie line on private land would total approximately 3.5 miles in length, and

Note: The state Clearinghouse will assign identification numbers for all new projects. If a SCH number already exists for a project (e.g. Notice of Preparation or previous draft document) please fill in.

Stetzer Electric, Inc.

520 W. Broadway
P.O. Box 25
Blair, WI 54616
Tel: (608) 989-2571
Fax: (608) 989-2570
http://www.stetzerelectric.com

To whom it may concern,

In April 2018 I tested a variety of properties and locations around Niagara and Haldimand Counties (Ontario) for ground current/stray voltage and for high frequency transients and harmonics. The release of the details of each of those reports is at the discretion of the individual property owners in question.

What I can confirm is the following: in each of the properties tested, varying degrees of electrical distortion and contact current were found inside and outside the homes in question, even with the power turned off. A number of these properties had been tested before the coming online of the Niagara Regional Wind farm and at those previous times levels of electrical pollution were much lower. Clear cases of violation of existing lax ground current standards during the April 2018 testing were found with for example 10 volts of current on a downwire being discharged into the earth near the industrial wind turbine installations.

What are the sources?

Both wind and solar have major issues with complying with the Institute of Electrical and Electronic Engineers Standards, specifically the IEEE 519. In most cases the electric utilities are mandated to buy "Green Energy" such as wind and solar power. The inverters on the devices generate harmonic currents and voltages as well as high frequency transients. These harmonic currents, voltages, and transients are coupled to the electrical company's transmission and distribution system that is eventually connected to homes, business, and industry. This distorted power causes appliances to fail, motors, wires, and transformers to overheat, inaccurate watt-hour meter readings, and, according to the published peer-reviewed scientific research papers, a drop in milk production in cows and other health issues associated with exposure to higher frequencies.

The Guide for Applying Harmonic Limits on Power Systems (72) – May 4, 1996 states:

> The electric utility is responsible for the quality of the voltage supplied to its customers. This voltage can become distorted due to harmonics introduced by nonlinear loads within customer facilities, due to harmonics introduced by nonlinear devices applied directly on the power system (e.g. static var systems, high voltage dc converters, traction power rectifiers, etc), or due to resonance conditions on the system. IEEE 519-1992 was developed to help with the coordination that is needed to keep voltage distortion levels on the overall system within reasonable limits.

Figure 1 below is copied from the IEEE 519 and shows the harmonic voltage distortion limits.

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Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq$ 69 kV	3.0	5.0
69 kV < $V \leq$ 161 kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Figure 1

Electrical distortion and contact current found during testing

In each of the properties tested, electrical pollution in the form of varying degrees of distortion was found to be riding on the 60-cycle waveform. Also, with measurement taken between the kitchen sink and floor in the homes, varying degrees of contact current were found. These were highly distorted 60 Hz sine wave that were measured when the power to each home was turned completely off. That indicates that there is nothing in the home causing his reading. Since the power to the home was turned completely off, the sole responsibility for this is the electric utility due to their use of the earth as a return path – a clear violation of electrical codes and rules. The electric utility is responsible for the 60Hz and the issue should be addressed using sound engineering practices.

A scientific report by Kavet published in *Bioelectromagnetics* states, “the absolute (as well as modest) level of contact current modeled (18µA) produces average electric fields in human tissue along its path that exceed 1 mV/m. At and above this level, the NIEHS Working Group [1998] accepts that biological effects relevant to cancer have been reported in “numerous well-programmed studies””.

Testing in a range of locations near the Niagara Regional Wind Farm shows high frequency transients riding along ground current measurable on people’s properties. Again, the source of the ground currents is clearly the responsibility of the electric utility once it is their lines. Instead of keeping these electrical currents on their wires, they elect to put them onto the earth where they come in contact with people and animals.

The *National Electrical Safety Code*, Rule 92D states: “Ground connection points shall be arranged so that under normal circumstances there will be no objectionable flow of current over the grounding conductor.”

The *Wiley Encyclopedia of Electrical and Electronics Engineers* states: “It is an unsafe practice to allow current to flow over the earth continuously, uncontrolled. All continuously flowing current must be contained within insulated electrical conductors.”

This is not an impossible task. Electrical Power Research Institute (EPRI) published a document – *Handbook for the Assessment and Management of Magnetic Fields Caused by Distribution Lines, EPRI TR-106003, Project 3959-07, Final Report, December 1995* – which states: “A

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method that practically eliminates ground currents associated with primary distribution lines and still maintains the advantages of a four-wire multi-grounded system, is the five-wire system….

Conclusion

In conclusion, it is my opinion that the electric utility is dumping distorted, high frequency currents into the earth where it flows uncontrolled over the ground back to their sub-stations. The wind turbines are a major source of these high frequency transients that are on the electric utility's electrical grid and end up on the earth. The IEEE Standards Association's NESC Handbook, Seventh Edition, Rule 215B, "prohibits the use of the earth normally as the sole conductor for any part of a supply circuit. … (Objections to use of the earth as part of a supply circuit are made from both safety and service standpoints.)" These currents destroy the infrastructure by electrolysis. They also affect milk production in dairy cows as shown in published, scientific, peer-reviewed papers. EPRI, the electric utility's own research arm, reports levels as low as 18µA cause cancer in humans. Rule 215B in the NESC Handbook also says:

> The destructive nature of current flow through the earth endangers other facilities through electrolysis. When earth returns were used in some rural areas before the 1960's, they became notorious offenders in dairy areas because circulating currents often caused both step and touch potentials. In some cases, these have adversely affected milking operations by shocking the cattle when they were connected to the milking machines and have affected feeding (see Rule 92D – Current in Grounding Conductor). The grounding methods required by the NESC, including the use of a metallic neutral throughout each span of a multi-grounded wye system, reduced the opportunity for such occurrences.

It should be noted that the measurements are a mere snapshot in time and will change continuously as electrical loads change on the system. They will only become worse as more non-linear loads are connected to the grid. The so called "Green" loads such as solar and wind generation will only amplify these problems due to their lack of filters and use of switch-mode power supplies and inverters.

David Stetzer
President
Stetzer Consulting, LLC

Petition to oppose Terra-Gen's 90 new 586 ft tall 4 MW turbines and new high-voltage line planned for about 4,500 acres of Campo Reservation (252 MW Campo Wind) and private ranch land in Boulevard (126 MW Torrey Wind) & Boulder Brush Gen-tie line. It is one big connected project--not 3 separate projects! Tribal vote to approve lease was allegedly illegal--not properly noticed for vote. Most jobs will go to out-of-area contractors and labor—not locals.

(Circulated by non-profit Backcountry Against Dumps as a public service. Return signed petitions to Donna Tisdale no later than March 17, 2019 via, PO Box 1275, Boulevard, CA 91905 or tisdale.donna@gmail.com;619-766-4170)

Petition summary and background	This petition is directed at decision makers at the Campo Band, Bureau of Indian Affairs, Dept. Of Interior, San Diego County, California Public Utilities Commission, and the general public who may think turbines are benign.
Action petitioned for	We, the undersigned, are concerned citizens who urge our leaders to act now to deny Terra-Gen's massive wind turbine projects based on significant, cumulative and disproportionate adverse impacts to: public health and safety, sleep deprivation & stress-related illnesses; noise, low-frequency noise, infrasound & vibrations; increased fire risk & insurances costs; loss of scenic landscapes &property values; light and electrical pollution; well water; wildlife; pets and livestock& habit. Turbines are planned far too close to homes & roads. Existing turbines around the world generate complaints related to the impacts stated above, basically making homes toxic and families sick. Homes have been abandoned and bought out. ***Courts and public agencies around the world are finally starting to recognize that industrial wind turbines do impact health and property values*. STOP THE TURBINES!**

	Printed Name	Signature	Address	Comment	Date
1	Janet Silva	[signature]	30105 Hwy 94 Campo		2-25-19
2	Larry Johnson	[signature]	1259 Dewey Pl. Campo, CA 91906	This project puts dollars ahead of the Indian real needs	2-25-19
3	Scott Haselton	[signature]	2147 Live Oak Spring RD BLVD CA 91905		2-25-19
4	AL Delalat	[signature]	29491 Yaweh Ln 91906		2-25-19
5	Karen McIntyre	[signature]	P.O. BOX 39 Campo CA 91906	Stop distroying our Quality of living at home	2-25-19
6	Bruce Herbert	[signature]	29412 Cacti Dr Campo, CA 91906		2-25-19
7	ADAM ANDERSON	[signature]			2/25/19
8	Erin Kayser	[signature]	32715 Highway 94 Campo ca 91906		2/28/19

	Printed Name	Signature	Address	Comment	Date
9	ROBERT O. MAUPIN	R.O. Maupin	904 MERRADEL SOC ROAD	SHUT THE PROJECT DOWN	2-25-2019
10	TAMMY DAUBACH	Tammy Daubach	39954 Ribbonwood Rd. Blvd. 91905	You need 2 look @ the facts not lies	2-25-19
11	Kenneth Daubach	[signature]	39954 Ribbonwood Rd BLVD CA 91905	STOP Already	2-25-19

Petition to oppose Terra-Gen's 90 new 586 ft tall 4 MW turbines and new high-voltage line planned for about 4,500 acres of Campo Reservation (252 MW Campo Wind) and private ranch land in Boulevard (126 MW Torrey Wind) & Boulder Brush Gen-tie line. It is one big connected project--not 3 separate projects! Tribal vote to approve lease was allegedly illegal--not properly noticed for vote. Most jobs will go to out-of-area contractors and labor—not locals.

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	Printed Name	Signature	Address	Comment	Date
12	Andrew H DeGroot	[signature]	2693 Paso Alto Ct		02-28-19
13	Teresa DeGroot	[signature]	2693 Paso Alto Ct	Already have many issues with ones that are working	02-28-19
14	Pam Gray	[signature]	2975 Ribbonwood RD Boulevard	No More Noise Flashing Lights	02-28-19
15	Sheryl Hayter	[signature]	42084 Old Hwy 80	NO MORE... MEDICAL PROBLEMS	2/28/19
16	Byron Polen	[signature]	512 tierra Del Sole	"Buy my property"	2/28/19
17	DAVID COOPER	[signature]	38402 PIONEER LN		2/28/19
18	Nancy Good	[signature]	PO Box 1165 - 91905	"Buy my property"	2-28-19
19	BARRANCE ZAKAR	[signature]	PO Box 776, Alpine 91903		

Petition to oppose Terra-Gen's 90 new 586 ft tall 4 MW turbines and new high-voltage line planned for about 4,500 acres of Campo Reservation (252 MW Campo Wind) and private ranch land in Boulevard (126 MW Torrey Wind) & Boulder Brush Gen-tie line. It is one big connected project--not 3 separate projects! Tribal vote to approve lease was allegedly illegal--not properly noticed for vote. Most jobs will go to out-of-area contractors and labor—not locals.

(Circulated by non-profit Backcountry Against Dumps as a public service. Return signed petitions to Donna Tisdale no later than March 17, 2019 via, PO Box 1275, Boulevard, CA 91905 or tisdale.donna@gmail.com;619-766-4170)

Petition summary and background	This petition is directed at decision makers at the Campo Band, Bureau of Indian Affairs, Dept. Of Interior, San Diego County, California Public Utilities Commission, and the general public who may think turbines are benign.
Action petitioned for	We, the undersigned, are concerned citizens who urge our leaders to act now to deny Terra-Gen's massive wind turbine projects based on significant, cumulative and disproportionate adverse impacts to: public health and safety, sleep deprivation & stress-related illnesses; noise, low-frequency noise, infrasound & vibrations; increased fire risk & insurances costs; loss of scenic landscapes &property values; light and electrical pollution; well water; wildlife; pets and livestock& habit. Turbines are planned far too close to homes & roads. Existing turbines around the world generate complaints related to the impacts stated above, basically making homes toxic and families sick. Homes have been abandoned and bought out. ***Courts and public agencies around the world are finally starting to recognize that industrial wind turbines do impact health and property values*. STOP THE TURBINES!**

	Printed Name	Signature	Address	Comment	Date
20	Benjamin Good	Benjamin Good	35252 old Hwy 80	NO	2/28/19
21	Carmen E Gomez Villalobos	[signature]	PO Box 1452 37785 High Pass Rd	Boulevard CA 91905	2-28-19
22	Leslie Mauro	Les Mauro	2945 Ribbonwood Rd	opposed to windmills	
23	CHARLES B. GOOD	Charles B. Good	37649 Old HWY 80	+ Solar	
24	Diana Harder	Diana Harder	42084 Old Hwy 80	NO	2-28-19
25	LANCE MORROW	[signature]	2910 RIBBONWOOD	[drawing]	2/25/19
26	Clifford Caldwell	Clifford Caldwell	2750+2754 Ribbon wood		2/28/19
27	Concepcion Caldwell	CCaldwell	2750/2754 Ribbonwood RD		2/28/19

Petition to oppose Terra-Gen's 90 new 586 ft tall 4 MW turbines and new high-voltage line planned for about 4,500 acres of Campo Reservation (252 MW Campo Wind) and private ranch land in Boulevard (126 MW Torrey Wind) & Boulder Brush Gen-tie line. It is one big connected project--not 3 separate projects! Tribal vote to approve lease was allegedly illegal--not properly noticed for vote. Most jobs will go to out-of-area contractors and labor—not locals.

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	Printed Name	Signature	Address	Comment	Date
28	Ricky Guy	[signature]	2975 Ribbonwood Rd	NO	2-28-19
29	Bill Davis	[signature]	892 Tierra Del Sol	NO	3-12-19

Petition to oppose Terra-Gen's 90 new 586 ft tall 4 MW turbines and new high-voltage line planned for about 4,500 acres of Campo Reservation (252 MW Campo Wind) and private ranch land in Boulevard (126 MW Torrey Wind) & Boulder Brush Gen-tie line. It is one big connected project--not 3 separate projects! Tribal vote to approve lease was allegedly illegal--not properly noticed for vote. Most jobs will go to out-of-area contractors and labor—not locals.

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	Printed Name	Signature	Address	Comment	Date
30	Charles Townsend	[signature]	2273 Angel dr. Boulevard CA PO Box 1083 Boulevard CA	we don't need more eye sores in the Back Country	3-7-19
31	Tammy Townsend	[signature]	2273 Angel Dr. BLVD. CA PoBox 1083 Boulevard CA	we live in the Country to enjoy the outdoors not wanting the eye sores	3-7-19

March 28, 2019

Bronwyn Brown
Planning & Development Services
5510 Overland Ave, Ste 110
San Diego, CA 9123

RE: BIOLOGICAL CONSEQUENCES OF LOW-FREQUENCY SOUND

Dear Bronwyn,

The enclosed book by Bruce Rapley, PhD, **The Biological Consequences of Low-Frequency Sound**, is the one that was incorporated fully by reference in the Boulevard Planning Group's Boulder Brush Gen-Tie NOP comments dated March 18, 2019 at page 18, with a request that it be included in the project record.

Instead of mailing the book directly to you, as requested, Dr. Rapley mailed the book to me instead.

Please confirm receipt via tisdale.donna@gmail.com .

Regards,
Donna Tisdale

Donna Tisdale
PO Box 1275
Boulevard, CA 91905
619-766-4170

County of San Diego

MARK WARDLAW
DIRECTOR

PLANNING & DEVELOPMENT SERVICES
5510 OVERLAND AVENUE, SUITE 310, SAN DIEGO, CA 92123
(858) 694-2962 • Fax (858) 694-2555
www.sdcounty.ca.gov/pds

KATHLEEN A. FLANNERY
ASSISTANT DIRECTOR

BOULDER BRUSH FACILITIES
MAJOR USE PERMIT (PDS2019-MUP-19-002)

FEBURARY 28, 2019 EIR PUBLIC SCOPING MEETING - COMMENT SHEET

I Carmen E. Gomez Villeda ~~am~~ opposed to the Boulder Brush Facilities, The Tule River Facilities, The Secret Facilities, and Solar Facilities Because it is hazardouse to humanity, Fedrally recognized and protected endangered animal, reptilian and Plants. It is dangerous to the environment and water. I am opposed to the Sunrise power link due to Fire hazard.
None of this is of any benefit to this Community. BIA + BLM are suppose to Protect this region. It is a conflict of interest that they are involved in these actions and are allowing this to take place. Enough studies have been performed in other Locations to establish the dangers. Carmen E Gomez Villeda

Submit by Mail, Fax or Email. Comments must be received no later than March 18, 2019 at 4:00 p.m.

Bronwyn Brown, Project Manager
County of San Diego
Planning and Development Services
5510 Overland Ave., Suite 310
San Diego, CA 92123

Email: bronwyn.brown@sdcounty.ca.gov

FAX: (858) 694-2555

Phone: (858) 495-5516

Carmen E Gomez Villeda March 2, 19
Commenter Signature, Date

Carmen E. Gomez Villeba
Print Name

37785 High Pass Rd
Address

Boulevard CA 91905
City, State, Zip Code

Stephan C. Volker
Alexis E. Krieg
Stephanie L. Clarke
Jamey M.B. Volker (Of Counsel)

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11.233.01

February 21, 2019

VIA EMAIL
Bronwyn.Brown@sdcounty.ca.gov

Bronwyn Brown
San Diego County Planning & Development Services
5510 Overland Avenue, Suite 110
San Diego, CA 92123

Re: Scoping Comments of Backcountry Against Dumps and Donna Tisdale on the Proposed Boulder Brush Gen-Tie Line and Switchyard Facilities for the Campo Wind Project (PDS2019-MUP-19-002, PDS2019-ER-19-26-001)

Dear Ms. Brown:

On behalf of Backcountry Against Dumps and Donna Tisdale (collectively, "Backcountry"), we respectfully submit the following scoping comments on Boulder Brush, LLC's (the "Applicant's") proposed Boulder Brush Gen-Tie Line and Switchyard Facilities for the Campo Wind Project ("Boulder Brush" or the "Project;" PDS2019-MUP-19-002, PDS2019-ER-19-16-001), pursuant to the California Environmental Quality Act ("CEQA"), Public Resources Code ("PRC") section 21000 *et seq*., San Diego County Planning & Development Services' (the "County's") February 14, 2019 Notice of Preparation of an Environmental Impact Report ("NOP"), and the County's Notice to Property Owners ("Notice," marked "received" by the County on January 22, 2019). Please include these comments in the public record for this Project.

As discussed below, the Project cannot be approved as currently proposed for at least four reasons. First, Torrey Wind's application is incomplete per the County's requirements, and for purposes of the Permit Streamlining Act (Government Code § 65920 *et seq.*). Second, the Project would violate the County's Zoning Ordinance. Third, the Project would likely have substantial environmental impacts that must be studied in an environmental impact report ("EIR") and avoided or mitigated, pursuant to CEQA. Fourth, the Project requires review and permitting by the California Public Utilities Commission ("CPUC"), and it must comply with CPUC General Order 131-D.

I. Boulder Brush's Project Application Is Incomplete

Boulder Brush's application either fails to provide or gives conflicting information on a wide range of key information required by the County. For example, Boulder Brush's Application for an Environmental Initial Study (form PDS-367) lists the Project acreage as 110 acres, while the County's NOP (p. 1) states that the Project "consists of approximately 200 acres."

Boulder Brush also fails to provide the site grading information required by that same form. The Initial Study (NOP Attachment 2, p. 20) states that the "Project involves site grading," yet Boulder Brush fails to provide the grading information required in form PDS-367, including the volume, maximum slope and maximum height of the cut or fill.

Boulder Brush also fails to specify how much water Project construction and operation would require. It also fails to demonstrate the viability of its proposed water sources. Boulder Brush identified two off-site water suppliers in its two Project Facility Availability – Water forms (PDS-399W), the Jacumba Community Services District and the Padre Dam Municipal Water District. Yet neither in the forms nor elsewhere does Boulder Brush indicate how much water those districts could provide or that they could do so in the time period required. For example, the water supply availability form for the Padre Dam Municipal Water District cautions that the availability "Letter expires 12/11/2019," which is almost assuredly before Project construction would be completed. *See* NOP, p. 1 ("Project construction on private land is anticipated to last approximately 9 months"). Indeed, Boulder Brush fails to even show that the districts can legally provide water to the Project. As discussed further below, because the Project is outside the sphere of influence of both districts, they would need approval by the San Diego Local Agency Formation Commission ("LAFCO"). Government Code §§ 56133(a), (c); 56375(p).

Boulder Brush provides even less certainty with respect to fire response services. It filed the Project Facility Availability – Fire form (PDS-399F), but it left the "Facility Availability" section entirely blank.

II. The Project Would Violate the County Zoning Code

The County's Zoning Ordinance governs and restricts land use in the unincorporated County. "The use and employment of all land and any buildings or structures located upon the land and the construction, reconstruction, alteration, expansion, or relocation of any building or structure upon the land shall conform to all regulations applicable to the zone in which the land is located." Zoning Ordinance § 1006(a). The proposed Project would violate the County Zoning Ordinance in at least two ways.

First, the Project would violate section 7359(b) of the Zoning Ordinance because it would "be materially detrimental to the surrounding community."[1] The area surrounding the Project site includes "rural residential homes and ranches." NOP, p. 1. The Project would harm those and other local residents by creating noise, visual eyesores and air pollution, stressing local water supplies, and harming wildlife of local, national and even international importance, as discussed further in section III and confirmed by the Boulevard Planning Group's February 12, 2019 initial comments on the Project ("BPG Comments"). There is no better judge of how the Project would impact the "surrounding community" than the Boulevard community itself, whose residents elect the Boulevard Planning Group members to "advise and assist County of San Diego officials on matters of planning and land use affecting the group's area."[2]

Second, the Project would violate ordinance sections 4610 and 4620 because it includes at least 32 150-foot-tall steel transmission poles in an area with a maximum allowed height of 35 feet (height designator G). Boulder Brush submitted a supplemental application – form PDS-346S – on January 22, 2019 in which it requests an "exemption to Height Limits . . . for proposed 150' tall steel poles for the gen-tie line, per County Zoning Ordinance Section 4620," but it fails to support its request with any evidence that an exemption is warranted.

III. CEQA Requires a Thorough EIR for the Project

The application materials submitted by Boulder Brush and the County's Initial Study indicate that the Project will have numerous significant environmental impacts, including those discussed below. Each of these impacts must be analyzed in an EIR. Furthermore, much more environmentally benign alternatives exist that could provide the same services as the Project and the connected Campo Wind and Torrey Wind projects, precluding Project approval under PRC section 21002.

A. The EIR Must Provide a Full and Accurate Project Description

"An accurate, stable and finite project description is the *sine qua non* of an informative and legally sufficient EIR." *County of Inyo v. City of Los Angeles* (1977) 71 Cal.App.3d 185, 193. In addition, "[t]he data in an EIR must not only be sufficient in quantity, it must be presented in a manner calculated to adequately inform the public and decision makers, who may not be previously familiar with the details of the project." *Vineyard Area Citizens for Responsible Growth v. City of Rancho Cordova* ("*Vineyard*") (2007) 40 Cal.4th 412, 431. The EIR must cure the informational defects in the Project descriptions in the County's NOP and

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[1] Section 7359(b) applies to "Large Wind Turbine[s]." The Project is subject to section 7359(b) because it is an integral part of the large-turbine Campo Wind Project. *See* Zoning Ordinance § 1110 (defining "Wind Turbine," and noting that it "may consist of a tower, turbine, support structures, *electrical wires*, guy wires and other related equipment;" emphasis added).

[2] https://www.sandiegocounty.gov/content/dam/sdc/pds/Groups/boulevard/2018_Agendas_Minutes/BL-FACTSHEET.pdf

Initial Study, Boulder Brush's application materials. Those documents fail to provide a host of critical Project information, as discussed above.

B. The EIR Must Analyze the Whole of the Project

CEQA forbids "piecemeal" environmental review. *Berkeley Keep Jets Over the Bay Commission v. Board of Port Commissioners of the City of Oakland* (2001) 91 Cal.App.4th 1344, 1358. CEQA mandates that "environmental considerations do not become submerged by chopping a large project into many little ones . . . [,] which cumulatively may have disastrous consequences." *Bozung v. Local Agency Formation Commission* (1975) 13 Cal.3d 263, 283-284.

Here, the Project's 8.5-mile 230-kilovolt ("kV") gen-tie transmission line would "carry wind energy from" the proposed 60-turbine Campo Wind Project "to the existing Sunrise Powerlink." NOP, p. 1. In addition, the Project's 500-kV substation and switchyard would be used by another proposed industrial-scale wind energy project, the 30-turbine Torrey Wind Project. NOP, p. 2. To avoid the piecemealing prohibited by CEQA, the County must analyze the Boulder Brush Project together with the Campo Wind Project and Torrey Wind Project in the same EIR.

C. The EIR Must Provide Project Purposes and Objectives

EIRs must include as part of the project description a "statement of the objectives sought by the proposed projects," including a description of the "underlying purpose of the project." 14 Cal. Code Reg. [CEQA Guidelines] § 15124(b). But neither Boulder Brush nor the County has yet demonstrated a need for the Project or the connected Campo Wind and Torrey Wind projects. To the contrary, at least four circumstances render the proposed projects unnecessary and inappropriately sited.

First, as reported by the *Los Angeles Times*, Californians are "using less electricity" statewide,[3] which means less need for new industrial-scale energy generation projects. *See also* California Energy Commission ("CEC"), 2017, Electricity Consumption by County (totals from 1990 through 2016, showing peak consumption in 2008).[4] In fact, "power plants are on track to be able to produce at least 21% more electricity than [California] needs by 2020." **Exhibit 1** at 2 (quote); CEC, 2018, Electric Generation Capacity & Energy.[5] California's investor-owned utilities are also well ahead of schedule in meeting the State's Renewables Portfolio Standard ("RPS"). San Diego Gas & Electric, for example, served 43.2 percent of its load with RPS-

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[3] Penn, I. and R. Menezes, February 5, 2017, "Californians are paying billions for power they don't need," *Los Angeles Times* (attached hereto as **Exhibit 1**, and also available here: http://www.latimes.com/projects/la-fi-electricity-capacity/).
[4] Available here: http://www.ecdms.energy.ca.gov/elecbycounty.aspx
[5] Available here:
http://www.energy.ca.gov/almanac/electricity_data/electric_generation_capacity.html

eligible resources in 2016, far surpassing the RPS requirement of 33 percent by 2020, and ahead of schedule in meeting the 2030 RPS requirement of 60 percent.[6] With California's electricity usage flatlining, and renewable energy generation including rooftop solar and other distributed generation capacity increasing rapidly, there is less need than ever for remote, industrial-scale projects like the proposed Campo Wind and Torrey Wind projects that the Boulder Brush Project would serve - and much less justification for their massive environmental impacts.

Second, industrial-scale wind energy projects rarely generate as much energy as predicted, as a 2015 study confirms.[7] The study's authors conclude that "expanding wind farms to large scales will limit generation rates . . ., thereby constraining mean large-scale generation rates to about 1 Wem-2 even in windy regions." **Exhibit 2** at 11174. This limitation is caused by the wind project itself interfering with and altering the wind patterns in the area. A "greater installed capacity of wind turbines removes more kinetic energy from the atmosphere and coverts it into electric energy, this causes a decrease in the hub-height wind speeds downwind, which decreases the mean per turbine electricity generation rate of the wind farm." **Exhibit 2** at 11171. The "more kinetic energy wind farms use, the greater the shift in the balance and the reduction of wind speeds." **Exhibit 2** at 11169. "[I]t is this decrease in wind speed with greater kinetic energy extraction by more wind turbines that limits the wind power generation at large scales." **Exhibit 2** at 1172. In short, large scale wind energy projects generate diminishing returns, as more kinetic energy is removed from the sky and less electricity is delivered to the consumer. Here, the risk of diminished returns is particularly high because the Campo Wind and Torrey Wind projects' turbines would be placed *directly adjacent* to the existing Kumeyaay and Tule Wind turbines.

Third, wildfire risk in the County is dangerously high, and getting worse with global warming. This risk would both impact and be exacerbated by the Project, which would be located in a Very High Fire Hazard Severity Zone, as designated by the California Department of Forestry and Fire Protection (CAL FIRE).[8] Initial Study, p. 26. As reported in the August 2017 Climate Change Vulnerability Assessment for San Diego County,[9] CalAdapt's wildfire tool

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[6] California Public Utilities Commission, November 2017, Renewables Portfolio Standard: Annual Report, p. 10 (attached hereto as **Exhibit 2**, and also available here: http://www.cpuc.ca.gov/uploadedFiles/CPUC_Website/Content/Utilities_and_Industries/Energy/Reports_and_White_Papers/Nov%202017%20-%20RPS%20Annual%20Report.pdf)

[7] Miller, L., *et al.*, 2015, "Two methods for estimating limits to large-scale wind power generation," *Proceedings of the National Academy of Sciences* 112(36) (attached hereto as **Exhibit 3**).

[8] CAL FIRE, 2009, "Very High Fire Hazard Severity Zones in LRA: As Recommended by CAL FIRE" (attached hereto as **Exhibit 4**, and also available here: http://frap.fire.ca.gov/webdata/maps/san_diego/fhszl_map.37.jpg).

[9] Available here: http://www.sandiegocounty.gov/content/dam/sdc/pds/advance/cap/publicreviewdocuments/CAPfilespublicreview/Appendix%20D%20Climate%20Change%20Vulnerability%20Assessment.pdf

estimates that under both a low-GHG-emissions scenario and a high-emissions scenario, substantially more land in the County will burn due to wildfire by 2099. San Diego County, Draft Climate Action Plan, Appendix D, p. 12. Under the low-emissions scenario, over 3,500 more acres are expected to burn *every year* by 2099. *Id.* Under a high-emissions scenario, the additional annual acreage scorched by wildfire increases to nearly 8,500. *Id.*

Wildfires triggered by downed or arcing power lines in rural areas such as East County can cause catastrophic losses of lives and property, not to mention wildlife, habitat and scenery. San Diego's catastrophic 2007 Witch Creek Fire, for example, burned 197,990 acres and 1,650 structures, and killed two people. Even more destructive wildfires have recently devastated Butte, Sonoma, Napa, Lake and Mendocino counties in Northern California. The November 2018 Camp Fire was the deadliest wildfire recorded in California history, tragically killing at least 86 people, burning 153,336 acres, and destroying 13,972 residences, 528 commercial buildings and 4,293 other buildings.[10]

The Boulder Brush Project and the connected Campo Wind and Torrey Wind projects would increase the risk of devastating wildfires in San Diego County, particularly in combination with the operational Kumeyaay and Tule Wind projects, as the Initial Study acknowledges. Initial Study, p. 26. This risk grows each year with the increased temperatures, aridity and severe winds caused by global warming. Such wildfires, in turn, exacerbate global warming by increasing carbon emissions and reducing the shade and moisture that the burned vegetation would have provided.

Fourth, water supplies are increasingly limited and unreliable in the Project area. This is due to growing water demand from development, as well as increasing summer temperatures and resulting aridity. As one 2015 study concluded, "anthropogenic warming is increasing the probability of co-occurring warm-dry conditions like those that have created the acute human and ecosystem impacts associated with the 'exceptional' 2012-2014 drought in California."[11] These co-occurring warm-dry conditions have, in turn, caused unprecedented groundwater depletion due to increased pumping to offset reductions in surface water supplies, as well as reduced groundwater recharge from rain and surface water flows.[12] Recent research using well

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[10] See CAL FIRE's December 14, 2018 "Camp Fire Incident Information," available here: http://www.fire.ca.gov/current_incidents/incidentdetails/Index/2277

[11] Diffenbaugh, N.S., D.L. Swain and D. Touma, March 31, 2015, "Anthropogenic warming has increased drought risk in California," *Proceedings of the National Academy of Sciences* 112(13) (attached hereto as **Exhibit 5**).

[12] Wang, S., Lin, Y., Gillies, R. And Hakala, K., March 2016, "Indications for Protracted Groundwater Depletion after Drought over the Central Valley of California," *Journal of Hydrometeorology* 17:947-955 (attached hereto as **Exhibit 6**); Castle, S.L., Thomas, B.F., Reager, J.T., Rodell, M., Swenson, S.C. and Famiglietti, J.S., 2014, "Groundwater Depletion During Drought Threatens Future Water Security of the Colorado River Basin," *Geophysical Research Letters*, 41:5904-5911 (attached hereto as **Exhibit 7**).

data from the Central Valley shows that groundwater depletion has long-term effects, including permanent subsidence as aquifers compress or collapse, with the result that subsequent attempts at recharge may be insufficient to restore previous groundwater levels. **Exhibit 6** at 1. The Project area is at particular risk of groundwater supply strain because it lies atop the Campo/Cottonwood Creek Sole Source Aquifer, as discussed further below with respect to hydrology and water supply impacts.[13]

D. The EIR Must Analyze the Full Range of Project Impacts and Measures to Mitigate Them.

The EIR must analyze the full range of potentially significant environmental impacts from the Project. Among other impacts, the Project and the connected Campo Wind and Torrey Wind projects would likely substantially and negatively impact birds, bats, other wildlife, humans (*e.g*, through Project-generated noise and magnetic field radiation), land use plan consistency, climate change, agricultural resources, water supplies, and fire risk and emergency services. The EIR must fully analyze these and other impacts.

Bird Impacts

Wind turbines and power lines kill birds.[14] The Boulder Brush's gen-tie lines and the 90 wind turbines proposed for the Campo Wind and Torrey Wind projects will be no different. A wealth of bird species have been documented inhabiting or otherwise using the Project area, including sensitive species like golden eagles. For example, a study of the nearby Tule Wind Project area identified at least 10 golden eagle territories within approximately 10 miles of the area.[15] The risk to golden eagles is particularly concerning because they are "currently known to be at risk of *population-level* effects from [wind turbine] collisions," and must be afforded every possible protection. **Exhibit 8** at 306.

In addition to killing and maiming birds through collisions with powerlines, turbine blades and related structures,[16] wind energy facilities can also cause significant *landscape*-scale

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[13] A map of the sole source aquifer is available here: https://archive.epa.gov/region9/water/archive/web/pdf/campo-cottonwood-ssa-map.pdf

[14] Dwyer, J.F., M.A. Landon, and E.K. Mojica, 2018, "Impact of Renewable Energy Sources on Birds of Prey," in J.H. Sarasola *et al.* (eds.), 2018, *Birds of Prey*, Springer International Publishing AG (attached hereto as **Exhibit 8**).

[15] *See* BLM and CPUC, Draft Environmental Impact Report/Environmental Impact Statement for East County Substation, Tule Wind, and Energia Sierra Juarez Gen-Tie Projects, December 2010, p. D.2-46, available at: http://www.cpuc.ca.gov/environment/info/dudek/ECOSUB/Draft_EIR/D-2_BioResources.pdf

[16] *See, e.g.*, Smallwood, S.K., and B. Karas, 2009, "Avian and Bat Fatality Rates at Old-Generation and Repowered Wind Turbines in California," *The Journal of Wildlife Management* 73(7) (attached hereto as **Exhibit 9**).

avoidance impacts.[17] A recent longitudinal study of bird densities at 12 wind farms in Ireland and their paired control sites found that "densities of open-habitat species were lower at wind farms" than at the control sites "independent of distance to turbines." **Exhibit 10** at 7. This "suggests that for open-habitat birds, effects were operating at a landscape scale." **Exhibit 10** at 8. The Boulder Brush Project and associated Campo Wind and Torrey Wind facilities could well have similar effects. While the bird species may be different near the Project site than at the study sites in Ireland, the terrain is more "open-habitat" than "forested" (the other type of habitat present at some of the Ireland study sites, and for which the authors found gradient rather than landscape effects).

A further risk factor is that the Project area would be developed with so many turbines – up to 90 between the proposed Campo Wind and Torrey Wind projects, paired with the existing 57 Tule Wind turbines and 25 Kumeyaay turbines . The Irish study found that bird densities decreased with wind farm size (number of turbines). **Exhibit 10** at 7. The Campo Wind and Torrey Wind projects combined would have almost triple the number of turbines than the largest wind farm in the Irish study (35 turbines).

Wind energy facilities can also cause long-term harm to birds through impacts on their migration patterns. **Exhibit 8**. For example, a 2016 study investigating "how anthropogenic mortality can influence the migratory pattern of a partial migrant," concluded that "human-induced mortality may be an important factor modifying" migration patterns and could possibly lead to the complete cessation of migration for an entire species.[18] **Exhibit 11** at 4.

The 2016 study identified a sharp decline in the proportion of male great bustards that were migratory (rather than sedentary) from 86 percent of the total population at the beginning of the study, to just 44 percent at the end. **Exhibit 11** at 15. Migrating males suffered far greater mortality from powerlines and other human disturbances than did the sedentary population, leading to a dramatic loss of the birds who historically lead their flocks on the periodic migrations needed for long term survival of the species. Loss of these migration "leaders" caused, in turn, a sharp decline in the proportion of young birds who had learned how to lead migrations from the older males who were disproportionately killed by powerlines and other disturbances. This study concluded that social learning leads to fewer yearly migrants because "immature birds will have more sedentary adults from which to learn their own strategy." *Id.* This tragic loss of migration skills and resulting decline in successful migrations will only get worse over time and will lead to increased competition for resources, reduced genetic diversity,

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[17] Fernández-Bellon, D., M.W. Wilson, S. Irwin, and J. O'Halloran, 2018, "Effects of Development of Wind Energy and Associated Changes in Land Use on Bird Densities in Upland Areas," *Conservation Biology* 0(0):1-10 (attached hereto as **Exhibit 10**).
[18] Palacín, C., J.C. Alonso, C.A. Martín, and J.A. Alonso, 2016, "Changes in Bird Migration Patterns Associated With Human-Induced Mortality," *Conservation Biology*, 31(1) (attached hereto as **Exhibit 11**).

impaired gene flow, and potentially the cessation of migration "lead[ing] to the extinction of the population." *Id*.

These migratory impacts are not limited to the great bustard, and can have significant effects on golden eagles, raptors, and other species that migrate through or near the Project's 150-foot-high, 230-kV gen-tie lines, and the highly destructive Campo Wind and Torrey Wind turbines. According to a recent study on mitigations for wind energy facility-induced avian mortality, "the cumulative effect of mortality from anthropogenic sources may be detrimental," or even "fatal" to some species.[19] "[C]ontinuous exposure to a certain risk may lead to increased discrimination (latent inhibition), but decreased associability (habituation)." **Exhibit 12** at 172. Avian exposure to wind turbines, powerlines and potential visual or acoustic deterrence measures, may cause migrating birds "to move away from the wind-power plant area to other possibly suboptimal habitat." **Exhibit 12** at 177. "The effect of [this avoidance] on the entire population may therefore be larger than the" already significant "effect of some birds colliding with wind turbines." *Id*.

Through the aforementioned mechanisms and others, the Project and the connected Campo Wind and Torrey Wind projects will almost assuredly kill and otherwise seriously harm local and migratory bird species. As a result, not only must the County analyze those impacts in the EIR prior to considering Project approval, Project operation may be *entirely prohibited* under other federal and state laws.

For example, golden eagles are protected by the Bald and Golden Eagle Protection Act ("BGEPA"), 16 U.S.C. section 668-668(d), and the Migratory Bird Treaty Act ("MBTA"), 16 U.S.C. section 703 *et seq*. The BGEPA prohibits the "take" – including the wounding or killing – of golden and bald eagles in the United States, unless specially permitted by the U.S. Fish and Wildlife Service. 16 U.S.C. § 668; 50 C.F.R. § 22.26. The MBTA more broadly prohibits the take of "*any* migratory bird" listed in 50 C.F.R. Part 10.13, which includes golden eagles. 16 U.S.C. § 703(a) (emphasis added). And the Fish and Wildlife Service's regulations only permit taking migratory birds for limited purposes, including taxidermy, scientific collection, and banding or marking, among other constrained purposes, none of which apply to the proposed wind energy use. 50 C.F.R. Part 21.

California Fish and Game Code section 3511 likewise prohibits the "take" of any "fully protected birds," which include golden eagles (common to the Project site). Fish and Game Code section 3513 also prohibits the "take" of "any migratory nongame bird as designated in the [federal] Migratory Bird Treaty Act," except as authorized by the Secretary of the Interior.

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[19] May, R., O. Reitan, K. Bevanger, S.H. Lorentsen, and T. Nygard, 2014, "Mitigating wind-turbine induced avian mortality: Sensory, aerodynamic and cognitive constraints and options," *Renewable and Sustainable Energy Reviews*, 42:170-181 (attached hereto as **Exhibit 12**).

Bat Impacts

Bats perform a vital biological function by preying on insects including disease-bearing mosquitoes. But as with birds, wind energy facilities also kill bats, through both collisions and barotrauma (abrupt drop in air pressure behind turbine blades sucks bats into low pressure zone, causing bats' lungs to expand and hemorrhage). And with "continued wind energy expansion, there are increasing concerns that there could be population-level implications for bats."[20] **Exhibit 13** at 125. This is even more concerning given recent evidence that bats are *attracted* to wind turbines and associated infrastructure, and use them as night or foraging roosts. **Exhibit 13**. The EIR must analyze the Project's impacts to bats.

Impacts to Other Wildlife

The EIR must also analyze the Project's impacts to the wide range of other plants, animals and ecosystems on the Project site or otherwise affected by the Project, including sensitive plant and animal species protected by the federal Endangered Species Act or the California Endangered Species Act. The Project area is ecologically sensitive, as indicated by the fact that it, like the Campo Wind and Torrey Wind projects, is entirely located in the East County Planning Area of the draft Multiple Species Conservation Program.[21]

The EIR must also look beyond direct impacts to individual species. It must analyze ecosystem-level impacts, including the cascading impacts across trophic levels that can occur when wind turbines "reduc[e] the impact of predatory birds in the area."[22] **Exhibit 14** at 1856. For example, a recent study of the ecosystem impacts of wind turbines in India found that "wind farms reduce the abundance of predatory birds . . ., which consequently increases the density of lizards." **Exhibit 14** at 1854. More broadly, the authors concluded that "anthropogenic disturbances such as wind farms act as effective apex predators. By reducing the impact of predatory birds in the area, wind turbines cause a cascade of changes in terrestrial prey, driven primarily by the ecological processes of predator release and density-mediated competition." **Exhibit 14** at 1856.

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[20] Bennett, V.J., A.M. Hale, and D.A. Williams, 2017, "When the Excrement Hits the Fan: Fecal Surveys Reveal Species-Specific Bat Activity at Wind Turbines," *Mammalian Biology* 87:125-129 (attached hereto as **Exhibit 13**).

[21] A draft map of the East County Planning Area is available here: https://www.sandiegocounty.gov/content/dam/sdc/pds/mscp/docs/ECMSCP/east_mscp_csa2_2_8x11.pdf

[22] Thaker, M., A. Zambre, and H. Bhosale, 2018, "Wind Farms Have Cascading Impacts on Ecosystems across Trophic Levels," *Nature Ecology & Evolution* 2:1854-1858 (attached hereto as **Exhibit 14**).

Noise Impacts

The County must analyze the Project's noise impacts in the EIR, and also ensure that the Project and the connected Torrey Wind Project comply with the County's Noise Ordinance and its Wind Energy Ordinance. That analysis must also cover the health impacts of wind turbine-generated noise, including stress, sleep disturbance and reduced quality of life.

Most wind turbine noise impact studies to date have assessed the relationship between noise and self-reported annoyance or sleep disturbance. But researchers are increasingly studying the physiological responses to wind turbine noise during sleep. For example, a pair of recent pilot studies investigated the physiologically measured sleep effects of nocturnal wind turbine noise in a laboratory setting.[23] The results provided "evidence that participants had more frequent awakenings, reduced amounts of N3 ("deep") sleep, reduced continuous N2 sleep, increased self-reported disturbance and [wind turbine noise]-induced tiredness in exposure nights with [wind turbine noise] compared to [wind turbine noise]-free nights." **Exhibit 15** at 10. The increase in self-reported sleep disturbance also comports with numerous survey-based studies on the subject.

In a 2015 peer-reviewed journal article, researchers "explore[d] the association between wind turbine noise, sleep disturbance and quality of life, using data from published observational studies."[24] **Exhibit 16** at 1. Through a meta-analysis of six studies, they "revealed that the odds of being annoyed is significantly increased by wind turbine noise (OR: 4.08; 95% CI: 3.37 to 7.04; $p<0.00001$)," and the "odds of sleep disturbance was also significantly increased with greater exposure to wind turbine noise (OR: 2.94; 95% CI: 1.98 to 4.37; $p < 0.00001$)." *Id.* In addition, four of the studies they analyzed "reported that wind turbine noise significantly interfered with [quality of life]." *Id.*

An even more recent literature review similarly concluded that the published literature "suggest[s] that exposure to wind turbine sound is associated with higher odds for annoyance."[25] **Exhibit 17** at 53. So too did a 2014 literature review, stating that "it seems reasonable to conclude that noise from wind turbines increases the risk of annoyance and disturbed sleep in exposed subjects in a dose-response relationship," with a "tolerable limit of around LAeq of 35

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[23] Morsing, J.A., M.G. Smith, M. Ögren, P. Thorsson, E. Pedersen, J. Forssén, and K.P Waye, 2018, "Wind Turbine Noise and Sleep: Pilot Studies on the Influence of Noise Characteristics," *International Journal of Environmental Research and Public Health*, 15(2573) (attached hereto as **Exhibit 15**).
[24] Onakpoya, I.J., J. O'Sullivan, M.J. Thompson, and C.J. Henghan, 2015, "The Effect of Wind Turbine Noise on Sleep and Quality of Life: A Systematic Review and Meta-analysis of Observational Studies," *Environment International* 82:1-9 (attached hereto as **Exhibit 16**).
[25] van Kamp, I., and F. van den Berg, 2018, "Health Effects Related to Wind Turbine Sound, Including Low-Frequency Sound and Infrasound," *Acoustics Australia* 46(1):31-57 (attached hereto as **Exhibit 16**).

dB."[26] **Exhibit 18** at 22. But audible wind turbine noise, as typically measured with A-weighted sound pressure levels, is not the only source of disturbance and physiological impact.

A 2018 review of the scientific literature affirmed not only that "there is ample evidence demonstrating that a component of the sound energy produced by a [wind turbine] is in the low and infrasonic frequency range," but also that the literature presents a "strong prima facia case for neural transduction of low-frequency sound] and [infrasound]."[27] **Exhibit 19** at 2 (first quote), 6 (second quote). That review also noted that weighted noise measurements – like the A-weighted measurements typically done for audible noise impact analyses, and the C-weighted measurements required by San Diego County Zoning Code section 6952(f)(1) – "exclude crucial low frequencies" from wind turbines. **Exhibit 19** at 3.

A-weighting "do[es] not give a valid representation of whether wind turbine noise affects the ear or other aspects of human physiology mediated by the [outer hair cells] and unrelated to hearing."[28] **Exhibit 20** at 299. "While normal sound perception depends on *inner* hair cell (IHC) function, human sensitivity to infrasound and low frequencies is thought to rely heavily on *outer* hair cells (OHCs)."[29] **Exhibit 21** at 52.

With respect to impact thresholds, research indicates that because the ear's electrical responses to infrasound and low-frequency noise "stimulation are larger" than its responses to audible noise, "and do not saturate [*i.e.*, reach an impact plateau] to the degree seen when higher-frequency components are present," it takes far *less* sound pressure (lower decibel level) for infrasound and low-frequency noise to cause measurable impacts than it takes for audible noise to have such effects.[30] **Exhibit 22** at 4. Put another way, infrasound causes far more measurable impacts – decibel for decibel – than does audible noise. As one study found, OHCs "could be stimulated [by very low frequency sounds] at levels up to 40 dB *below* those that stimulate the IHC" and can be heard.[31] **Exhibit 23** at 16 (original emphasis).

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[26] Schmidt, J.H., and M. Klokker, 2014, "Health Effects Related to Wind Turbine Noise Exposure: A Systematic Review," *PLoS ONE* 9(12) (attached hereto as **Exhibit 18**).
[27] Carlile, S., J.L. Davy, D. Hillman, and K. Burgemeister, 2018, "A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise," *Trends in Hearing* 22:1-10 (attached hereto as **Exhibit 19**).
[28] Salt, A., and J. Kaltenbach, 2011, "Infrasound from Wind Turbines Could Affect Humans," *Bulletin of Science, Technology and Society*, 31(4): 296-302 (attached hereto as **Exhibit 20**).
[29] Chen, H.A., and P. Narins, 2012, "Wind Turbines and Ghost Stories: The Effects of Infrasound on the Human Auditory System," *Acoustics Today*, 8(2):51-55 (attached hereto as **Exhibit 21**),
[30] Salt, A., and J. Lichtenhan, 2012, "Perception-based protection from low-frequency sounds may not be enough," presented at InterNoise 2012 in New York City, New York, August 19-22, 2012 (attached hereto as **Exhibit 22**).
[31] Salt, A., and T. Hullar, 2010, "Responses of the Ear to Low Frequency Sounds, Infrasound and Wind Turbines," *Hearing Research*, 268:12-21 (attached hereto as **Exhibit 23**).

The EIR must analyze the audible, low-frequency and infrasound noise impacts of the Project and the Campo Wind and Torrey Wind projects it would enable. The noise analysis should therefore include unweighted noise measurements and estimates, as well as the A- and C-weighted estimates commonly used in noise impact analyses.

Magnetic Field Radiation Impacts

"Magnetic field (MF) non-ionizing radiation is a ubiquitous environmental exposure and a serious looming public health challenge."[32] **Exhibit 24** at 1. The International Agency for Research on Cancer classifies MF radiation as a possible carcinogen. **Exhibit 24** at 1. And a recent study found that higher MF exposure is associated with an increased risk of miscarriage in pregnant women. **Exhibit 24**.

Power lines and transformers emit MFs, and are both integral Project components (the substation houses at least one transformer). **Exhibit 24** at 1; **Exhibit 8**; Initial Study, p. 4. The EIR must analyze the impacts on humans and wildlife alike of the Project's MF radiation.

Greenhouse Gas Emission and Climate Change Impacts

The EIR must analyze not only the greenhouse gas emissions from Project construction and operation, but also its lifecycle emissions, including those associated with both the manufacturing and the transporting of the Project components. Currently, the Initial Study indicates that the EIR will only analyze the greenhouse gas emissions Project construction activities and operation. Initial Study, p. 22.

Hydrology and Water Supply Impacts

As discussed above in section III(C), water supplies are increasingly limited and unreliable in the Project area. The EIR must identify the likely sources of water supply for the Project and analyze the "reasonably foreseeable impacts of supplying [that] water." *Vineyard Area Citizens for Responsible Growth v. City of Rancho Cordova* (2007) 40 Cal.4th 412, 434.

As part of that analysis, the County must assess the viability of Boulder Brush's proposed water sources. Boulder Brush identified two off-site water suppliers in its two Project Facility Availability – Water forms (PDS-399W), the Jacumba Community Services District and the Padre Dam Municipal Water District. Yet neither in the forms nor elsewhere does Boulder Brush indicate how much water those districts could provide or that they could do so in the time period required. For example, the water supply availability form for the Padre Dam Municipal Water District cautions that the availability "Letter expires 12/11/2019," which is almost

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[32] Li, D-K, H. Chen, J.R. Ferber, R. Odouli, and C. Quesenberry, 2017, "Exposure to Magnetic Field Non-Ionizing Radiation and the Risk of Miscarriage: A Prospective Cohort Study," *Scientific Reports* 7:17541 (attached hereto as **Exhibit 24**).

assuredly before Project construction would be completed. *See* NOP, p. 1 ("Project construction on private land is anticipated to last approximately 9 months").

Indeed, Boulder Brush fails to even show that the districts can legally provide water to the Project. Because the Project is outside the sphere of influence of both districts, they would need approval by the San Diego Local Agency Formation Commission ("LAFCO"). Government Code §§ 56133(a), (c); 56375(p); *Habitat and Watershed Caretakers v. City of Santa Cruz* ("*HAWC*") (2013) 213 Cal.App.4th 1277, 1283 ("'A . . . district may provide new or extended services outside its jurisdictional boundaries only if it first requests and receives written approval from [LAFCO].'"). In *HAWC*, the court set aside Santa Cruz' extraterritorial extension of water services because the EIR failed to "provid[e] LAFCO with relevant information" about the project's water supply impacts. 213 Cal.App.4th at 1305.

The EIR must also assess the Project's impacts to the Campo/Cottonwood Creek Aquifer. The aquifer was designated as a sole source aquifer pursuant to section 1424(e) of the federal Safe Drinking Water Act on May 28, 1993, with the Environmental Protection Agency ("EPA") making the determination that "contamination of [the] aquifer would create a significant hazard to public health." 58 Fed. Reg. 31025 (May 28, 1993). As a result of this designation, before the Project can receive any federal funds it is "subject to EPA review to ensure that [it is] designed so as not to create a significant hazard to public health." *Id*.

Fire Impacts and Emergency Services

As discussed above in section III(C), wildfire risk in San Diego County is dangerously high, and getting worse with global warming. This risk would both impact, and be exacerbated by, the Project and the connected Campo Wind and Torrey Wind projects. The EIR must analyze these impacts, as well as the impact to effective firefighting and emergency services in the area.

Aesthetic Impacts

The EIR must analyze the panoply of visual impacts the Project's infrastructure and the connected projects' wind turbines would have on local scenery, aesthetic enjoyment and human health. That includes shadow flicker. The Minnesota Department of Health stated in a report on the public health impacts of wind turbines that the "[r]hythmic light flicker from the blades of a wind turbine casting intermittent shadows has been reported to be annoying in many locations."[33] **Exhibit 25** at 14. Shadow flicker can also present numerous dangers, such as distracting drivers on roads close to turbines.

[33] Minnesota Department of Health, Environmental Health Division, "Public Health Impacts of Wind Turbines," Report prepared May 22, 2009 (attached hereto as **Exhibit 25**).

Agricultural Impacts

The Initial Study acknowledges that "due to past and present cattle grazing on site," the Project could result in a potentially significant impact to agricultural resources. Initial Study, p. 14. The EIR must analyze these direct agricultural impacts alongside the cumulative agricultural impacts from other development, especially energy-related development, in East County.

E. The EIR Must Analyze a Full Range of Project Alternatives

CEQA requires EIRs to "describe a range of reasonable alternatives to the project . . . which would feasibly attain most of the basic objectives of the project but would avoid or substantially lessen any of the significant effects of the project, and evaluate the comparative merits of the alternatives." Guidelines § 15126.6(a). Alternatives that would lessen significant effects should be considered even if they "would impede to some degree the attainment of the project objectives, or be more costly." *Id*. § 15126.6(b). The range of alternatives considered must "foster informed decisionmaking and public participation." *Id*. § 15126.6(a). Alternatives may only be eliminated from "detailed consideration" when substantial evidence in the record shows that they either (1) "fail[] to meet most of the basic project objectives," (2) are "infeasibl[e]," or (3) do not "avoid significant environmental impacts." *Id*. § 15126.6(c).

Energy conservation and other less impactful alternatives than utility-scale wind projects exist to conserve or generate electricity from renewable sources. For example, the EIR should analyze programs to develop or incentivize the development of distributed photovoltaic ("PV") generation projects near energy demand centers in already-disturbed areas. Beyond traditional distributed generation, a recent study shows that installing PV and concentrating solar power ("CSP") technologies throughout California's built environment could substantially exceed the state's forecasted 2020 energy needs.[34] Another recent study estimates that deploying PV and CSP solely on developed land (built environment), land with salt-affected soils, contaminated land and reservoirs in California's Central Valley "could meet CA's projected 2025 needs for electricity consumption between 10-13 times over" (for PV technologies) and "over two times over with CSP technologies."[35] **Exhibit 27** at 14479. The EIR must analyze these environmentally superior alternatives.

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[34] Hernandez, R.R., M.K. Hoffacker, M.L. Murphy-Mariscal, G. Wu, and M.F. Allen, 2015, "Solar Energy Development Impacts on Land-Cover Change and Protected Areas," *Proceedings of the National Academy of Sciences*, 112(44) (attached hereto as **Exhibit 26**).
[35] Hoffacker, M.L., M.F. Allen, and R.R. Hernandez, 2017, "Land-Sparing Opportunities for Solar Energy Development in Agricultural Landscapes: A Case Study of the Great Central Valley, CA, United States," *Environmental Science & Technology* 51:14472-14482 (attached hereto as **Exhibit 27**).

IV. The Project Must Comply with CPUC General Order 131-D.

The Project includes construction and operation of a 230-kV transmission line, a 500-kV substation and a 500-kV switchyard. The EIR must discuss, and the County must ensure, the Project's compliance with the California Public Utilities Commission's General Order 131-D. For example, the Project requires a certificate of public convenience and necessity because it includes "major electric transmission line facilities which are designed for immediate or eventual operation at 200 kV or more." G.O. 131-D § III(A).

V. Conclusion

For each of the foregoing reasons, the Project cannot be approved as currently proposed. Before considering Project approval, the applicant must provide much more detail on the Project. In addition, the County must analyze the Project's environmental impacts in an EIR. The County must also examine the need for the Project and alternatives to it. The alternatives analysis is particularly important, given that under applicable laws, the proposed Project's avian impacts may preclude Project operation as currently proposed.

Respectfully submitted,

Stephan C. Volker
Attorney for Backcountry Against Dumps
and Donna Tisdale

SCV:taf

Attachments:

Exhibit 1 – Penn, I. and R. Menezes, February 5, 2017, "Californians are paying billions for power they don't need," *Los Angeles Times* (available here: http://www.latimes.com/projects/la-fi-electricity-capacity/).

Exhibit 2 – California Public Utilities Commission, November 2017, Renewables Portfolio Standard: Annual Report, p. 10 (available here: http://www.cpuc.ca.gov/uploadedFiles/CPUC_Website/Content/Utilities_and_Industries/Energy/Reports_and_White_Papers/Nov%202017%20-%20RPS%20Annual%20Report.pdf).

Exhibit 3 – Miller, L., *et al.*, 2015, "Two methods for estimating limits to large-scale wind power generation," *Proceedings of the National Academy of Sciences* 112(36).

Exhibit 4 – CAL FIRE, 2009, "Very High Fire Hazard Severity Zones in LRA: As Recommended by CAL FIRE" (available here: http://frap.fire.ca.gov/webdata/maps/san_diego/fhszl_map.37.jpg).

Exhibit 5 – Diffenbaugh, N.S., D.L. Swain and D. Touma, March 31, 2015, "Anthropogenic warming has increased drought risk in California," *Proceedings of the National Academy of Sciences* 112(13).

Exhibit 6 – Wang, S., Lin, Y., Gillies, R. And Hakala, K., March 2016, "Indications for Protracted Groundwater Depletion after Drought over the Central Valley of California," *Journal of Hydrometeorology* 17:947-955.

Exhibit 7 – Castle, S.L., Thomas, B.F., Reager, J.T., Rodell, M., Swenson, S.C. and Famiglietti, J.S., 2014, "Groundwater Depletion During Drought Threatens Future Water Security of the Colorado River Basin," *Geophysical Research Letters*, 41:5904-5911.

Exhibit 8 – Dwyer, J.F., M.A. Landon, and E.K. Mojica, 2018, "Impact of Renewable Energy Sources on Birds of Prey," in J.H. Sarasola *et al.* (eds.), 2018, *Birds of Prey*, Springer International Publishing AG.

Exhibit 9 – Smallwood, S.K., and B. Karas, 2009, "Avian and Bat Fatality Rates at Old-Generation and Repowered Wind Turbines in California," *The Journal of Wildlife Management* 73(7).

Exhibit 10 – Fernández-Bellon, D., M.W. Wilson, S. Irwin, and J. O'Halloran, 2018, "Effects of Development of Wind Energy and Associated Changes in Land Use on Bird Densities in Upland Areas," *Conservation Biology* 0(0):1-10

Exhibit 11 – Palacín, C., J.C. Alonso, C.A. Martín, and J.A. Alonso, 2016, "Changes in Bird Migration Patterns Associated With Human-Induced Mortality," *Conservation Biology*, 31(1).

Exhibit 12 – May, R., O. Reitan, K. Bevanger, S.H. Lorentsen, and T. Nygard, 2014, "Mitigating wind-turbine induced avian mortality: Sensory, aerodynamic and cognitive constraints and options," *Renewable and Sustainable Energy Reviews*, 42:170-181.

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Exhibit 14 – Thaker, M., A. Zambre, and H. Bhosale, 2018, "Wind Farms Have Cascading Impacts on Ecosystems across Trophic Levels," *Nature Ecology & Evolution* 2:1854-1858 (attached hereto as **Exhibit 14**).

Exhibit 15 – Morsing, J.A., M.G. Smith, M. Ögren, P. Thorsson, E. Pedersen, J. Forssén, and K.P Waye, 2018, "Wind Turbine Noise and Sleep: Pilot Studies on the Influence of Noise Characteristics," *International Journal of Environmental Research and Public Health*, 15(2573).

Exhibit 16 – Onakpoya, I.J., J. O'Sullivan, M.J. Thompson, and C.J. Henghan, 2015, "The Effect of Wind Turbine Noise on Sleep and Quality of Life: A Systematic Review and Meta-analysis of Observational Studies," *Environment International* 82:1-9.

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Exhibit 18 – Schmidt, J.H., and M. Klokker, 2014, "Health Effects Related to Wind Turbine Noise Exposure: A Systematic Review," *PLoS ONE* 9(12).

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Exhibit 20 – Salt, A., and J. Kaltenbach, 2011, "Infrasound from Wind Turbines Could Affect Humans," *Bulletin of Science, Technology and Society*, 31(4): 296-302.

Exhibit 21 – Chen, H.A., and P. Narins, 2012, "Wind Turbines and Ghost Stories: The Effects of Infrasound on the Human Auditory System," *Acoustics Today*, 8(2):51-55.

Exhibit 22 – Salt, A., and J. Lichtenhan, 2012, "Perception-based protection from low-frequency sounds may not be enough," presented at InterNoise 2012 in New York City, New York, August 19-22, 2012.

Exhibit 23 – Salt, A., and T. Hullar, 2010, "Responses of the Ear to Low Frequency Sounds, Infrasound and Wind Turbines," *Hearing Research*, 268:12-21.

Exhibit 24 – Li, D-K, H. Chen, J.R. Ferber, R. Odouli, and C. Quesenberry, 2017, "Exposure to Magnetic Field Non-Ionizing Radiation and the Risk of Miscarriage: A Prospective Cohort Study," *Scientific Reports* 7:17541.

Exhibit 25 – Minnesota Department of Health, Environmental Health Division, "Public Health Impacts of Wind Turbines," Report prepared May 22, 2009.

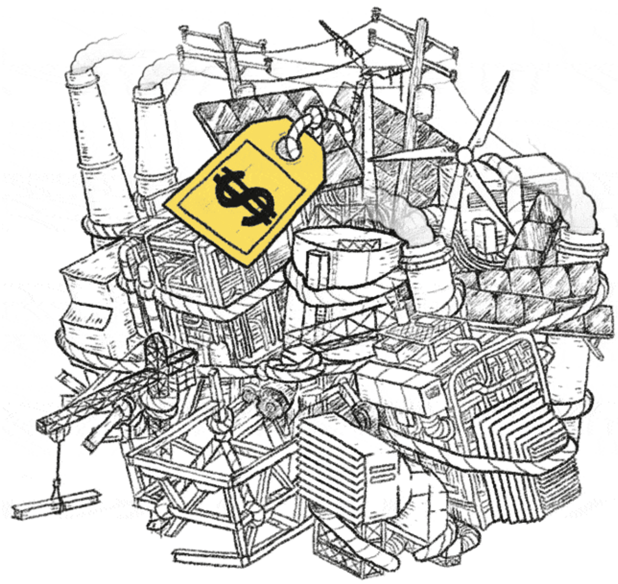
Exhibit 26 – Hernandez, R.R., M.K. Hoffacker, M.L. Murphy-Mariscal, G. Wu, and M.F. Allen, 2015, "Solar Energy Development Impacts on Land-Cover Change and Protected. Areas," *Proceedings of the National Academy of Sciences*, 112(44).

Exhibit 27 – Hoffacker, M.L., M.F. Allen, and R.R. Hernandez, 2017, "Land-Sparing Opportunities for Solar Energy Development in Agricultural Landscapes: A Case Study of the Great Central Valley, CA, United States," *Environmental Science & Technology* 51:14472-14482.

EXHIBIT
1

Los Angeles Times (HTTP://WWW.LATIMES.COM/)

Californians are paying billions for power they don't need



We're using less electricity. Some power plants have even shut down. So why do state officials keep approving new ones?

By IVAN PENN (HTTP://WWW.LATIMES.COM/LA-BIO-IVAN-PENN-STAFF.HTML) and RYAN MENEZES (HTTP://WWW.LATIMES.COM/LA-BIO-RYAN-MENEZES-STAFF.HTML) | Reporting from Yuba City, Calif.

FEB. 5, 2017

Read the story

View the graphic (/projects/la-fi-electricity-capacity-graphic/)

The bucolic orchards of Sutter County north of Sacramento had never seen anything like it: a visiting governor and a media swarm — all to christen the first major natural gas power plant in California in more than a decade.

At its 2001 launch, the Sutter Energy Center was hailed as the nation's cleanest power plant. It generated electricity while using less water and natural gas than older designs.

A year ago, however, the $300-million plant closed indefinitely, just 15 years into an expected 30- to 40-year lifespan. The power it produces is no longer needed — in large part because state regulators approved the construction of a plant just 40 miles away in Colusa that opened in 2010.

"We are building more power plants in California than ever before. Our goal is to make California energy self–sufficient." - Gov. Gray Davis at the opening of Sutter Energy Center in 2001. (Carolyn Cole / Los Angeles Times)

Sutter Energy Center has been offline since 2016, after just 15 years of an expected 30- to 40-year lifespan. (David Butow / For The Times)

Two other large and efficient power plants in California also are facing closure decades ahead of schedule. Like Sutter, there is little need for their electricity.

California has a big — and growing — glut of power, an investigation by the Los Angeles Times has found. The state's power plants are on track to be able to produce at least 21% more electricity than it needs by 2020, based on official estimates. And that doesn't even count the soaring production of electricity by rooftop solar panels that has added to the surplus.

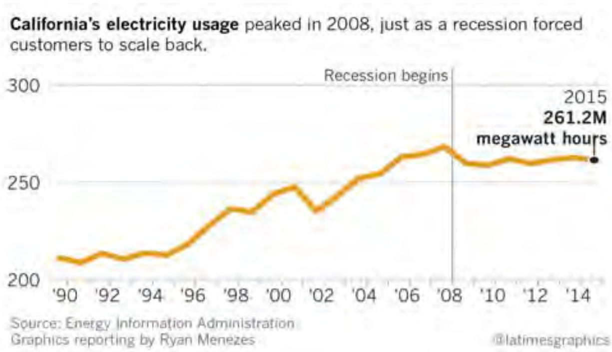
To cover the expense of new plants whose power isn't needed — Colusa, for example, has operated far below capacity since opening — Californians are paying a higher premium to switch on lights or turn on electric stoves. In recent years, the gap between what Californians pay versus the rest of the country has nearly doubled to about 50%.

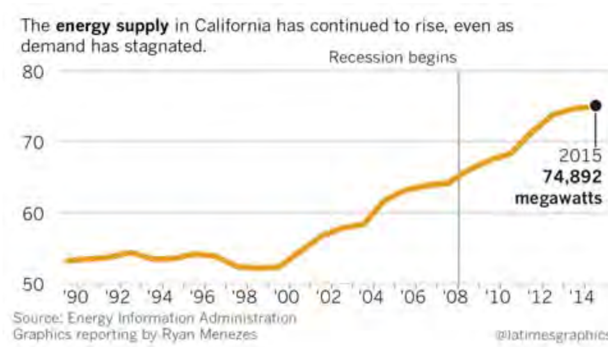
This translates into a staggering bill. Although California uses 2.6% less electricity annually from the power grid now than in 2008, residential and business customers together pay $6.8 billion more for power than they did then. The added cost to customers will total many billions of dollars over the next two decades, because regulators have approved higher rates for years to come so utilities can recoup the expense of building and maintaining the new plants, transmission lines and related equipment, even if their power isn't needed.

How this came about is a tale of what critics call misguided and inept decision-making by state utility regulators, who have ignored repeated warnings going back a decade about a looming power glut.

"In California, we're blinding ourselves to the facts," said Loretta Lynch, a former president of the California Public Utilities Commission, who along with consumer advocacy groups has fought to stop building plants. "We're awash in power at a premium price."

California regulators have for years allowed power companies to go on a building spree, vastly expanding the potential electricity supply in the state. Indeed, even as electricity demand has fallen since 2008, California's new plants have boosted its capacity enough to power all of the homes in a city the size of Los Angeles — six times over. Additional plants approved by regulators will begin producing more electricity in the next few years.





The missteps of regulators have been compounded by the self-interest of California utilities, Lynch and other critics contend. Utilities are typically guaranteed a rate of return of about 10.5% for the cost of each new plant regardless of need. This creates a major incentive to keep construction going: Utilities can make more money building new plants than by buying and reselling readily available electricity from existing plants run by competitors.

Regulators acknowledge the state has too much power but say they are being prudent. The investment, they maintain, is needed in case of an emergency — like a power plant going down unexpectedly, a heat wave blanketing the region or a wildfire taking down part of the transmission network.

"We overbuilt the system because that was the way we provided that degree of reliability," explained Michael Picker, president of the California Public Utilities Commission. "Redundancy is important to reliability."

Some of the excess capacity, he noted, is in preparation for the retirement of older, inefficient power plants over the next several years. The state is building many new plants to try to meet California environmental standards requiring 50% clean energy by 2030, he said.

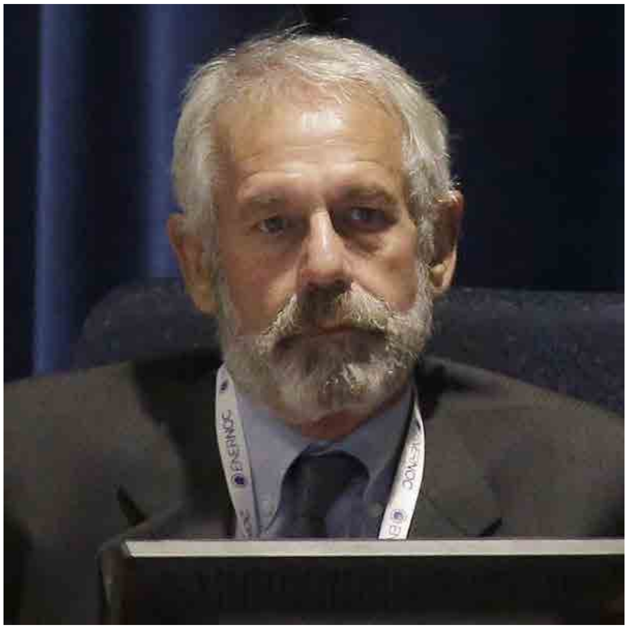
In addition, he said, some municipalities — such as the Los Angeles Department of Water and Power — want to maintain their own separate systems, which leads to inefficiencies and redundancies. "These are all issues that people are willing to pay for," Picker said.

Critics agree that some excess capacity is needed. And, in fact, state regulations require a 15% cushion. California surpasses that mark and is on pace to exceed it by 6 percentage points in the next three years, according to the Western Electricity Coordinating Council, which tracks capacity and reliability. In the past, the group has estimated the surplus would be even higher.

Michael Picker, current president of California's Public Utilities Commission, said the state's excess power supply is a strategic decision to ensure reliability. Loretta Lynch, who held the same position from 2002 to 2005, has been a critic of overbuilding since she chaired the regulatory agency. (Associated Press)

Even the 15% goal is "pretty rich," said Robert McCullough of Oregon-based McCullough Research, who has studied California's excess electric capacity for both utilities and regulators. "Traditionally, 10% is just fine. Below 7% is white knuckle. We are a long way from white-knuckle time" in California.

Contrary to Picker's assertion, critics say, customers aren't aware that too




much capacity means higher rates. "The winners are the energy companies," Lynch said. "The losers are businesses and families."

The over-abundance of electricity can be traced to poorly designed deregulation of the industry, which set the stage for blackouts during the energy crisis of 2000-2001.

Lawmakers opened the state's power business to competition in 1998, so individual utilities would no longer enjoy a monopoly on producing and selling electricity. The goal was to keep prices lower while ensuring adequate supply. Utilities and their customers were allowed to buy electricity from new, unregulated operators called independent power producers.

The law created a new exchange where electricity could be bought and sold, like other commodities such as oil or wheat.

Everyone would benefit. Or so the thinking went.

In reality, instead of lowering electricity costs and spurring innovation, market manipulation by Enron Corp. and other energy traders helped send electricity prices soaring.

That put utilities in a bind, because they had sold virtually all their natural gas plants. No longer able to produce as much of their own electricity, they ran up huge debts buying power that customers needed. Blackouts spread across the state.

State leaders, regulators and the utilities vowed never to be in that position again, prompting an all-out push to build more plants, both utility-owned and independent.

“They were not going to allow another energy crisis due to a lack of generation,” said Alex Makler, a senior vice president of Calpine, the independent power producer that owns the Sutter Energy plant not far from Sacramento.

But the landscape was starting to change. By the time new plants began generating electricity, usage had begun a decline, in part because of the economic slowdown caused by the recession but also because of greater energy efficiency.

The state went from having too little to having way too much power.

“California has this tradition of astonishingly bad decisions,” said McCullough, the energy consultant. “They build and charge the ratepayers. There’s nothing dishonest about it. There’s nothing complicated. It’s just bad planning.”

> California has this tradition of astonishingly bad decisions.
>
> — Robert McCullough, energy consultant

The saga of two plants — Sutter Energy and Colusa — helps explain in a microcosm how California came to have too much energy, and is paying a high price for it.

Sutter was built in 2001 by Houston-based Calpine, which owns 81 power plants in 18 states.

Sutter Energy Center, now closed, made money only if Calpine Corp. found customers for the plant's power. Other large, natural gas plants in the state also face early closures. (David Butow / For The Times)

Colusa Generating Station opened in 2010. Pacific Gas & Electric will charge ratepayers more than $700 million over the plant's lifespan, to cover its operating costs and the profit guaranteed to public utility companies. (Rich Pedroncelli / AP)

Independents like Calpine don't have a captive audience of residential customers like regulated utilities do. Instead, they sell their electricity under contract or into the electricity market, and make money only if they can find customers for their power.

Sutter had the capacity to produce enough electricity to power roughly 400,000 homes. Calpine operated Sutter at an average of 50% of capacity in its early years — enough to make a profit.

But then Pacific Gas & Electric Co., a regulated, investor-owned utility, came along with a proposal to build Colusa.

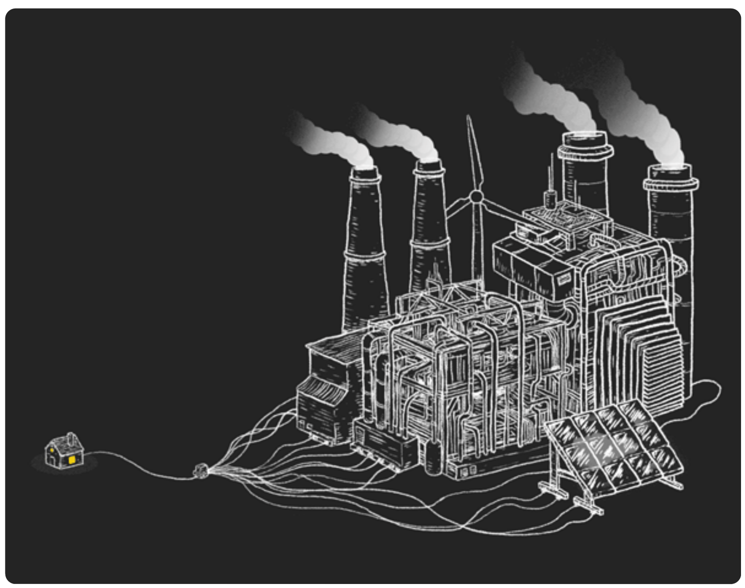
It was not long after a statewide heat wave, and PG&E argued in its 2007 request seeking PUC approval that it needed the ability to generate more power. Colusa — a plant almost identical in size and technology to Sutter — was the only large-scale project that could be finished quickly, PG&E said.

More than a half-dozen opponents, including representatives of independent power plants, a municipal utilities group and consumer advocates filed objections questioning the utility company. Wasn't there a more economical alternative? Did California need the plant at all?

They expressed concern that Colusa could be very expensive long-term for customers if it turned out that its power wasn't needed.

That's because public utilities such as PG&E operate on a different model.

If electricity sales don't cover the operating and construction costs of an independent power plant, it can't continue to run for long. And if the independent plant closes, the owner — and not ratepayers — bears the burden of the cost.



(/projects/la-fi-electricity-capacity-graphic/) (/projects/la-fi-electricity-capacity-graphic/) (/projects/la-fi-electricity-capacity-graphic/) California's energy supply: From blackouts to glut (/projects/la-fi-electricity-capacity-graphic/)

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In contrast, publicly regulated utilities such as PG&E operate under more accommodating rules. Most of their revenue comes from electric rates approved by regulators that are set at a level to guarantee the utility recovers all costs for operating the electric system as well as the cost of building or buying a power plant — plus their guaranteed profit.

Protesters argued Colusa was unnecessary. The state's excess production capacity by 2010, the year Colusa was slated to come online, was projected to be almost 25% — 10 percentage points higher than state regulatory requirements.

The looming oversupply, they asserted, meant that consumers would get stuck with much of the bill for Colusa no matter how little customers needed its electricity.

And the bill would be steep. Colusa would cost PG&E $673 million to build. To be paid off, the plant will have to operate until 2040. Over its lifetime, regulators calculated that PG&E will be allowed to charge more than $700 million to its customers to cover not just the construction cost but its operating costs and its profit.

Pacific Gas & Electric's Colusa Generating Station has operated at well below its generating capacity — just 47% in its first five years. (Rich Pedroncelli / AP)

The urgent push by PG&E "seems unwarranted and inappropriate, and potentially costly to ratepayers," wrote Daniel Douglass, a lawyer for industry groups that represent independent power producers.

The California Municipal Utilities Assn. — whose members buy power from public utilities and then distribute that power to their customers — also complained in a filing that PG&E's application appeared to avoid the issue of how Colusa's cost would be shared if it ultimately sat idle. PG&E's "application is confusing and contradicting as to whether or not PG&E proposes to have the issue of stranded cost recovery addressed," wrote Scott Blaising, a lawyer representing the association. ("Stranded cost" is industry jargon for investment in an unneeded plant.)

The arguments over Colusa echoed warnings that had been made for years by Lynch, the former PUC commissioner.

A pro-consumer lawyer appointed PUC president in 2000 by Gov. Gray Davis, Lynch consistently argued as early as 2003 against building more power plants.

"I was like, 'What the hell are we doing?' " recalled Lynch.

She often butted heads with other commissioners and utilities who pushed for more plants and more reserves. Midway though her term, the governor replaced her as president — with a former utility company executive.

One key battle was fought over how much reserve capacity was needed to guard against blackouts. Lynch sought to limit excess capacity to 9% of the state's electricity needs. But in January 2004, over her objections, the PUC approved a gradual increase to 15% by 2008.

"We've created an extraordinarily complex system that gives you a carrot at every turn," Lynch said. "I'm a harsh critic because this is intentionally complex to make money on the ratepayer's back."

With Lynch no longer on the PUC, the commissioners voted 5-0 in June 2008 to let PG&E build Colusa. The rationale: The plant was needed, notwithstanding arguments that there was a surplus of electricity being produced in the market.

PG&E began churning out power at Colusa in 2010. For the nearby Sutter plant, that marked the beginning of the end as its electricity sales plummeted.

In the years that followed, Sutter's production slumped to about a quarter of its capacity, or just half the rate it had operated previously.

Calpine, Sutter's owner, tried to drum up new business for the troubled plant, reaching out to shareholder-owned utilities such as PG&E and other potential buyers. Calpine even proposed spending $100 million to increase plant efficiency and output, according to a letter the company sent to the PUC in February 2012.

PG&E rejected the offer, Calpine said, "notwithstanding that Sutter may have been able to provide a lower cost."

Asked for comment, PG&E said, "PG&E is dedicated to meeting the state's clean energy goals in cost-effective ways for our customers. We use competitive bidding and negotiations to keep the cost and risk for our customers as low as possible." It declined to comment further about its decision to build Colusa or on its discussions with Calpine.

Without new contracts and with energy use overall on the decline, Calpine had little choice but to close Sutter.

During a 2012 hearing about Sutter's distress, one PUC commissioner, Mike Florio, acknowledged that the plant's troubles were "just the tip of the proverbial iceberg." He added, "Put simply, for the foreseeable future, we have more power plants than we need."

Colusa, meanwhile, has operated at well below its generating capacity — just 47% in its first five years — much as its critics cautioned when PG&E sought approval to build it.

Sutter isn't alone. Other natural gas plants once heralded as the saviors of California's energy troubles have found themselves victims of the power glut. Independent power producers have announced plans to sell or close the 14-year-old Moss Landing power plant at Monterey Bay and the 13-year-old La Paloma facility in Kern County.

> "Put simply, for the foreseeable future, we have more power plants than we need.
>
> — Mike Florio, former PUC commissioner

Robert Flexon, chief executive of independent power producer Dynegy Inc., which owns Moss Landing, said California energy policy makes it difficult for normal market competition. Independent plants are closing early, he said, because regulators favor utility companies over other power producers.

"It's not a game we can win," Flexon said.

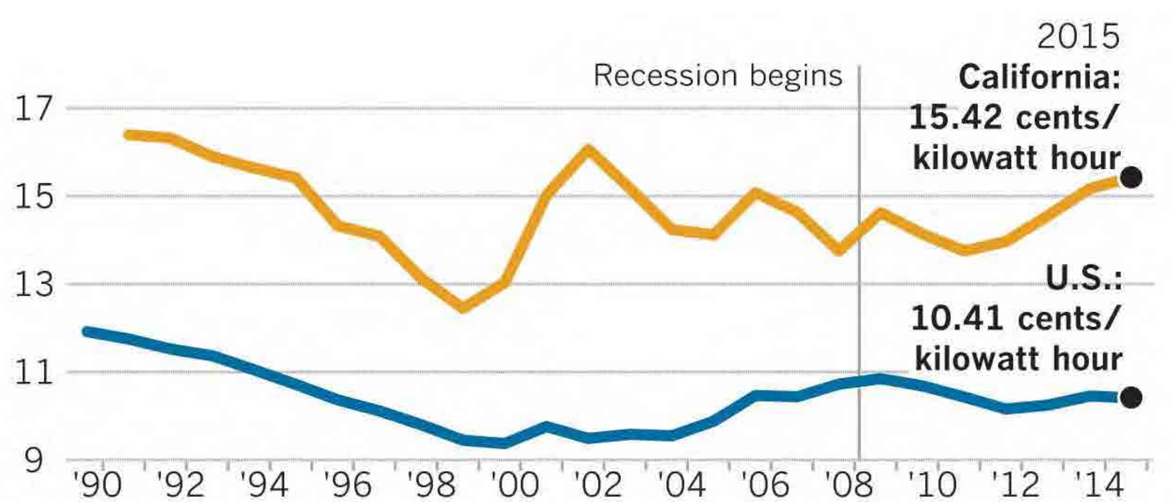
Since 2008 alone — when consumption began falling — about 30 new power plants approved by California regulators have started producing electricity. These plants account for the vast majority of the 17% increase in the potential electricity supply in the state during that period.

Hundreds of other small power plants, with production capacities too low to require the same level of review by state regulators, have opened as well.

Most of the big new plants that regulators approved also operate at below 50% of their generating capacity.

So that California utilities can foot the bill for these plants, the amount they are allowed by regulators to charge ratepayers has increased to $40 billion annually from $33.5 billion, according to data from the U.S. Energy Information Administration. This has tacked on an additional $60 a year to the average residential power bill, adjusted for inflation.

Another way of looking at the impact on consumers: The average cost of electricity in the state is now 15.42 cents a kilowatt hour versus 10.41 cents for users in the rest of the U.S. The rate in California, adjusted for inflation, has increased 12% since 2008, while prices have declined nearly 3% elsewhere in the country.



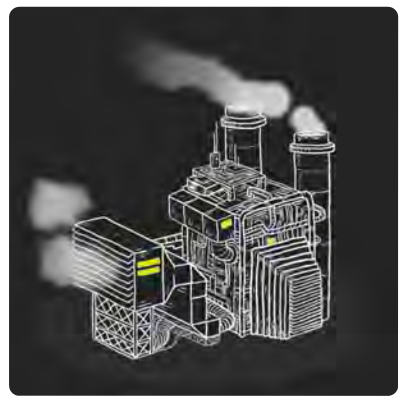
Note: cost of power figures are adjusted for inflation.
Source: Energy Information Administration
Graphics reporting by Ryan Menezes
@latimesgraphics

California utilities are "constantly crying wolf that we're always short of power and have all this need," said Bill Powers, a San Diego-based engineer and consumer advocate who has filed repeated objections with regulators to try to stop the approval of new plants. They are needlessly trying to attain a level of reliability that is a worst-case "act of God standard," he said.

Even with the growing glut of electricity, consumer critics have found that it is difficult to block the PUC from approving new ones.

In 2010, regulators considered a request by PG&E to build a $1.15-billion power plant in Contra Costa County east of San Francisco, over objections that there wasn't sufficient demand for its power. One skeptic was PUC commissioner Dian Grueneich. She warned that the plant wasn't needed and its construction would lead to higher electricity rates for consumers — on top of the 28% increase the PUC had allowed for PG&E over the previous five years.

The PUC was caught in a "time warp," she argued, in approving new plants as electricity use fell. "Our obligation is to ensure that our decisions have a legitimate factual basis and that ratepayers' interest are protected."



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California's energy supply: From blackouts to glut (/projects/la-fi-electricity-capacity-graphic/)

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Her protests were ignored. By a 4-to-1 vote, with Grueneich the lone dissenter, the commissioners approved the building of the plant.

Consumer advocates then went to court to stop the project, resulting in a rare victory against the PUC. In February 2014, the California Court of Appeals overturned the commission, ruling there was no evidence the plant was needed.

Recent efforts to get courts to block several other PUC-approved plants have failed, however, so the projects are moving forward.

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Times data editor Ben Welsh contributed to this report. Illustrations by Eben McCue. Graphics by Priya Krishnakumar and Paul Duginski. Produced by Lily Mihalik

EXHIBIT 1

RESULTS OF AMBIENT NOISE MEASUREMENTS

OF THE EXISTING KUMEYAAY WIND AND TULE WIND FACILITIES

IN THE AREA OF BOULEVARD AND JACUMBA HOT SPRINGS

PERTAINING TO THE PROPOSED TORREY AND CAMPO WIND TURBINE FACILITIES

18 March 2019

Submitted to:

Donna Tisdale

Backcountry Against Dumps

Submitted by:

Richard A. Carman, Ph.D., P.E.

Michael A. Amato

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EXECUTIVE SUMMARY

Two wind turbine (WT) farms, Torrey Wind, with thirty (30) WTs, and Campo Wind with sixty (60) WTs are proposed for construction in the Boulevard, California area. Noise recordings were obtained between November 13 and November 17, 2018 in the area of Boulevard and Jacumba Hot Springs. The purpose of the recordings was to measure and document the existing infrasound and low frequency noise (ILFN) generated by the existing wind turbines in the area. Another purpose of the measurements was to document the existing C-weighted noise levels at several locations on the boundaries of the Torrey and Campo wind farm projects. During the noise recordings, amplitude modulated (AM) noise was observed in the field. Analysis of the noise recordings indicated the existence of AM noise generated by the WTs.

There are currently two WT farms in the Boulevard area: Kumeyaay with twenty-five (25) WTs and Tule with fifty-seven (57) WTs. To the east is the Ocotillo wind farm with one hundred and twelve (112) WTs, which are about 11 miles between the closest recording location and wind turbine. To the southeast in Mexico is the Energia Sierra Juarez (ESJ) wind farm with forty-seven (47) WTs, which are about 7 miles between the closest recording location and wind turbine.

In 2013 noise measurements were conducted in the Boulevard and Ocotillo areas. At that time only the Kumeyaay and Ocotillo wind farms existed. The 2014 Wilson Ihrig (WI) report[1] documents the results of the 2013 measurements. The current report and the 2014 WI report conclusively document the presence of WT generated infrasound (IS) as measured at residential and other locations up to 8 miles from the wind turbines at the Kumeyaay and Tule facilities. Analysis of the current noise recordings also indicates excessive amplitude modulated noise generated by the existing WTs.

It is clear from the measured noise data obtained for the Kumeyaay and Tule and other wind turbine facilities in the area that there is significant wind turbine-generated ILFN. This was to be expected as it has been documented by others such as in the Falmouth noise study[2], the Shirley Wind Turbine study[3], and by Epsilon Associates.[4] And indeed the measured ILFN levels near Kumeyaay and Tule wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

Both the Falmouth and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth,

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[1] Kumeyaay and Ocotillo Wind Turbine Facilities, Noise Measurements, report by Wilson Ihrig submitted to Stephen C. Volker, Esq., 28 February 2014.

[2] Ambrose, S. and R. Rand, The Bruce McPherson Infrasound and Low Frequency Noise Study, 14 December 2011.

[3] Channel Islands Acoustics, et al, A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin, Report No. 122412-1, December 24, 2012.

[4] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce ILFN, and whether that ILFN was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated ILFN at numerous nearby residences that correlated with residents' reported impacts.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then.

Research and investigations into human response to ILFN seem to provide strong evidence of a cause and effect relationship. The work of Salt, et al.[5] has made a clear case for perception of ILFN below the threshold of hearing as defined by ISO 389-7 which is related to the response of the ear's inner hair cells (IHC). Salt has demonstrated that it is possible for the ears' outer hair cells (OHC) to respond to ILFN at sound pressure levels that are much lower than the IHC threshold. Salt has reported that ILFN levels commonly generated by wind turbines can cause physiologic changes in the ear.[6] Salt and Kaltenbach "estimated that sound levels of 60 dBG will stimulate the OHC of the human ear."[7]

Furthermore, Matsumoto et al.[8] have demonstrated in a laboratory setting that humans can perceive ILFN at sound pressure levels below the IHC threshold when the noise is a complex spectrum (i.e. contains multiple frequency components). From this laboratory research it was clearly demonstrated that humans can sense sound pressure levels, although not through the normal hearing mechanism, that are from 10 to 45 decibels (dB) less than the OHC threshold in the ILFN range. In fact, the Matsumoto thresholds clearly follow the OHC threshold down to the frequency below which the two diverge. The Matsumoto thresholds are lower than the OHC thresholds at frequencies below the point at which they diverge.

The studies cited above, and more recent studies demonstrate that wind turbines (specifically wind turbine-generated ILFN) have the potential to not only annoy humans, but harm them physiologically. For example, an extensive literature review by Carlile, et al.[9] presents data and discusses findings from numerous sources that document the existence

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[5] Alec Salt, and J. Lichtenhan, Perception based protection from low-frequency sounds may not be enough, Internoise 2012, August 2012.

[6] Alec Salt, and J.A. Kaltenbach, "Infrasound from Wind Turbines Could Affect Humans," Bulletin of Science, Technology and Society, 31(4), pp.296-302, September 12, 2011.

[7] Ibid., p. 300, "As discussed below, G-weighting (with values expressed in dBG) is one metric that is used to quantify environmental noise levels. While it is a more accurate measure of ILFN than most other metrics, G-weighting still de-emphasizes infrasound."

[8] Yasunao Matsumoto, et al., An investigation of the perception thresholds of band-limited low frequency noises; influence of bandwith, published in The Effects of Low-Frequency Noise and Vibration on People, Multi-Science Publishing Co. Ltd.

[9] Carlile, Simon, John L. Davy, David Hillman and Kym Burgermeister, A review of the possible perceptual and physiological effects of wind turbine noise, Trends in Hearing, v.22, Jan-Dec 2018.

and sources of ILFN from large wind turbines and the potential physiological effects on humans resulting from wind turbine ILFN. In discussing human reaction to WT ILFN, Carlile, et al. highlight that "a further mechanism considered by Salt and Hullar[10] is the increased fluid coupling of vestibular cells to sound input produced by changes in the input impedance of the vestibular system in conditions such as superior canal dehiscence (SCD), which can result in sound induced dizziness or vertigo, nausea, and nystagmus (Tullio phenomena)." This is relevant since many who tell of adverse effects of WT ILFN report that dizziness or vertigo is one of the effects they feel.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay, Tule, Ocotillo and Energia Sierra Juarez facilities. Higher wind speeds generally produce higher noise levels and particularly higher ILFN. This was clearly demonstrated in the Ocotillo data from 2013 when comparing the daytime and nighttime levels.

INTRODUCTION

As requested, WI performed noise measurements in November 2018 in the areas of the proposed Torrey and Campo wind farms, the existing Kumeyaay wind farm, located on the Campo Indian Reservation, and the existing Tule wind farm, located on Bureau of Land Management (BLM) land. In 2013 WI conducted similar noise measurements in the Boulevard area and in the vicinity of the Ocotillo Wind Energy Facility located near Ocotillo, California. The results of those measurements are contained in Appendix D.

The purpose of the current measurements is to determine whether, and at what levels and under what conditions, the Kumeyaay and Tule wind turbines generate ILFN[11], and how far the ILFN is propagated. A subsidiary goal was to accurately show the pressure fluctuations in the sound, to allow an accurate and robust analysis of the human health and other environmental impacts of the ILFN generated. Another goal was to document the existing ambient (C-weighted) noise levels at the boundaries of the proposed Torrey and Campo wind farms.

Between November 13 and November 16, 2018, WI recorded noise samples at numerous residential and proposed wind farm project boundary locations. The wind turbines at the Tule wind farm were operating the entire time during which we conducted our noise recordings. Some but not all the WTs at the Kumeyaay wind farm were operating during this time. On the morning of November 17, the wind turbines at Kumeyaay Wind and Tule Wind that were observable from the last measurement location were not operating. However, on review of the spectral data, it appears that some WTs, most likely on the northern end at Tule Wind were operating. Through a spectral analysis of the noise recordings, we obtained sound

[10] Salt, A.N., T.E. Hullar, Responses of the ear to low frequency sounds, infrasound and wind turbines, Hearing Research, 16 June 2010.

[11] Infrasound is defined as sound at frequencies less than 20 Hz. The focus of this report is frequencies less than 40 Hz, which includes low frequency sound as well.

pressure level data demonstrative of wind turbine-generated ILFN. In this report, we present and analyze the study results.

WIND TURBINE DETAILS

Kumeyaay Wind Farm

Kumeyaay Wind is owned by Kumeyaay Wind LLC (part of Leeward Renewable Energy LLC) and managed by Kumeyaay Holdings LLC, on 45 acres of land on the Campo Indian Reservation in southeastern San Diego County.[12] The nearest community outside of the tribal land is Boulevard, California. Currently there are twenty-five (25) wind turbines operating at this facility. The wind turbines are located on a north-south ridge (Tecate Divide) at elevations ranging from 4,200 to 4,600 feet. The turbines started generating power in December 2005.

Kumeyaay Wind's turbines are Gamesa model G87X-2.0, with a rated power of 2.0 megawatts (MW). According to the manufacturer's published data, the G87X-2.0 has a hub height (height of the nacelle, which houses the gearbox, transmission and generator) that can vary from 217 to 325 feet depending on site conditions. The manufacturer also represents that the turbine has a rotor diameter of 283 feet, with three 138-foot-long, adjustable pitch blades. According to Councilman Miskwish the hub height of the Kumeyaay Wind turbines is typically 228 feet, and the blades are 145 feet long. Figure 1 shows some of the wind turbines at Kumeyaay Wind as seen from the Morgan residence.

The G87-2.0 model has a reported cut-in wind speed of 8.9 mph and achieves its rated (max) power generation at about 31 mph. The operational speed of the turbines is reported by the manufacturer to be in the range of 9 to 19 revolutions per minute (rpm) depending on wind conditions.

[12] "Kumeyaay Wind Energy Project," PowerPoint presentation by Councilman Michael Connolly Miskwish, Campo Kumeyaay Nation, November 30, 2008., *available here:* http://www.lawseminars.com/materials/08TRIBDC/tribdc%20m%2017%20Connolly%20A.pdf

Figure 1 Gamesa Wind G87-2.0 Turbines at Kumeyaay Wind 1.7 Miles from Morgan Res.

Tule Wind Farm

The Tule Wind facility is owned and operated by Avangrid Renewables, on 12,360 acres of public land located in southeastern San Diego County and managed by the United States Bureau of Land Management (BLM). Tule Wind currently has fifty-seven (57) operating wind turbines. The wind turbines are located on a ridge line adjacent to the community of Boulevard, California, at elevations ranging from approximately 3,880 to 4,550 feet above sea level. The Tule WTs are GE model 2.3-107 ESS, with a rated power of 2.3 MW. Figure 2 shows some of WTs at Tule Wind as seen from the Chase residence. Figure 1 shows Tule WTs as seen from the Guy residence.

Figure 2 GE 2.3-107 ESS Wind Turbines at Tule Wind 1.4 Miles from Chase Residence

Figure 3 GE 2.3-107 ESS Wind Turbines at Tule Wind 4,300 Feet from Guy Residence

According to the manufacturer's published data, the 2.3-107 ESS model has a nominal hub height of 260 feet depending on site conditions, with a turbine rotor diameter of 348 feet and three 174-foot-long blades. The 2.3-107 ESS has a manufacturer-reported cut-in wind speed of 6.6 mph and achieves its rated power at wind speeds in the range of 16 to 24 mph. The manufacturer stated range of operational rpm is 5 to 14.9 rpm depending on wind conditions.

Torrey Wind and Campo Wind Farm Projects

Two wind turbine (WT) farms, Torrey Wind, with thirty (30) WTs, and Campo Wind with sixty (60) WTs are proposed for construction in the Boulevard area. The developer of both projects is Terra Gen. The proposed Torrey Wind will install 4.2 MW WTs on private land. The proposed Campo project will install 4.2 MW WTs on reservation land. Torrey Wind will also construct a collector substation, a 230-kV/500-kV substation/switchyard, which will be shared by Campo Wind and an operations and maintenance building. The zones for WT sites for Torrey Wind have been identified[13]. A map of Torrey Wind is contained in Appendix E. A map of Campo Wind is contained in Appendix F.

MEASUREMENT LOCATIONS

Kumeyaay and Tule Wind Area Residences

Both indoor and outdoor noise recordings were made at fifteen (15) residences in the Boulevard area near the Kumeyaay Wind and Tule Wind turbines and in Jacumba Hot Springs. Table 1 lists the addresses of the residences at which the measurements were taken, along with the dates and times of the recordings. The area residences where measurements were obtained are located at distances of from 4,430 feet to 8.02 miles from the nearest wind turbine at either Kumeyaay Wind or Tule Wind. A map showing the Kumeyaay and Tule wind area measurement locations is provided in Appendix A. Some of the residents wished to remain anonymous and are identified as such.

Table 1 Addresses of Residences for Measurements

Resident/Owner	Address	Distance to Closest Wind Turbine	Date	Recording Start Time[1]
J.&T. Morrison	2920 Ribbonwood Road, Boulevard	1.46 miles	Nov.13	9:54
W.&H. Skains	2810 Ribbonwood Road, Boulevard	1.65 miles	Nov.13	10:56
K.&T. Daubach	39954 Ribbonwood Road, Boulevard	2.9 miles	Nov.13	11:58
R.&P. Guy	2975 Ribbonwood Road, Boulevard	4,430 feet	Nov.13	14:43

[13] Plot Plan - Torrey Wind, San Diego County, PDS2018-MUP-18-014-PDS-PLN, 21 June 2018.

B.&B. Chase	2948 Ribbonwood Road, Boulevard	1.40 miles	Nov.14	9:33
Anonymous Residence 1	--	1.49 miles	Nov.14	11:07
Anonymous Residence 2	--	1.50 miles	Nov.14	13:30
M.&S. Morgan	2912 Ribbonwood Road, Boulevard	1.58 miles	Nov.14	15:16
J.&S. McKernan	37131 Hwy. 94, Boulevard	4.72 miles	Nov. 14	16:45
Anonymous Residence 3	--	2.91 miles	Nov.15	9:34
M.&L. Ostrander	43477 Old Hwy 80, Jacumba Hot Springs	8.02 miles	Nov.15	10:33
A.&T. DeGroot	2693 Paso Alto Court, Boulevard	4,970 feet	Nov.15	11:46
R.&B. Blaisdell	2941 La Posta Circle East, Pine Valley	3.87 miles	Nov.15	14:41
D.&E. Tisdale	1250 Tierra Real Ln, Boulevard	5.70 miles	Nov.15	15:36
M. Strand	2235 Tierra Heights Road, Boulevard	2.24 miles	Nov.17	8:57

[1] Recordings were nominally 15 to 20 minutes long

Torrey and Campo Wind Project Boundary

To document the existing ambient, C-weighted noise levels near the proposed Torrey Wind and Campo Wind projects, we obtained noise recordings at locations near the proposed boundary lines of the two projects. Table 2 indicates the Torrey Wind project boundary ambient measurement locations, the distances to the closest existing wind turbine, dates, and times of the recordings. Table 3 indicates the Campo Wind project boundary ambient measurement locations, the distances to the closest wind turbine, dates, and times of the recordings. A map showing the Torrey Wind and Campo Wind project boundary measurement locations is provided in Figure A-2.

Table 2 Torrey Project Boundary - Ambient Measurements

Location	Dist. to Closest Existing Wind Turbine (mi)	Date	Recording Start Time[1]
Torrey PL1	1.43	Nov. 14	10:15
Torrey PL2	1.52	Nov. 14	12:10

[1] Recordings were nominally 15 to 20 minutes long

Table 3 Campo Project Boundary - Ambient Measurements

Location	Dist. to Closest Existing Wind Turbine (mi)	Date	Recording End Time[1]
Campo PL1	7.73	Nov. 16	10:45
Campo PL2	0.98	Nov. 16	12:16
Campo PL3	2.68	Nov. 16	14:07
Campo PL4	5.30	Nov. 15	16:41

[1] Recordings were nominally 15 to 20 minutes long

NOISE RECORDING METHODOLOGY

WI conducted similar noise measurements in 2013. The way sound recordings were made are described in detail in the 2014 WI report, which is included as Appendix D. For a discussion of the sound recording instrumentation refer to Appendix D. To record noise samples in 2018, WI used a RION DA21 digital recorder, which provides a linear frequency response (i.e., ±0.1% or less) to a lower frequency limit of essentially 0.1 Hz when used in the "AC mode" (which we did). Twenty-minute (nominal) noise recordings were made at each location. At the residence locations recordings were made simultaneously both indoors and outdoors at using two different microphones. This same approach was also used in the Shirley Wind Farm study[14]. All measurement data reported herein are based on an analysis of the noise recordings played back in the WIA laboratory in Emeryville, California.

[14] Channel Islands Acoustics, et al, A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin, Report No. 122412-1, December 24, 2012.

Measurements at Residences

For measurements conducted at the residences, a microphone was set up inside each residence mounted on a tripod at 4.5 feet above the floor, typically in the middle of the room. The indoor recordings were made in the living room (mostly), dining room or bedroom of the residences. Indoors, the microphone was oriented vertically and covered with a 3-inch-diameter wind screen.

Figure 4 shows the microphone and windscreen mounted on a tripod inside one of the residences.

A second microphone was set up outside of each residence. Following IEC Standard 61400-11, the outside microphone was rested horizontally (i.e., flush mounted) on a ½-inch-thick plywood “ground board” that is 1 meter in diameter. The microphone was oriented in the direction of the nearest visible wind turbine and the ground board was placed in a flat location between the residence and the wind turbines. For a discussion of details of microphone and windscreens used refer to Appendix D. Figure 4 shows the indoor microphone on a tripod. Figure 5 shows the outdoor microphone, secondary windscreen, and ground board outside one of the residences. Inside and outside noise signals were recorded simultaneously to allow for correlation of interior and exterior sound levels during subsequent analysis.

Figure 4 Microphone Inside Residence

Figure 5 Microphone Outside Residence

Proposed Torrey Wind and Campo Wind Project Boundary Ambient Measurements

Two B&K 4193 microphones were used to obtain ambient noise measurements at locations adjacent to the Torrey and Campo project boundaries. The microphones were powered by a B&K Type-5935 power supply and amplifier, with the signals recorded on a RION DA21 recorder. The same type of windscreen and ground board configuration (i.e., primary and secondary windscreen) used for the residential recordings, were also used for the project boundary ambient measurements.

NOISE MEASUREMENT BACKGROUND

Purpose of Measurements

The primary purpose of making the wind turbine noise measurements in 2018, which are reported herein was to determine whether, and at what levels and under what conditions, the Kumeyaay Wind, Tule Wind and Ocotillo Wind WTs generate ILFN, and how far the ILFN is propagated. In light of increasing evidence in the literature that ILFN can affect and harm humans[15,16,17,18,19], along with numerous complaints of health impacts from Boulevard residents[20] since the wind turbines near their respective residences began operating, we had a subsidiary goal to obtain measurements that accurately show the pressure fluctuations in the sound, so as to allow an accurate and robust analysis of the human health and environmental impacts of the ILFN generated.

Another purpose of the current measurements was to document the existing C-weighted, ambient noise levels at several locations on the boundaries of the two proposed wind turbine facilities, Torrey Wind and Campo Wind.

Noise Measurements in Presence of Wind

For a discussion of the effects of local wind on noise measurements and the analysis procedures WI used to minimize wind effects on the measurement refer to Appendix D.

WIND TURBINE OPERATION DURING MEASUREMENTS

Video recordings were made several times during the study period to document the operation of the wind turbines. Using the video recordings, we determined both the rotational speed of the wind turbine rotor (Ω in rpm) and the so-called "blade passage frequency" (f_0, also referred to as "blade passing frequency" or BPF), which is calculated in cycles per second, where $f_0 = N \times \Omega / 60$, and N is the number of blades. For a three-bladed rotor ($N = 3$) the blade passage frequency is given by the equation:

$$f_0 = \frac{\Omega}{20}.$$

Associated with the blade passage frequency are harmonics, which are integer multiples of the blade passage frequency. In this study, we typically observed at least five discrete harmonics in the measurement data. This pattern was also observed in the Shirley Wind Farm study.

The harmonic frequencies are given by:

$$f_n = (n+1) \times f_0 \, , where \; n \geq 1 \, .$$

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[15] Salt, A.N., T.E. Hullar, Responses of the ear to low frequency sounds, infrasound and wind turbines, Hearing Research, 16 June 2010.

[16] Salt, A.N., J.T. Lichtenhan, Reponses of the Inner Ear to Infrasound, Fourth International Meeting on Wind Turbine Noise, Rome, Italy, April 2011.

[17] Salt, A.N., J.A. Kaltenbach, Infrasound from Wind Turbines Could Affect Humans, Bulletin of Science, Technology & Society, 31, 296-302, 2011.

[18] Salt, A.N., J.T. Lichtenhan, Perception-based protection from low-frequency sounds may not be enough, Inter-Noise 2012, New York, New York, August 2012.

[19] Lichtenhan, J.T., A.N. Salt, Amplitude Modulation of Audible Sounds by Non-Audible Sounds: Understanding the Effects of Wind-Turbine Noise, Proceedings of JASA, 2013.

[20] San Diego Reader, Volume 42, Number 34, August 22, 2013.

For example, if Ω = 17 rpm, then f_0 = 0.85 Hz and the frequencies of the first six harmonics (n = 1 through 6) are: 1.7, 2.6, 3.4, 4.3, 5.1 and 6.0 Hz.

Table 4 summarizes a representative selection of the wind turbine speeds observed during the recordings. The average rotational speed for Tule WTs was approximately 14 rpm and for Kumeyaay WTs it was approximately 16 rpm.

Table 4 Rotational Speeds Observed for Nearest Visible Wind Turbines

Facility	Date	Location[1]	Time	Speed (rpm)	BPF (Hz)
Tule Wind (GE Turbines – rated speed of 5.0 to 14.9 rpm)	November 13	Morrison	10:59	14.5	0.72
		Guy	14:37	14.1	0.70
			16:03	14.4	0.72
	November 14	Chase	9:42	13.9	0.69
			10:15	13.9	0.69
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	November 13	Guy	15:25	16.6	0.83
	November 14	Chase	10:17	15.8	0.79

[1] Locations refer to where video was recorded
[2] Based on observed rotor speeds during recording

Most WTs at Kumeyaay were observed to be operating from the start of recording on 11/13 through the last recording on 11/16. Approximately seven (7) Kumeyaay WT located approximately in the center of the array of WTs were not operating for all or most of this time period. On the morning of 11/17 it was observed that the WTs at Kumeyaay were not operating during the time the last recording was being made.

Visual observation indicated essentially all the WTs at Tule were operating 11/13 through 11/16. On the morning of 11/17 it was observed that the WTs at Tule that were visible from the last measurement location were not operating during the time the last recording was being made. However, the noise measurement data from that morning would indicate that some of the Tule WTs were operating. It is possible that only a few WTs at the northern of Tule Wind were operating, which the noise data seems to indicate.

As far as could be discerned by visual observation the WTs at Energia Sierra Juarez were not operating on the morning of 11/17 during the last recording. Information concerning operation of WTs at Ocotillo indicated that on the morning of 11/17 WTs there started operating at 7:54 am, which was just before the start of the last recording.

METEOROLOGICAL DATA

Weather Underground[21] is a source for local weather data including wind speed and direction, temperature, precipitation, and atmospheric pressure. The closest weather monitoring station to Boulevard is approximately 12 miles away in Campo. Weather Underground data are archived by Meso West[22] from which we obtained meteorological data for the days of noise recordings. The hourly wind speeds are plotted in Appendix B for the days of measurement (November 13 through 17).

On the 13th and 14th wind speeds ranged from 15 to a high of 45 mph. Starting on the morning of the 15th wind speeds decreased. From the 13th through 6am on the 15th the wind was primarily out of the northeast at times varying from NNE to ENE. Wind speeds decreased on the 15th through the morning of the 17th with the wind direction primarily continuing from the NE.

METHOD OF ANALYSIS OF RECORDED DATA

The 15 to 20-minute recordings were subsequently analyzed in the WIA laboratory with a Larson Davis type-2900 2-channel FFT analyzer. We first viewed each recorded sample in digital strip chart format to visually locate periods of lower local wind gusts to minimize low-frequency wind pressure transient effects on the data. We set the FFT analyzer for 40-Hz bandwidth, with 400-line and 0.1-Hz resolution. We used linear averaging. A Hanning window was used during a one- to two-minute, low-wind period to obtain an “energy average” with maximum sampling overlap. We stored the results for each sample, including autospectra, coherence, and coherent output power for both channels of data at the residential locations (i.e., indoors and outdoors). We also obtained autospectra for the reference locations.

Autospectra and Coherent Output Power

One of the strengths of our indoor-outdoor sampling procedure is that it made possible the use of what is called the “coherent output power” to minimize the effect of the low-frequency wind pressure transients caused by local wind gusts. For a discussion of coherent output power and its applicability to ILFN noise measurements refer to the WI 2014 report in Appendix D.

Sound Level Correction Due to Use of Ground Board

For a discussion of why it is not necessary to make a correction to ILFN noise measurement data when using a ground board refer to the WI 2014 report in Appendix D.

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[21] https://wunderground.com

[22] https://mesowest.utah.edu/

NOISE MEASUREMENT RESULTS

Plots of coherent output power are provided in Appendix C. Before reviewing the spectral data from 2018, it is instructive to first re-examine the spectra measured in 2013 at the Live Oak Springs Resort when there was wind at the Kumeyaay turbines (determined from observing the closest turbine rotating at the time), but virtually no local wind at the recording microphone. This 2013 measurement clearly demonstrates and establishes the validity of noise measurement results using coherent output power.

ILFN Data from 2013 -- Live Oak Springs Resort Measurements

Plots of the coherent output power spectra measured inside residences are provided in Figures C-1 and C-2. Live Oak Springs Resort is somewhat sheltered from wind but has a direct line of sight to the closest Kumeyaay wind turbine 5,950 feet away. Looking at Figure C-1, it is evident in the coherent output spectrum for both indoor and outdoor measurements that the discrete frequencies predominating in the infrasound range correspond to the blade passage frequency of the nearest wind turbine (0.8 Hz) and its first five harmonics (1.6, 2.4, 3.2, 4.1 and 4.9 Hz). A blade passage frequency of 0.8 Hz corresponds to a rotational speed of 16 rpm. We note that the indoor levels at these frequencies are slightly higher than the outdoor levels, an indication of possible amplification associated with the building structure.

Figure C-2 presents the coherence of the indoor to outdoor signals. At the blade passage frequency (0.8 Hz) and in the range of 1.6 to 5 Hz (including the first five blade passage frequency harmonics of 1.6, 2.4, 3.2, 4.1 and 4.9 Hz), the coherence is 0.75 or greater, indicating a strong correlation between indoor and outdoor sound levels.

A high coherence indicates that two signals are strongly correlated and contain the same frequency content. This is what one would expect from a large rotating mechanical device such as a wind turbine that produces a steady, tonal (periodic) sound, whereas the effects of wind are random in time and space for signals from two different microphones, one of which is indoors. Thus, there will in general be a low coherence associated with the wind and its effects on the two different signals averaged over time. The correlation of the wind effects in the indoor and outdoor signals should be weak for the random effects of the wind. Averaging the total microphone signal over time and weighting the result by the coherence results in a diminished contribution from the wind, because of the low coherence of the wind effects.

Inside the guest cabin at Live Oak Springs Resort, sound pressure levels in the infrasound range measured between 45 and 49 dB. The outside sound pressure levels were somewhat lower in the ILFN range, seeming to indicate an amplification occurring from outside to inside, which became even more pronounced in the range of 5 to 8 Hz.

ILFN Data from 2018 Residential Measurements

There were two wind turbine facilities in 2013 and are now there are four wind turbine facilities with a combined total of two hundred and forty-one (241) WTs within 11 miles of the residences at which recordings were made in 2018. Each of the current WT facilities has an array of WTs made by a different manufacturer or installed with a different WT model. Consequently, the WTs at each facility have different rotational speeds.

It is not possible to simultaneously observe all the WTs at the four facilities and the rotational speeds of individual WTs vary over time depending on local wind conditions. Furthermore, the WTs at Kumeyaay Wind and Tule Wind operate at rotational speeds that are not too dissimilar (i.e., about 14 and 16 rpm respectively). These factors make linkage of ILFN at certain frequencies with a specific wind turbine facility somewhat more challenging than in 2013.

It should be clear from the discussion above that well-defined spectral peaks at frequencies less than 10 Hz are generally mechanically generated infrasound (IS), and at frequencies less 5 Hz the IS is obviously generated by WTs. We note that in general for large, industrial wind turbines the highest operational speed is 20 rpm, which corresponds to a BPF of 1.0 Hz. Consequently, peaks below 1.0 Hz are clearly BPFs of various WTs, and peaks that are multiples of a BPF between the frequencies of 1.0 Hz and 10 Hz are harmonics of BPF, although harmonics that appear in the spectral data are typically limited to about 5 Hz.

The turbine rotational speeds observed in 2018 for Tule Wind and Kumeyaay Wind (about 14 and 16 rpm respectively) correspond to BPFs of 0.7 and 0.8 Hz respectively. In the 2013 measurements, the Kumeyaay WTs were observed to operate at a rotational speed ranging from 16.3 to 17.3 rpm or slightly higher than observed in 2018.

In 2013, the Ocotillo wind turbines were observed to have a wide range of rotational speeds varying from 6.5 to 16.2 rpm. This wide range seemed to be related to the local wind conditions, which varied significantly over the period measurements were made. Using this information on WT rotational speeds, we can identify which WTs in 2018 are mostly like associated with the spectral peaks in the 2018 data plots.

Plots of the coherent output power spectra measured inside residences are provided in Figures C-3 through C-17. It is apparent from the data plots for the fifteen residences that there are reoccurring spectral peaks at specific frequencies at frequencies less than 5 Hz. Although not all the peaks occur for all the residences, where they are present, they are present regardless of time of day or location, which is a clear indication of IS generated by WTs.

Infrasound Data for Residences

Table 5 lists the frequencies of the infrasound (IS) peaks present in the spectral plots for each of the fifteen residences and the WTs that generate the IS. The peaks indicated correspond to turbine blade rotational speeds of 7.8, 9.8, 11.7, 13.7 and 17.6 rpm respectively. The observed rotational speeds of turbines in Kumeyaay Wind and Tule Wind indicated in Table 4 above, represent a snapshot in time of a couple of WTs. They are not meant to be representative of all to the WTs in a wind farm nor are they representative of speeds over many hours since wind conditions change. WTs in a wind farm tend to operate at the same rotational speed at any given time. However, it should be expected there will be some variation in speed of any two WTs, especially where there are many WTs spread out over some distance.

As indicated in the column headers in Table 5, certain BPF frequencies are identified with either Kumeyaay Wind (KWT), Tule Wind (TWT) or Ocotillo Wind (OWT). Since Ocotillo WTs (OWT) operate over a wide range of speeds and specifically less than 10 rpm, we can conclude that the first two frequencies (0.39 and 0.49 Hz) are most likely generated by Ocotillo WTs as well as the third frequency (0.59 Hz). Kumeyaay WTs (KWT) and Tule WTs (TWT) have been observed to operate over a much narrower range of speeds. The next highest BPF (0.68 Hz) is associated with Tule Wind IS. The highest BPF (0.88 Hz) is associated with Kumeyaay Wind since it is the closest frequency to the observed BPF shown in Table 4.

Other than to determine if they were operating (i.e., turbine blades could be seen to be rotating), visual observation of rotational speeds of ESJ WTs was difficult given the distance even at the closest residence (Ostrander) to ESJ and when there was intervening terrain between the residence measurement location and ESJ. Although clear evidence of ESJ IS was not indicated in the measured spectral data, under other wind conditions ESJ IS may impact the residences included in this study.

Table 5 IS Spectral Peaks Corresponding to WT BPFs

Date	Residence	BPF range Peak (Hz) OWT	OWT	OWT	TWT	KWT
13-Nov	Morrison					0.88
	Skains		0.49		0.68	
	Daubach	0.39			0.68	
	Guy				0.68	0.88
14-Nov	Chase	0.39				
	Anon Res 1[1]					
	Anon Res 2			0.59		
	Morgan	0.39		0.59		
	McKernan	0.39			0.68	0.88
15-Nov	Anon Res 3		0.49			
	Ostrander				0.68	
	DeGroot		0.49		0.68	0.88
	Blaisdell	0.39				0.88
	Tisdale	0.39				
17-Nov	Strand	0.39			0.68	0.88

[1] No BPF peak present, but several harmonics are (e.g., 1.46 Hz and higher)

It might be asked why all the BPF peaks don't occur at all the locations measured if the WTs are operating. The answer is that the distance from the measurement location to a set of WTs, the orientation of WT blades to that location, the possible shielding provided by the intervening terrain, and atmospheric conditions can affect the sound pressure level at a location. There may also be some cancellation of IS at certain frequencies emitted by different wind turbines due to some or all these factors.

Once peaks associated with BPFs are identified it is possible to identify peaks corresponding to their harmonics (i.e., peaks at frequencies which are integer multiples of the BPF). Any peak that corresponds to a rotational speed greater than 20 rpm (i.e., 1.0 Hz) is clearly a harmonic of one of the BPFs, since the highest rotational speed of the WTs in the area (including Ocotillo and Energia Sierra Juarez) is 19 rpm. Table 6 lists the more prominent harmonic peaks observed in the spectral plots up to a frequency of 1.6 Hz. It is not uncommon for harmonics to be present and BPF peaks missing in the spectrum. Harmonic peaks also tend to be more pronounced than BPF peaks.

Table 6 IS Spectral Peaks Corresponding to Harmonics of WT BPFs

Nov. Date	Residence	Harmonic Range								
		Peak (Hz)								
		OWT[1]	OWT[2]	OWT[3]	OWT[4]	OWT[5]	TWT[6]	OWT[7]	OWT[8]	TWT[9]
13	Morrison							1.46		
	Skains		0.98				1.37		1.56	
	Daubach		0.98				1.37			
	Guy							1.46		2.15
14	Chase		0.98		1.17			1.46		
	Anon 1	0.78					1.37			2.15
	Anon 2			1.07						
	Morgan	0.78	0.98					1.46		2.15
	McKernan					1.27				2.15
15	Anon 3	0.78		1.07		1.27		1.46		2.15
	Ostrander				1.17					
	DeGroot			1.07		1.27				2.15
	Blaisdell			1.07			1.37			
	Tisdale	0.78	0.98				1.37			2.15
17	Strand			1.07			1.37			

[1] 1^{st} harmonic of 0.39 Hz (7.8 rpm)
[2] 1^{st} harmonic of 0.49 Hz (9.8 rpm)
[3] 2^{nd} harmonic of 0.39 Hz (7.8 rpm) or 1^{st} harmonic of 0.59 Hz (11.8 rpm)
[4] 1^{st} harmonic of 0.54 Hz (10.8 rpm)
[5] 1^{st} harmonic of 0.64 Hz (12.8 rpm)
[6] 1^{st} harmonic of 0.68 Hz (13.6 rpm)
[7] 2^{nd} harmonic of 0.49 Hz (9.8 rpm)
[8] 3^{rd} harmonic of 0.39 Hz (7.8 rpm)
9 2^{nd} harmonic of 0.72 Hz (14.4 rpm)

The peaks at 2.15 Hz are identified as the 2^{nd} harmonic of a BPF of 0.72 Hz or 14.4 rpm even though this BPF doesn't appear in the spectra. Since the observed rotational speed of the Tule WTs was on average 14, we can associate these peaks with Tule WTs.

Table 7 lists each of the residential measurement locations, along with their distance from the nearest wind turbine, the highest measured indoor sound pressure levels, and the frequency of those peak sound pressure levels of ILFN and whether it corresponds to a BPF or harmonic.

We note that during the measurement on the morning of 11/17, Ocotillo was starting to operate. The peak at 0.39 Hz corresponds to an Ocotillo WT BPF, whereas the peak at 0.68 Hz corresponds to a Tule WT BPF. It is most likely that a few WTs at Tule were operating during the measurements, even though the Tule WTs we could see from our last measurement location were not operating. The sound pressure level at 0.68 Hz measured at Strand is 35 dB, which would, given the distance to the Strand residence, be expected if only a few Tule WTs on the northern end of the facility were operating.

The peaks at 0.98 Hz are identified as 1st harmonics corresponding to a BPF of 0.49 or 9.8 rpm. From the 2014 report this was identified with Ocotillo WTs. It was also observed in 2013 as noted above that not all Ocotillo WTs operate at the same rotational speed at the same time. The operational speed of individual WTs depends on their location and the local wind conditions, which may vary. Consequently, the highest IS level of 66 dB measured in 2018 is most likely generated by Ocotillo Wind WTs.

Table 7 Summary of Wind Turbine IS Inside Residences

Residence	**Distance[1]**	**Highest Sound Pressure Spectrum Level Indoors[2,3]**	**Peak Frequency (Hz)**	**Rotor Rotational Component**
Morrison	11 miles	62	0.78	1st Harmonic OWT
Skains	11 miles	63	0.98	1st Harmonic OWT
Daubach	12 miles	63	0.98	1st Harmonic OWT
Guy	4,430 feet	59	2.15	2nd Harmonic TWT
Chase	11 miles	66	0.98	1st Harmonic OWT
Anon Res 1	1.7 miles	52	2.15	2nd Harmonic TWT
Anon Res 2	1.5 miles	48	2.15	2nd Harmonic TWT
Morgan	1.6 miles	53	2.15	2nd Harmonic TWT
McKernan	4.7 miles	49	0.88	BPF KWT
Anon Res 3	11 miles	47	0.78	1st Harmonic OWT

Ostrander	8.0 miles	50	0.68	BPF TWT
DeGroot	4,970 feet	61	0.88	BPF KWT
Blaisdell	3.87 miles	63	0.88	BPF KWT
Tisdale	16 miles	49	0.98	1st Harmonic OWT
Strand	6.4 miles[4]	35	0.68	BPF TWT

[1] Distance to the closest wind turbine in WT farm associated with highest spectral peak

[2] Decibels (re: 20 μPa)

[3] All data are coherent output power sound levels

[4] Estimate

In summary, putting aside the measurement on 11/17, the sound pressure level of the dominant peaks of the infrasound measured in 2018 were in the range of 47 to 66 dB. On the 17th the levels measured at Strand residence were considerably lower (i.e., 35 dB), because no Kumeyaay WTs were operating and only a few of the most distant Tule Wind WTs along with a few Ocotillo WTs were likely operating. It is important to note again that the measured levels of IS only represent the wind conditions which existed at the time of the recordings. Higher wind speeds exist at times and typically generate higher levels of IS.

Low Frequency Noise Data for Residences

Several residents stated that they are bothered most noticeably in the evening and night by a low frequency rumble that is generated by the WTs. Some of the residents describe the noise they hear as being like noise from jets flying overhead that never land. One property owner reported losing two tenants to the disturbance from turbine noise. We note that all our 2018 measurements were conducted during the day. LFN may not be as pronounced in the measured spectra as it would be at night.

Low frequency noise occurs in the range of 20 to 100 Hz. We see examples of LFN in the spectra from both 2013 and 2018. There is a substantial peak at 27 Hz in the LOSR cabin measurements from 2013 in Figure C-1 in Appendix C. There were also other peaks in the spectra from 2013, that can be seen in Appendix C. For example, at one on the Kumeyaay Wind reference measurement locations in 2013, there was a substantial peak at 34 Hz. At the Guy residence in 2018, we see in Figure C-18 a very substantial peak at 20.4 Hz.

Amplitude Modulation Noise Levels for Tule Wind

While WI was making recordings, several of the residents commented on what they characterized as a "whooshing" sound from the WTs that bothered them. Wilson Ihrig noticed this sound at several of the measurement locations in the Ribbonwood Road area. It was most pronounced at the Guy residence, the closest measurement to the Tule WTs. An analysis of the Guy residence recording clearly indicates amplitude modulation (AM).

The phenomenon of AM has been identified and documented by others (e.g., 23,24,25) in the past although all do not use the same descriptive labels. Stigwood, et. al, discuss two types of amplitude modulation, "lashing" and "thumping", where the former is centered around 125 Hz and the latter around 315 Hz. Others have referred to AM as a "swishing" sound. Regardless of the onomatopoetic label used, AM is the fluctuation of sound, in this case air flow turbulence noise generated at the WT blades' trailing edge[25], modulated (changing sound level) at the frequency of the BPF.

Cooper defines "excessive modulation" as a peak-to-peak variation of 4 (dBA) or more and that such situation would require a 5-dBA penalty to the measured level. Oerlemans indicates the AM from one blade may be up to 5 dB, but that the effective sound level variation will be much smaller because of the summation of the noise from three (3) blades. Oerlemans defines what he calls "enhanced amplitude modulation," which are swish amplitudes that vary by more than that predicted by a standard swish model (i.e., 6 dB).

Kim, et.al.[26] have developed a noise prediction model for amplitude modulation from large WTs. The authors' noise model predicts that the overall sound pressure level is greatest on-axis (in the direction of the turbine rotor, which is the direction that the wind is blowing) and that the amount (or depth) of modulation is greatest in the plane of the turbine blades (perpendicular to the rotor). Their prediction is that the modulation depth is by from 1 to 3 dB greater in a stable atmosphere, which can have a greater wind gradient than in an unstable atmosphere. From their prediction model, Kim et.al. conclude that amplitude modulated, wind turbine noise can be perceived up to 1 mile away, which implies residents living up to this distance and possibly further may feel annoyance due to the perception of amplitude modulation.

We analyzed a sample of recorded noise from the Guy locations. Figure C-18 shows the 1/3-octave filtered levels (dB) of the same sample. Although there is AM at 160, 200 and 250 Hz, the strongest AM is at 200 Hz. At 200 Hz the AM ranges from 8 to 11 dB. If we consider the A-wtd level variation as shown in Figure C-19, ranges from 3 to 9 dBA with the typical variation of from 5 to 6 dBA. Consequently, under either definition (Cooper or Oerlemans) of the amount of AM, the measured level at the Guy residence would be considered excessive.

---

[23] Stigwood, M., S. Large, and Duncan Stigwood, Audible amplitude modulation – results of field measurements and investigations compared to phyco-acoustical assessment and theoretical research, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

[24] Cooper, S., Hiding wind farm noise in ambient measurements – Noise floor, wind direction and frequency limitations, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

[25] Oerlemans, S., An explanation of enhanced amplitude modulation of wind turbine noise, report for the National Aerospace Laboratory, July 2011.

[26] Lee, Seunghoon, H. Kim, Kyutae Kim, and Soogab Lee, Perception of amplitude-modulated noise from wind turbines, 17th International Congress on Sound and Vibration, Cairo, 18-22 July 2010.

Ambient Noise Data for Torrey and Campo Project Boundaries

The Use Permit for Torrey Wind is contingent on the project complying with a San Diego County Zoning Ordinance related to large wind turbines[27]. The ordinance states: "the C-weighted sound level from each large wind turbine while operating does not exceed the Residual Background Sound Criterion for Wind Energy Facilities by more than 20 decibels as both sound levels are measured at the lot line on which the turbine is located."

The residual background sound level (L_{90}) is defined as "the sound level exceeded for 90 percent of the total measurement period as described in the current edition of Quantities and Procedures for Description and Measurement of the Environmental Sound by the American National Standards Institution. When C-weighted, the L_{90} is denoted L_{C90}.

Recorded samples of ambient noise were analyzed to obtain C-weighted levels. Table 8 list the measured, L_{C90} noise levels.

Table 8 Torrey and Campo Project Boundary, C-weighted Ambient Noise Levels

Location	Nearest Address	L_{C90} (dBC)
Torrey PL1	2948 Ribbonwood Rd	51.4
Torrey PL2	Anon. Residence 2	51.2
Campo PL1	35876 Shockey Trail (one car)	48.2
Campo PL1	35876 Shockey Trail (no cars)	43.7
Campo PL2	Near 37573 Old Hwy 80	46.0
Campo PL3	Hwy 94 at Shasta Way	38.6
Campo PL4	1250 Tierra Hts.	40.6

DISCUSSION OF RESULTS

It is clear from the measured noise data obtained that there is significant wind turbine-generated IS and there are approximately 240 wind turbines in the area at the Kumeyaay, Tule, Ocotillo and Energia Sierra Juarez facilities. This was to be expected as it has been documented by others such as in the Falmouth noise study, the Shirley Wind Turbine study, and by Epsilon Associates.[28] And indeed the measured ILFN levels near Kumeyaay and Tule wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

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[27] Subsection 6952.c.5.f(b) of the San Diego Zoning Ordinance.

[28] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

Both the Falmouth and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth, Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce IS, and whether that IS was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated IS at numerous nearby residences that correlated with residents' reported impacts.

In 2017 a Superior Court Judge in a case[29] involving noise generated by WTs in Falmouth Massachusetts found for the defendants "that the operation of the town's wind turbines and the consequent sound emissions constitute a substantial and unreasonable interference with the Funfars' enjoyment of their property and constitute a nuisance." Brown County Board of Health (Falmouth, Massachusetts) approved a motion[30] that stated: *"To declare the Industrial Wind Turbines at Shirley Wind project in the town of Glenmore, Brown County, WI, a human health hazard for all people (residents, workers, visitors, and sensitive passersby) who are exposed to infrasound/low-frequency noise and other emissions potentially harmful to human health"*.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then demonstrating the potential for annoyance and physiological effects of ILFN from WTs.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay, Tule, Ocotillo and Energia Sierra Juarez facilities. Higher wind speeds generally produce higher overall noise levels and higher levels of IS.

POTENTIAL EFFECTS OF TULE WIND AND CAMPO WIND PROJECTS

Both Torrey Wind and Campo Wind if implemented would install larger wind turbines (i.e., 4.2 MW) than those in Kumeyaay Wind (2.0 MW) and Tule Wind (2.3 MW). As Moller and Pedersen[31] have demonstrated, larger wind turbines are expected to produce higher levels of LFN than wind turbines in the 2.0 MW range. The authors also show that it should be expected that the LFN will shift down in frequency with larger WTs.

The Torrey Wind WT sites have already been designed. A map of Torrey Wind is contained in Appendix E. The zones for WT sites for Campo Wind are indicated in the map in Appendix F. Some of the proposed sites for WTs at Torrey Wind and the zones for WT sites will be

[29] Town of Falmouth (Plaintiff) v. Falmouth Zoning Board of Appeals and Matthew McNamara, Patricia Johnson, Kenneth Forman, Edwin Zylinski, David Haddad and Mark Cool as members of the Falmouth Zoning Board of Appeals and Barry Funfar and Diane Funfar (Defendants), 20 June 2017.

[30] Proceedings of the Brown County Board of Health Meeting, Tuesday, October 12, 2014.

[31] Moller, H. and Christian Sejer Pedersen, Low-frequency noise from large wind turbines, Journal of the Acoustical Society of America, p.3727-3744, **129**(6), June 2011.

much closer than the existing Tule Wind and Kumeyaay Wind WTs to the Guy, Chase, Morrison and Morgan residences as well as other residences in the area. Although actual WT sites have not yet been proposed for Campo it is conceivable that they will be much closer to residences than the Kumeyaay WTs. An example of this is the DeGroot residence and a neighboring residence that could be only hundreds of feet from a Campo WT site.

The Morrisons are considering moving out at great expense due to the current health problems that he and his wife say they are suffering that they attribute to operation of the Kumeyaay Wind and Tule Wind WTs. Tule Wind seems to bother them the most. Other residents indicated they suffer from negative impacts due to ILFN, which effects are greater at night. This phenomenon of increased nighttime effects has been documented in other studies[32,33,34].

NOISE METRICS FOR MEASURING ILFN

There are several noise metrics which are used to quantify environmental noise levels. The most common metric is A-weighting (A-wt). The A-wt curve is shown in Figure 6. The A-wt metric is intended to approximate the loudness sensitivity of the human ear for common environmental sounds in the range of 20 to 20,000 Hz. A-wt at 1 Hz is -149 dB. Hence a noise limit based on A-wt would not be appropriate to address ILFN, a major component of which is infrasound below 20 Hz.

A noise metric sometimes used when there is low frequency noise is the C-weighting (C-wt). While the C-wt metric does attempt to address low frequency noise better than A-wt, it would also not be appropriate for quantifying infrasound, since it still strongly de-emphasizes sound at frequencies below 20 Hz as shown in in Figure 6. C-wt at 1 Hz is -52.5 dB.

One noise metric recently used to quantify ILFN is G-weighting (G-wt). The G-wt measure has been used in Europe. G-wt would certainly be a more representative measure of ILFN than either the A- wt or the C- wt metrics, but as shown in Figure 6 it too de-emphasizes the very low frequency infrasound by -40 dB at 1 Hz.

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[32] Leventhall G, Pelmear P, Benton S. A review of published research on low frequency noise and its effects. London: Report for Department for Environment, Food and Rural Affairs; 2003.

[33] Bakker RH, Pedersen E, van den Berg GP, Stewart R, Lok W, Bouma J. Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. Sci Total Environ. 2012; 425:42–51.

[34] Pedersen E. Health aspects associated with wind turbine noise-results from three field studies. Noise Control Eng. J. 2011; 59:47–53.

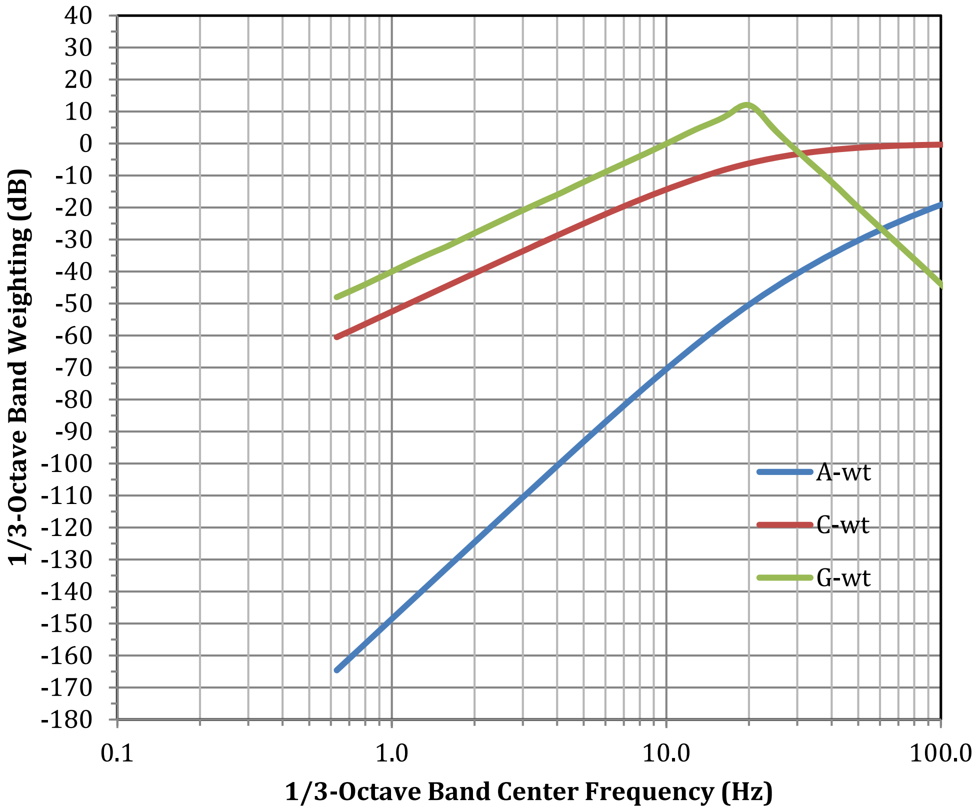

Figure 6 A, C and G Spectral Weighting Curves

CONCLUSIONS

The results of this study conclusively demonstrate that both the Kumeyaay Wind and Tule Wind facilities' wind turbines generate infrasound at residential locations up to 8 miles away based on the current measurements. Ocotillo Wind infrasound from wind turbines 11 to 12 miles away from Boulevard and Jacumba Hot Springs were measured at levels as high as 66 dB. The current data indicates that there is also significant low frequency noise in the range of 20 to 34 Hz. The measurement results also show excessive amplitude modulation of wind turbine noise. Although Energia Sierra Juarez Wind turbine-generated IS was not detected in the current measurements, under different wind conditions (wind direction and speed), high levels of infrasound from those wind turbines could impact the residences in the current study.

TERMINOLOGY

- Autospectrum: The autospectrum is the narrow band, energy average sound pressure level spectrum (in dB) measured for a specific time interval.
- Amplitude modulation: periodic fluctuation of audible noise.
- Coherence: The spectral coherence is a statistic that can be used to examine the relation between two signals or data sets. It is commonly used to estimate the power transfer between input and output of a linear system. If the signals are ergodic, and the system function linear, it can be used to estimate the causality between the input and output.
- Cross-spectrum: In time series analysis, the cross-spectrum is used as part of a frequency domain analysis of the cross correlation or cross covariance between two time series.
- Cycles per second: A unit of frequency, same as hertz (Hz).
- Decibel (dB): A unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm (to the base 10) of this ratio. For sound, the reference sound pressure is 20 micro-Pascals.
- FFT (fast Fourier transform): An algorithm to compute the discrete Fourier transform and its inverse. A Fourier transform converts time to frequency and vice versa; an FFT rapidly computes such transformations.
- ILFN: Infrasound and low frequency noise.
- IS: Infrasound at frequencies lower than 20 Hz.
- LFN: Low frequency noise at frequencies between 20 and 100 Hz.
- Noise level: The sound pressure energy measured in decibels.

APPENDIX A – 2018 NOISE MEASUREMENT LOCATIONS

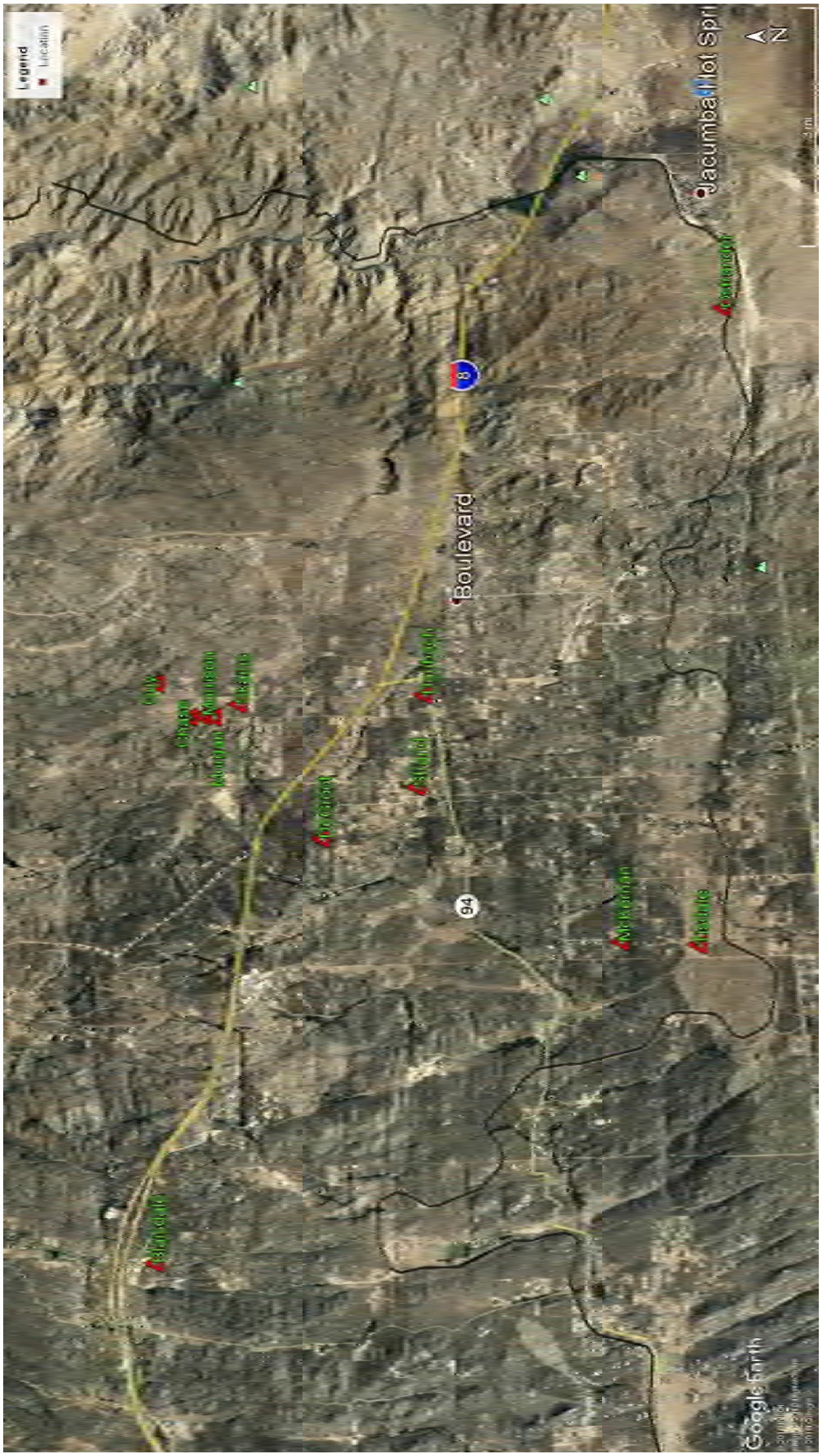

Figure A - 1 Residential Measurement Locations

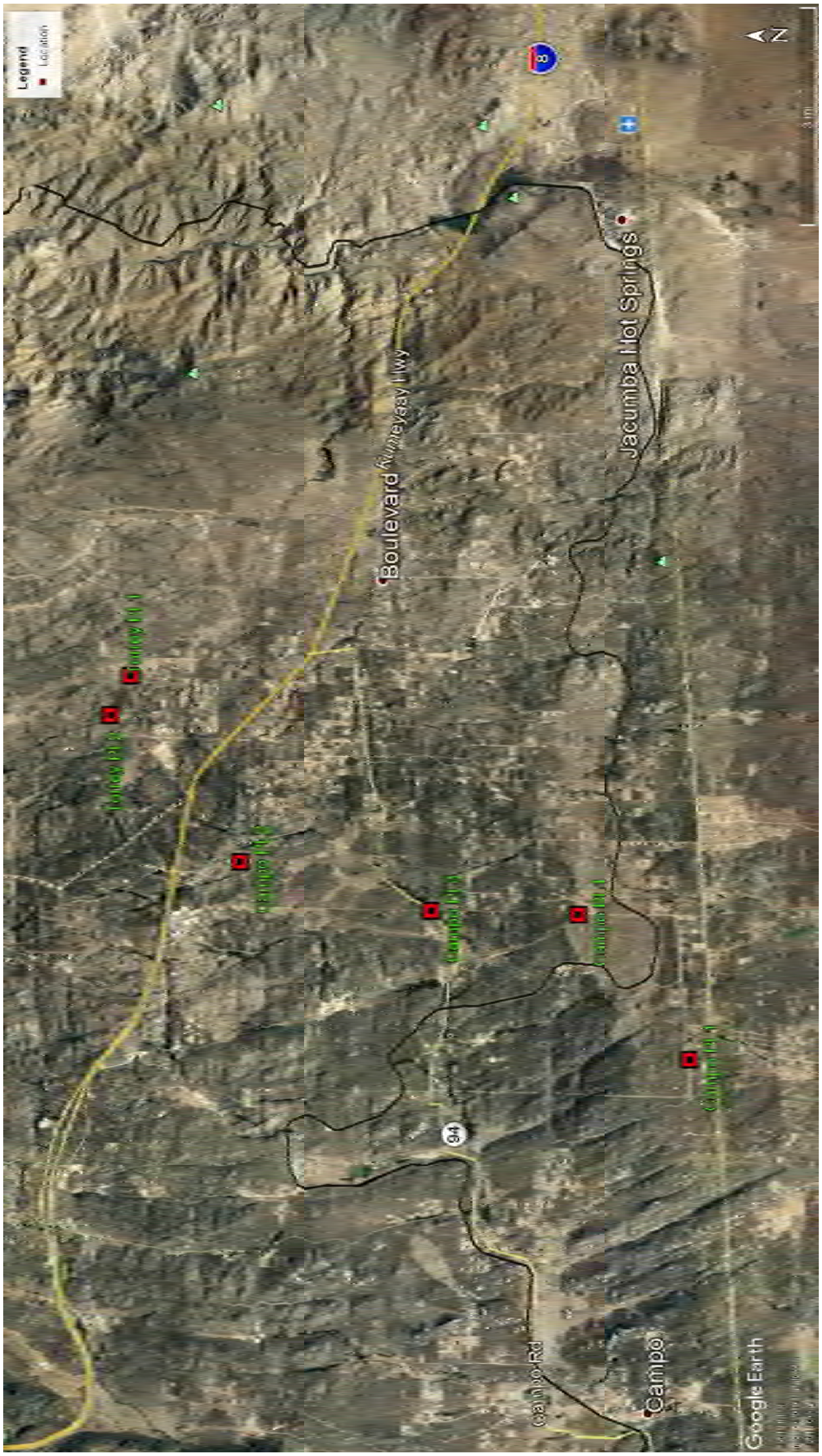

Figure A - 2 Torrey Wind and Campo Wind Boundary, Ambient Noise Measurement Locs

APPENDIX B – METEOROLOGICAL DATA

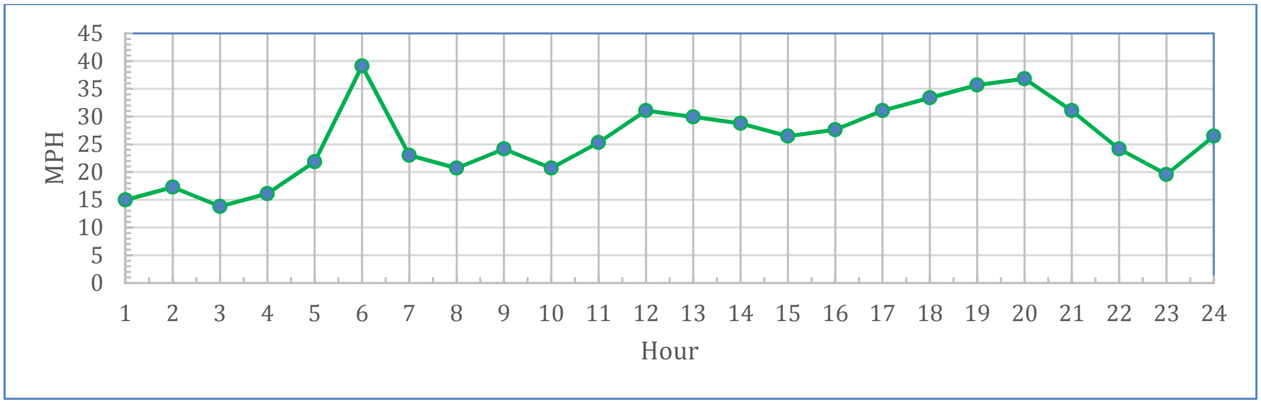

Figure B - 1 Wind Speed for Boulevard Area 11/13/18

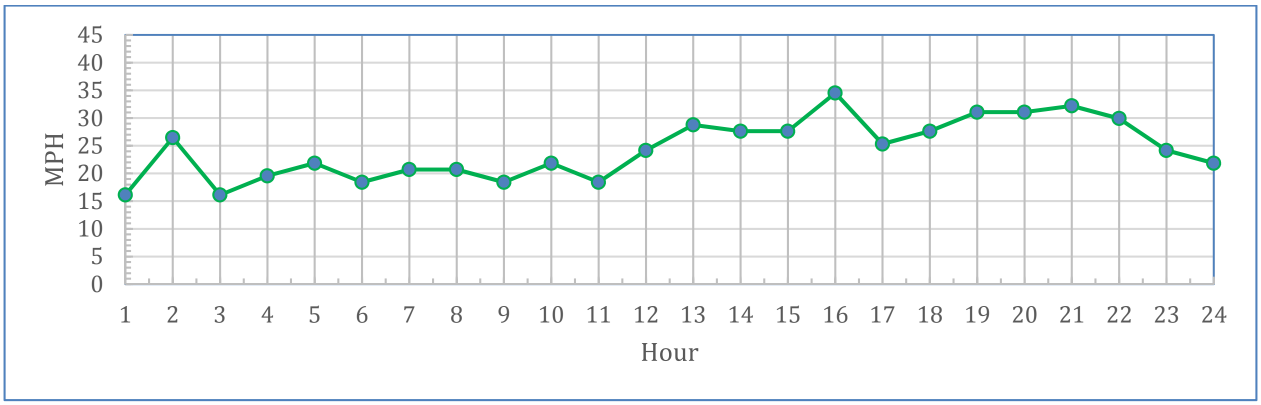

Figure B - 2 Wind Speed for Boulevard Area 11/14/18

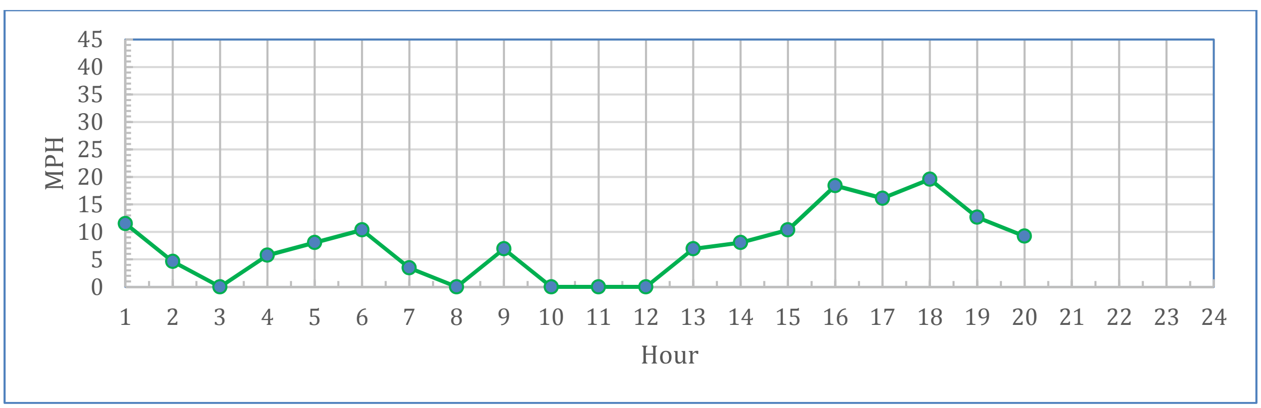

Figure B - 3 Wind Speed for Boulevard Area 11/15/18

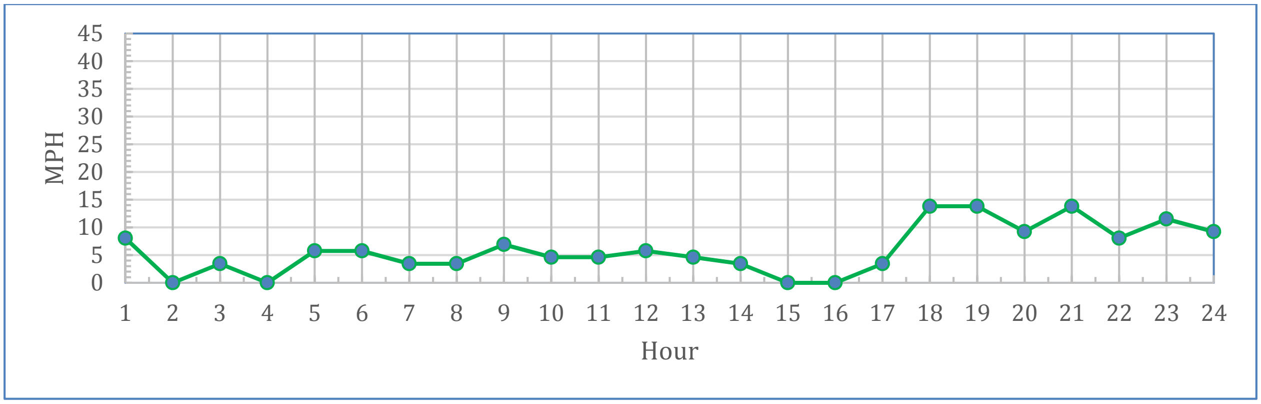

Figure B - 4 Wind Speed for Boulevard Area 11/16/18

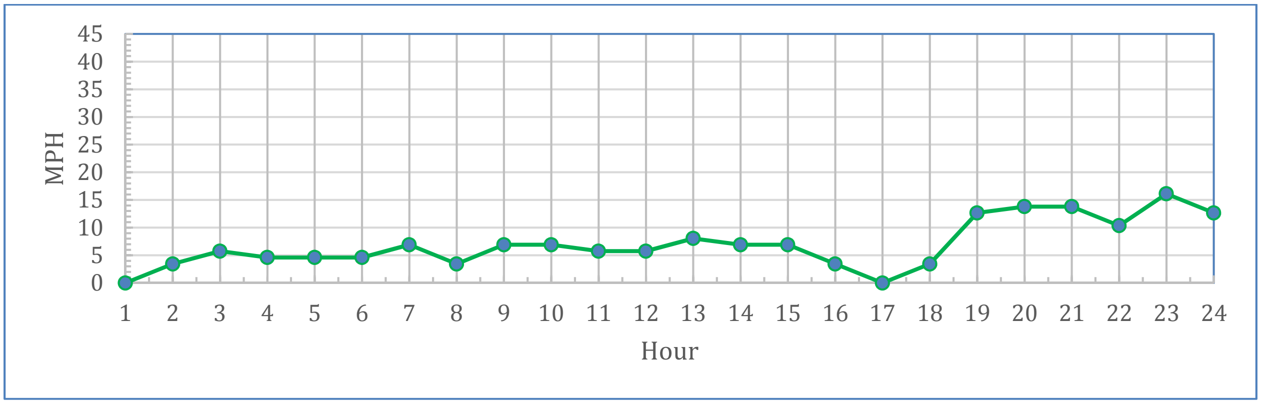

Figure B - 5 Wind Speed for Boulevard Area 11/17/18

APPENDIX C – 2018 NOISE MEAUREMENT DATA

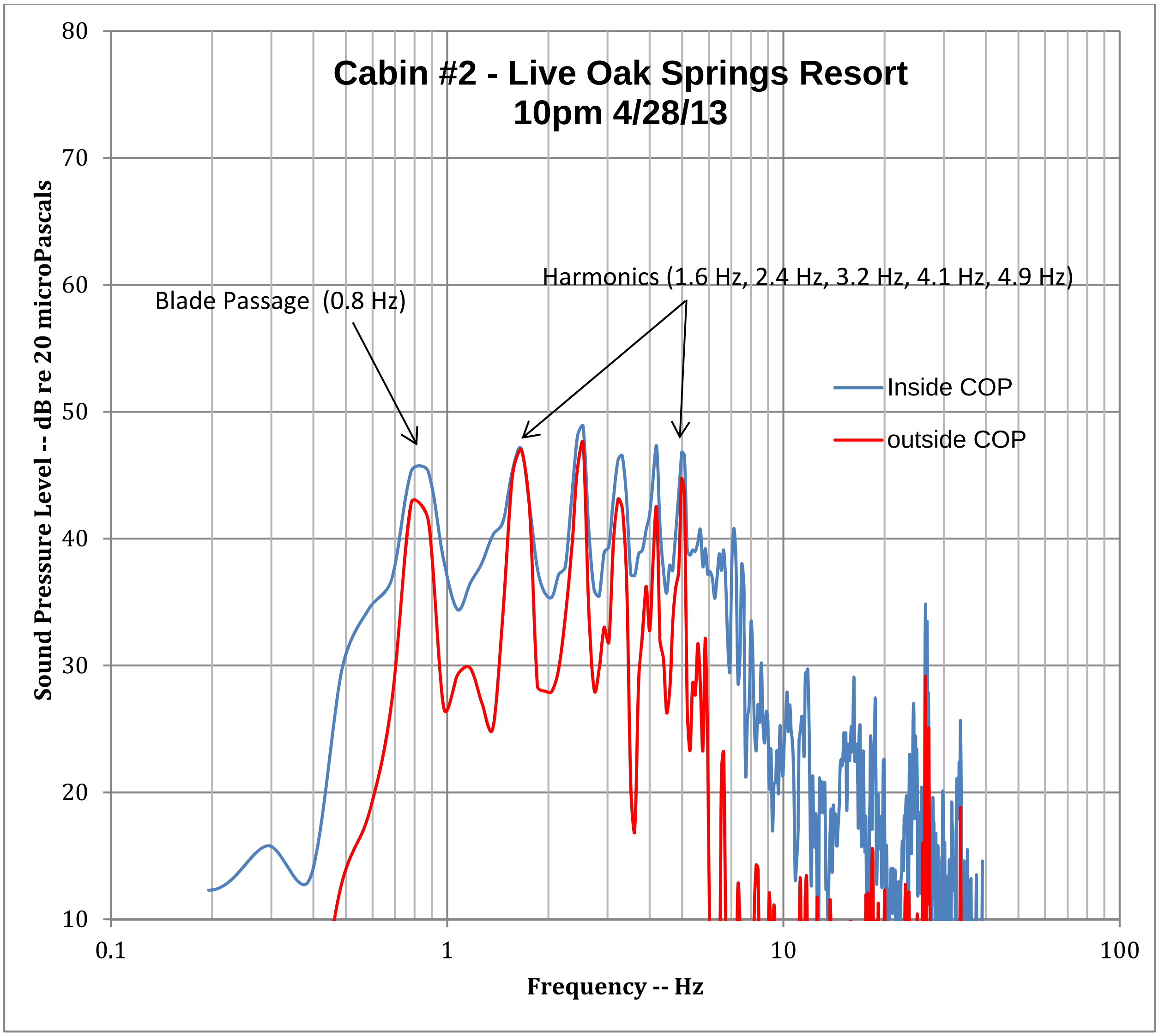

Figure C - 1 Cabin #2 at Live Oak Springs Resort – Coherent Output Power

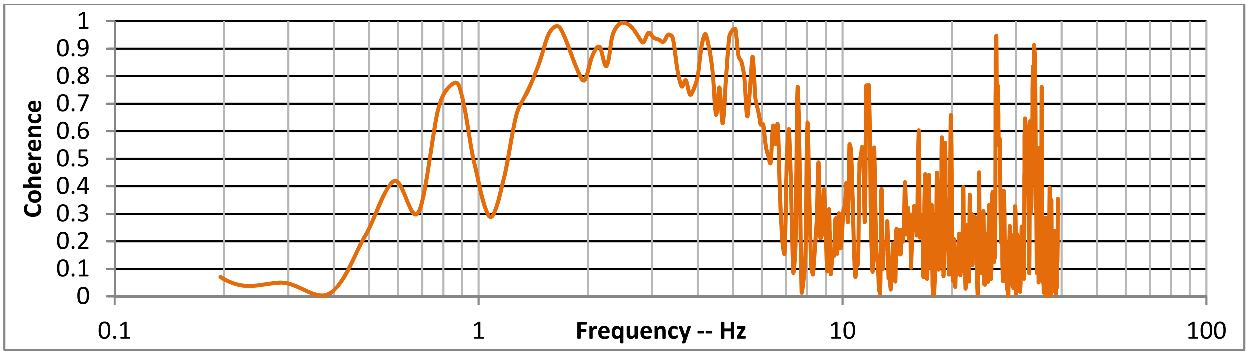

Figure C - 2 Cabin #2 at Live Oak Springs Resort – Coherence

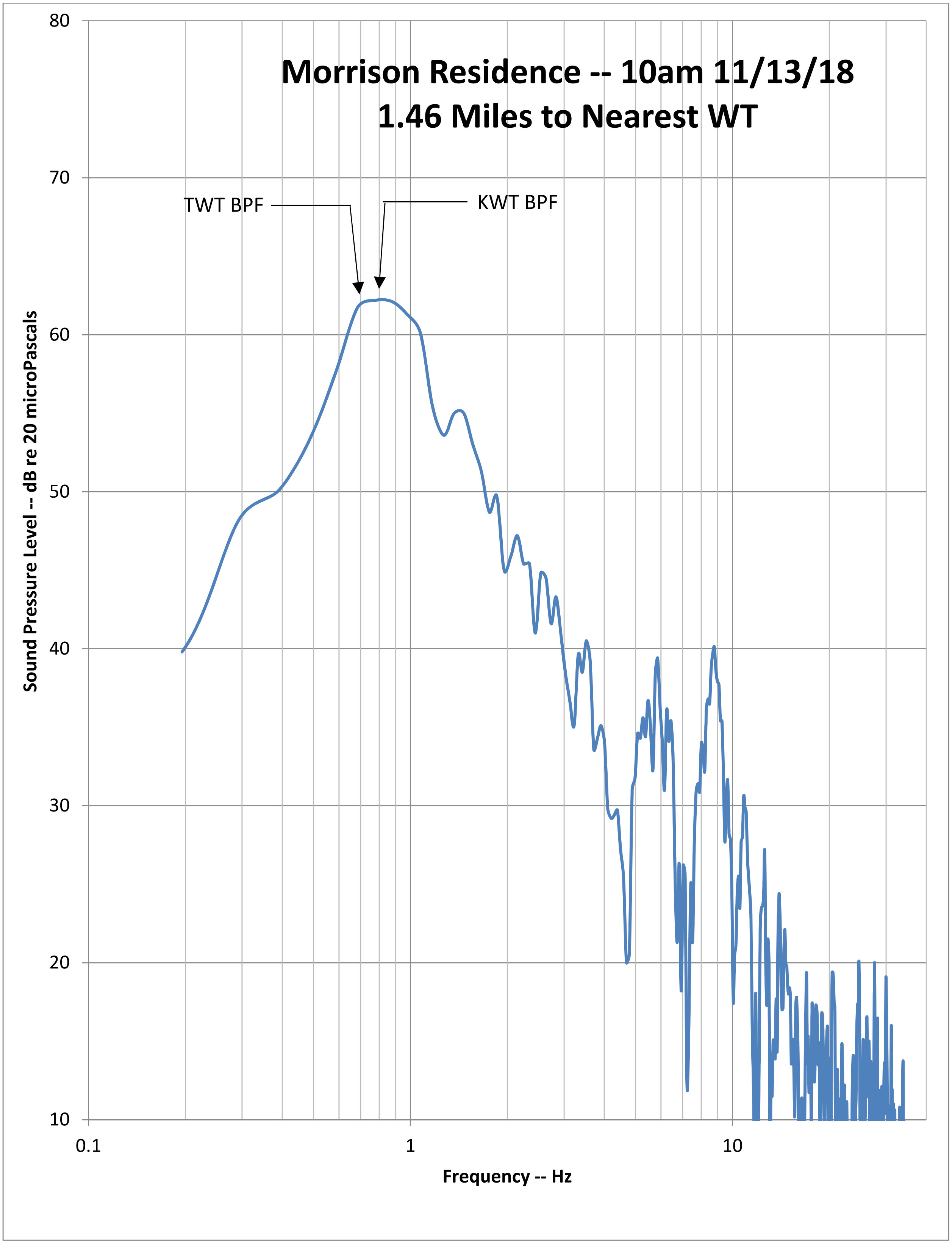

Figure C - 3 Morrison Residence

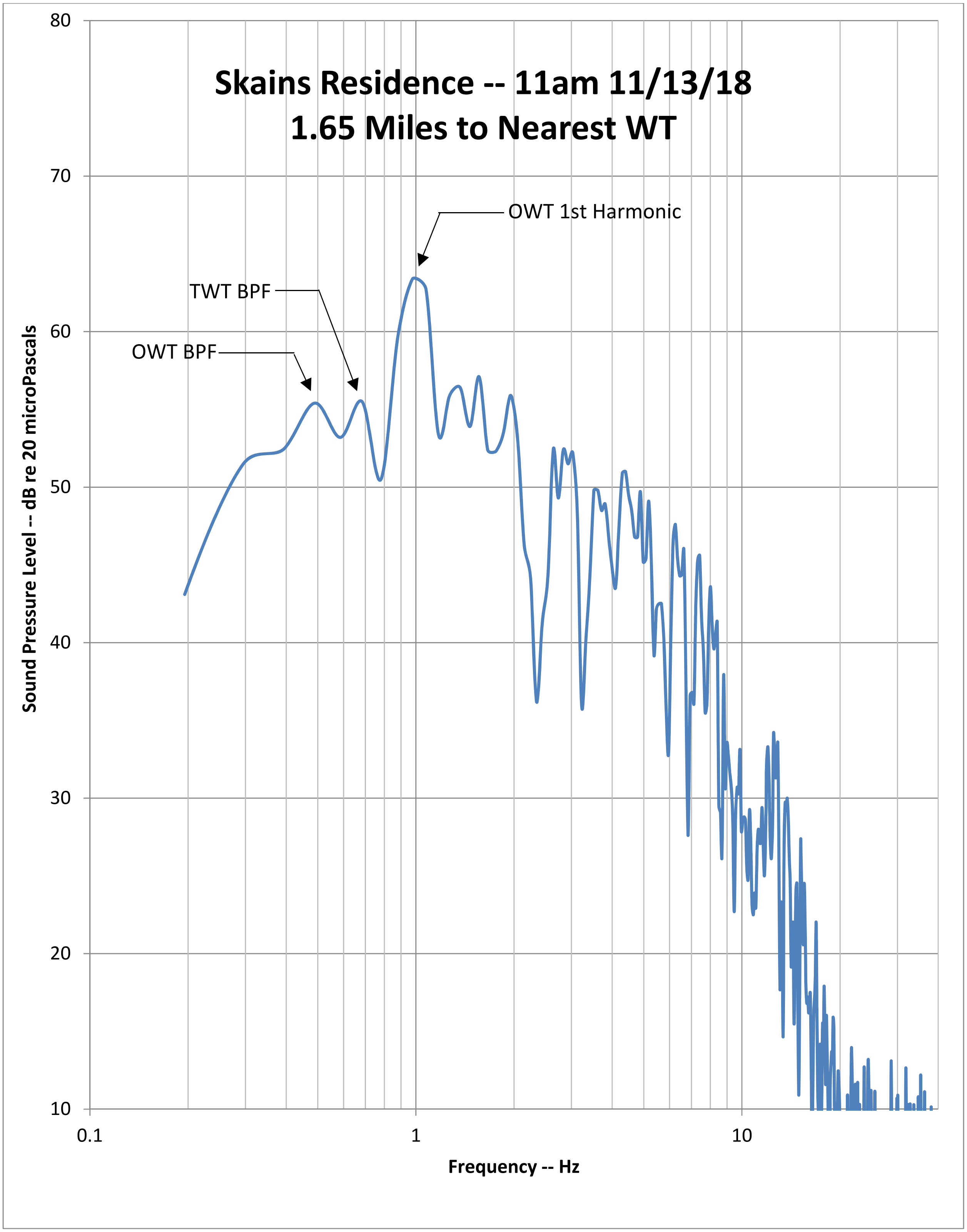

Figure C - 4 Skains Residence

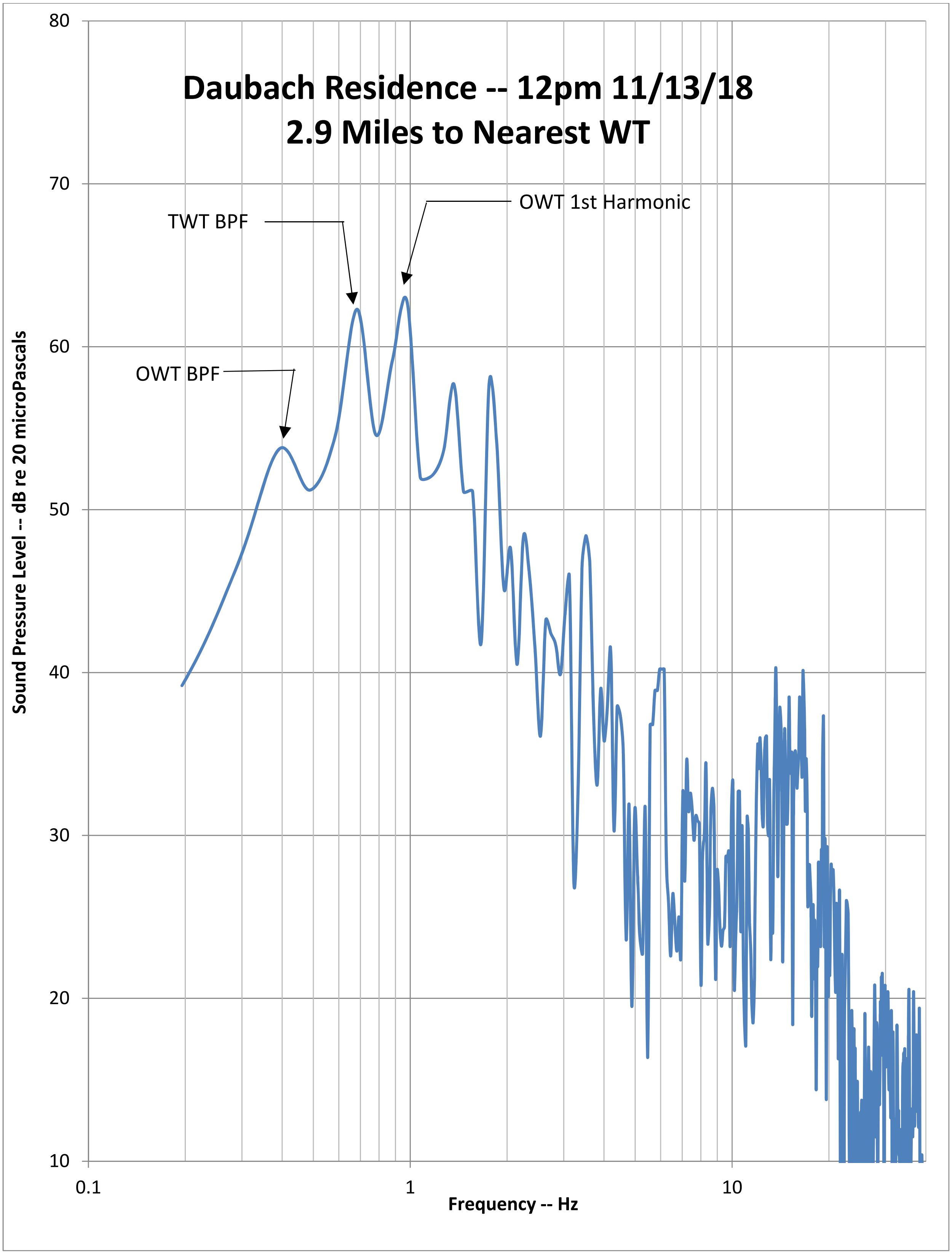

Figure C - 5 Daubach Residence

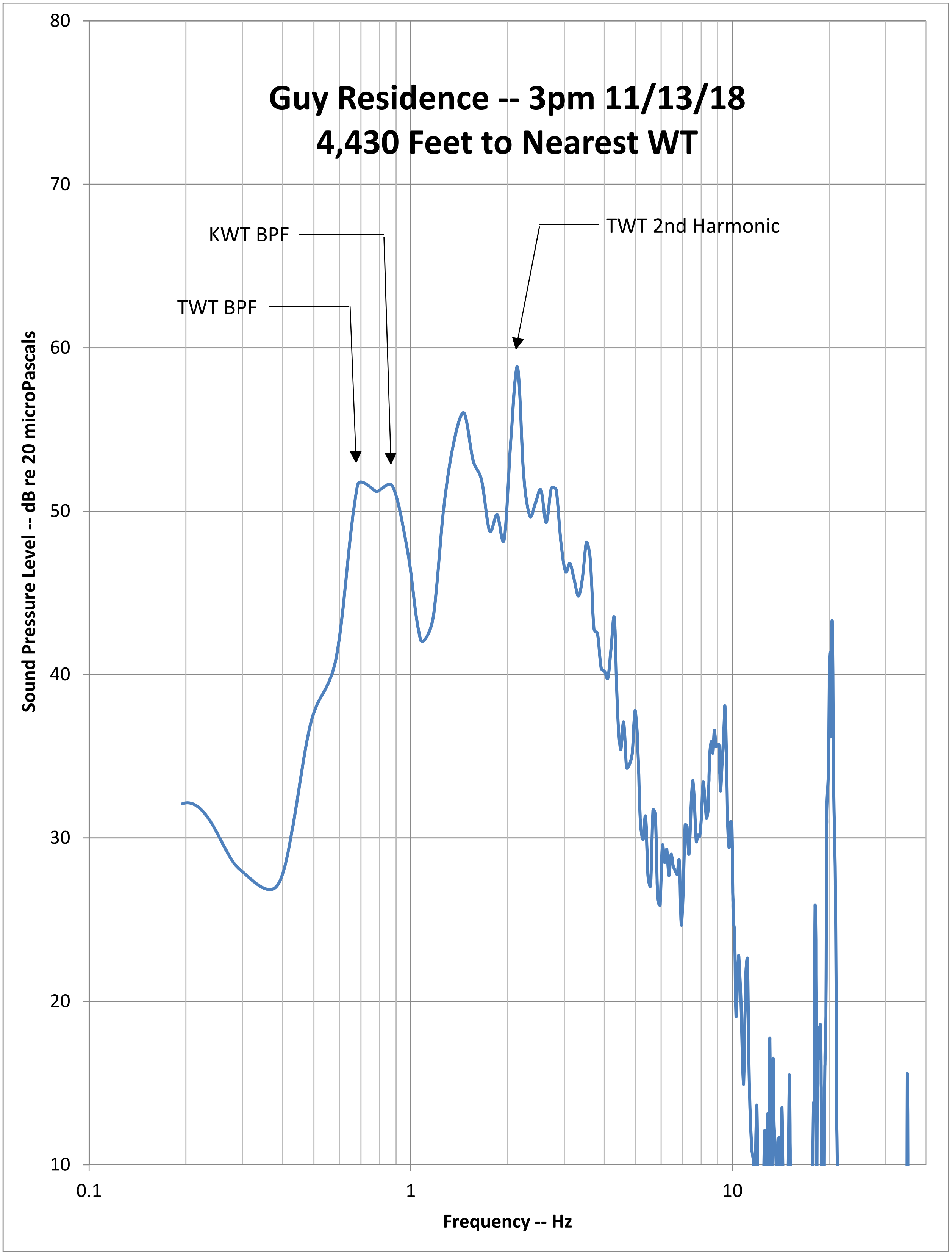

Figure C - 6 Guy Residence

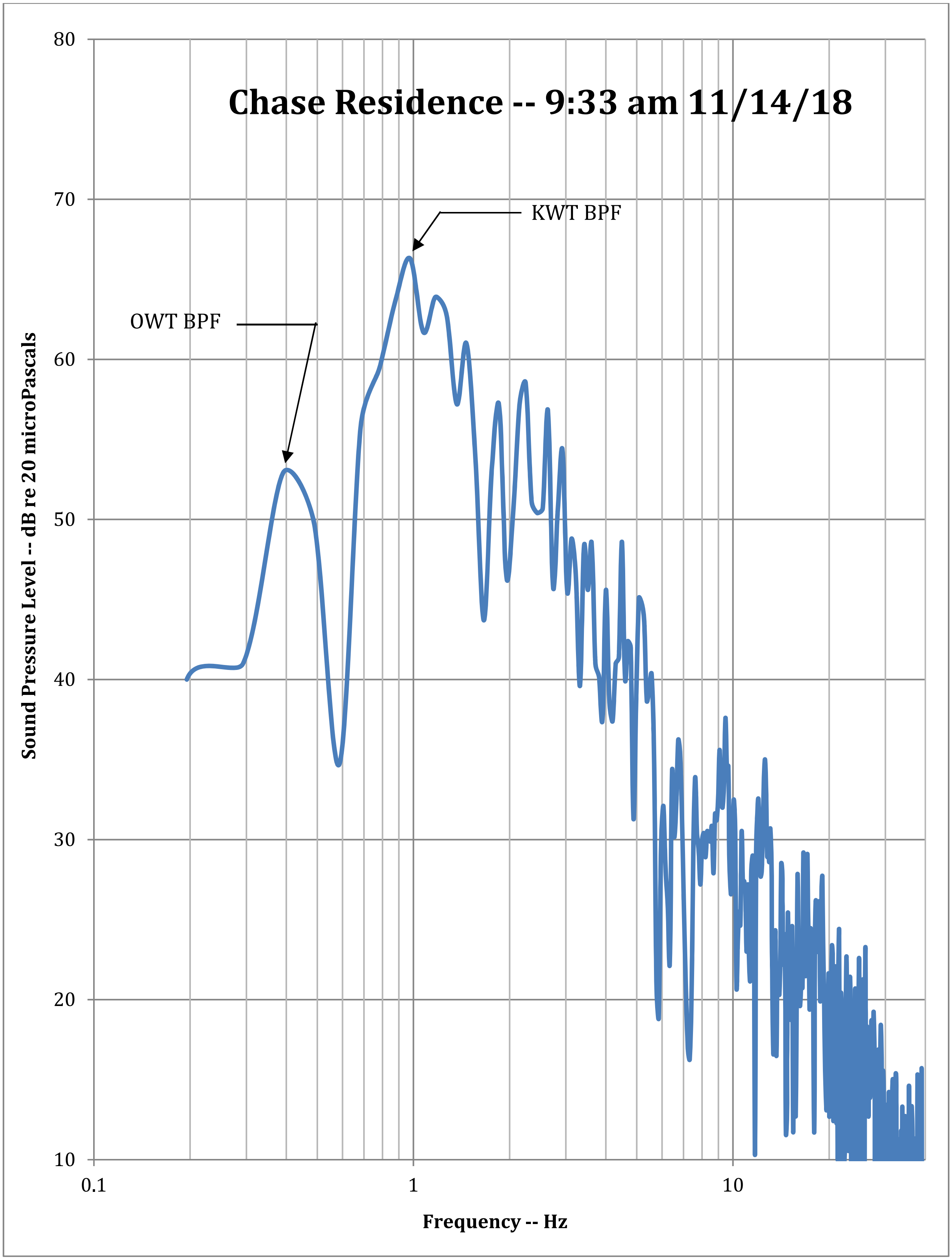

Figure C - 7 Chase Residence

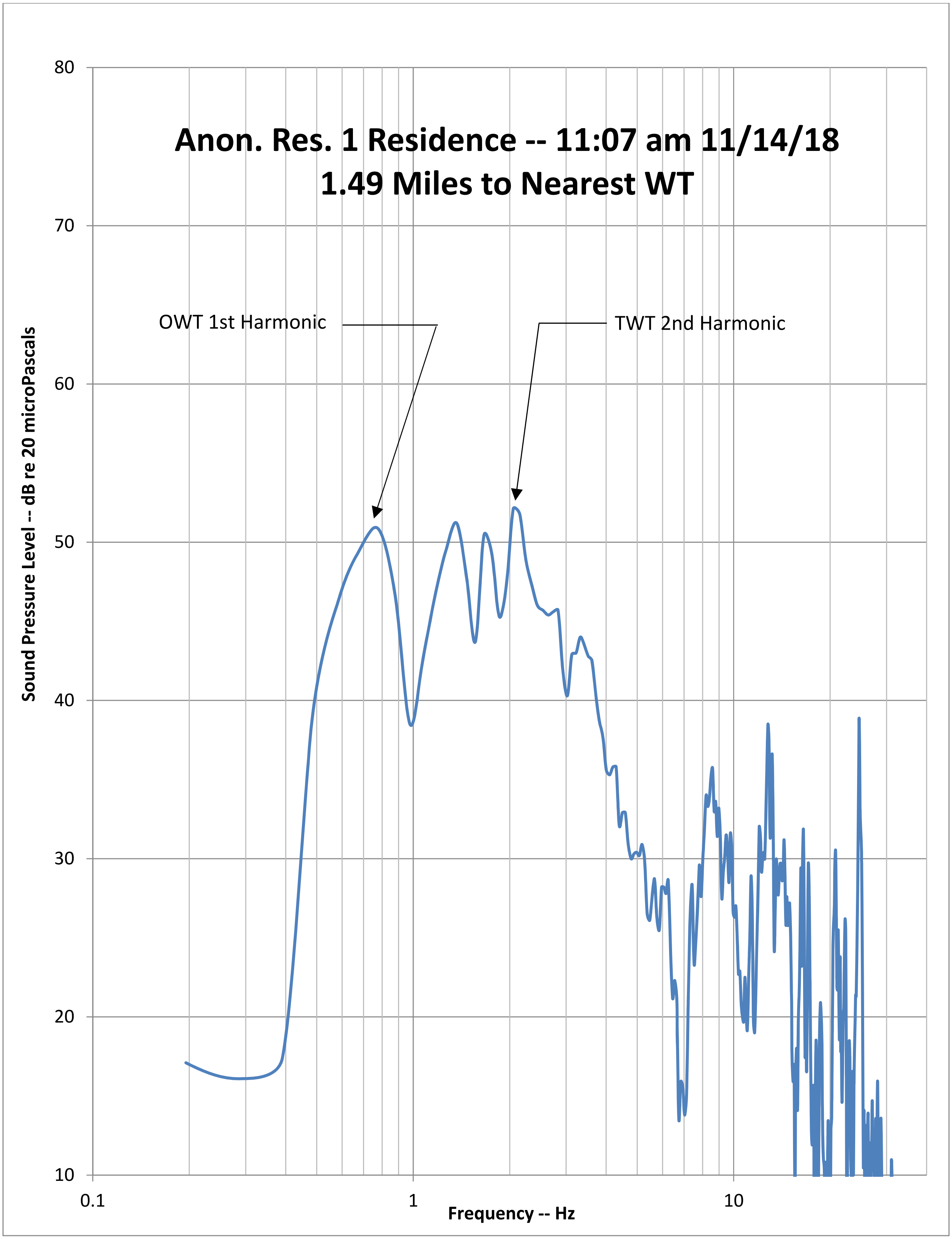

Figure C - 8 Anonymous Residence 1

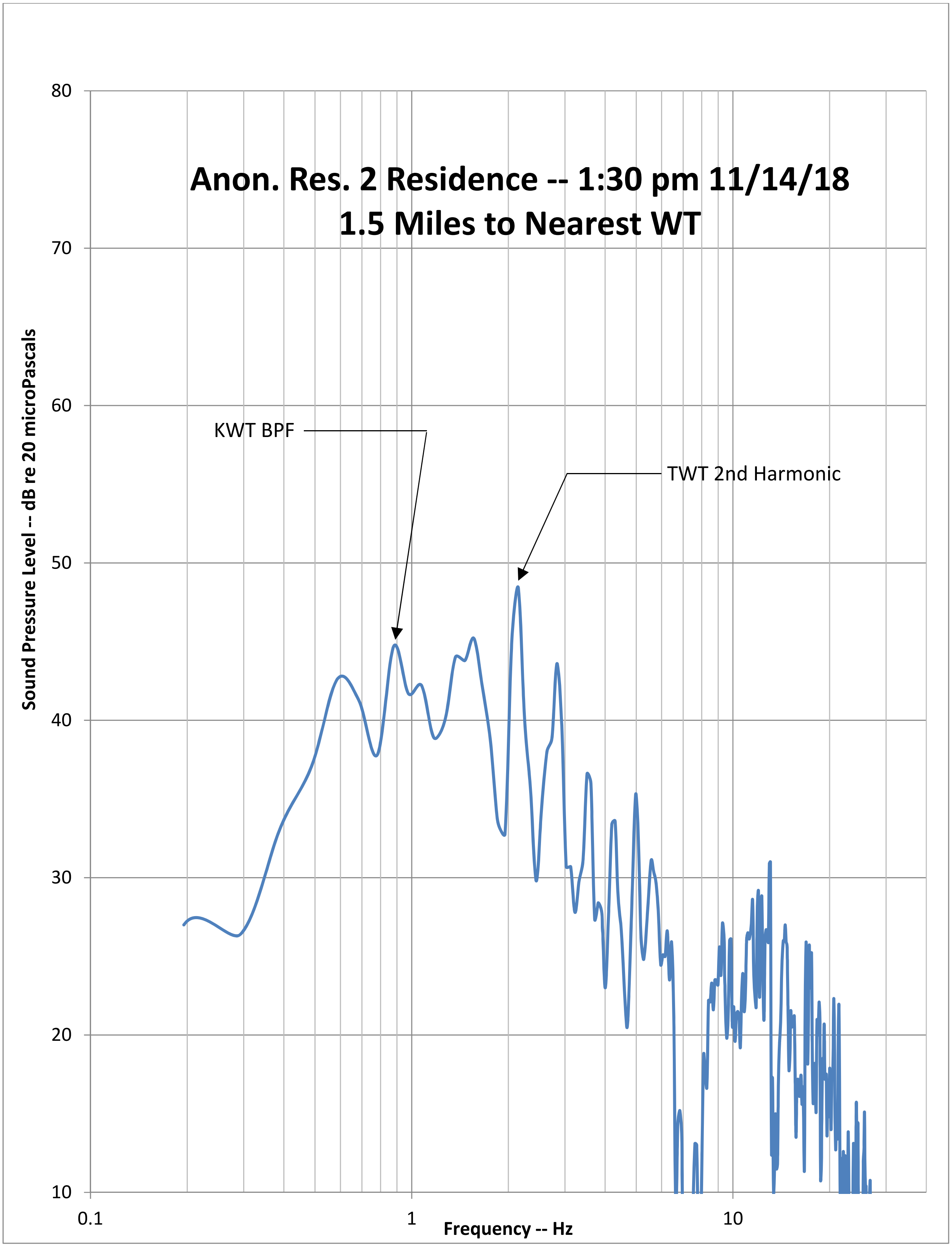

Figure C - 9 Anonymous Residence 2

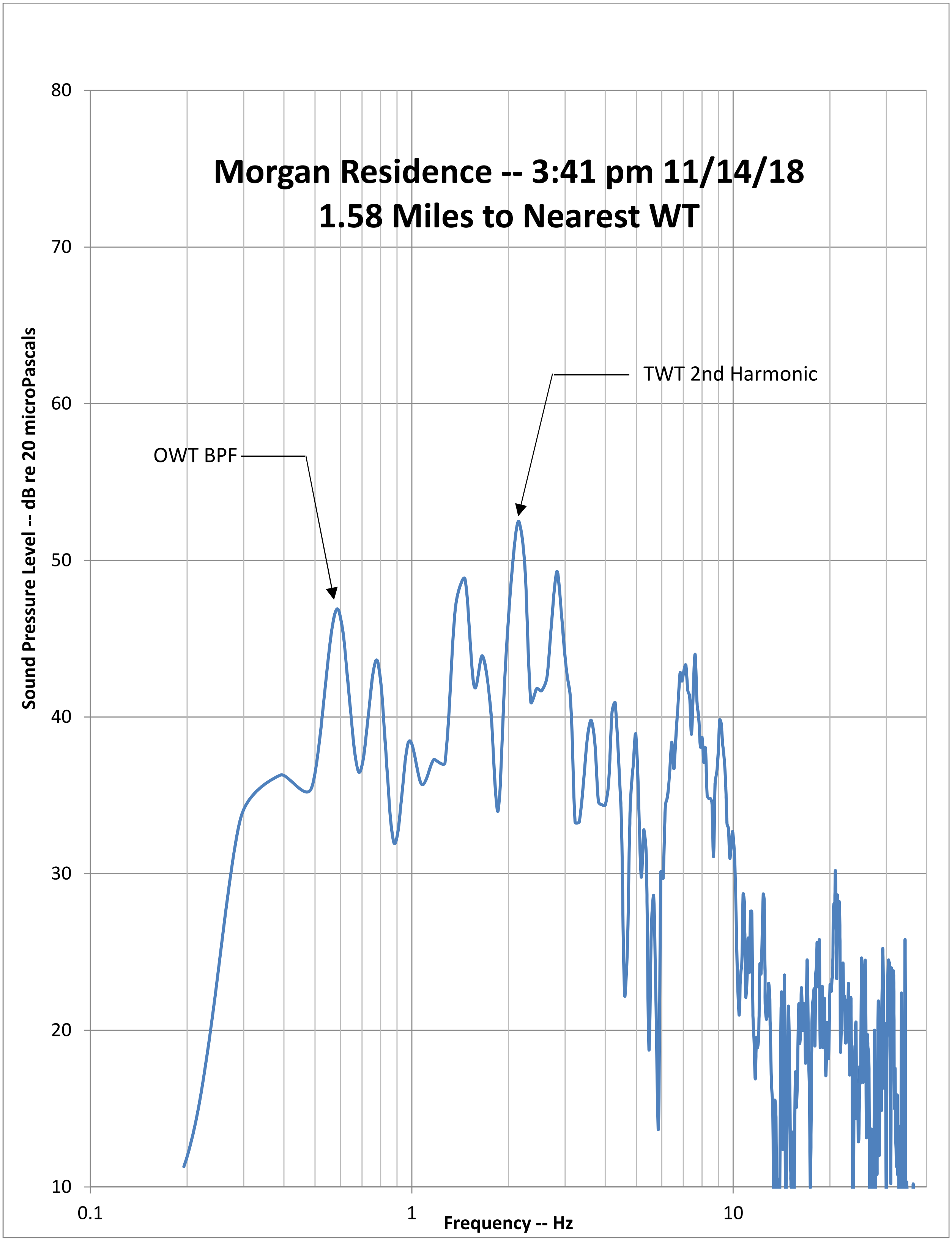

Figure C - 10 Morgan Residence

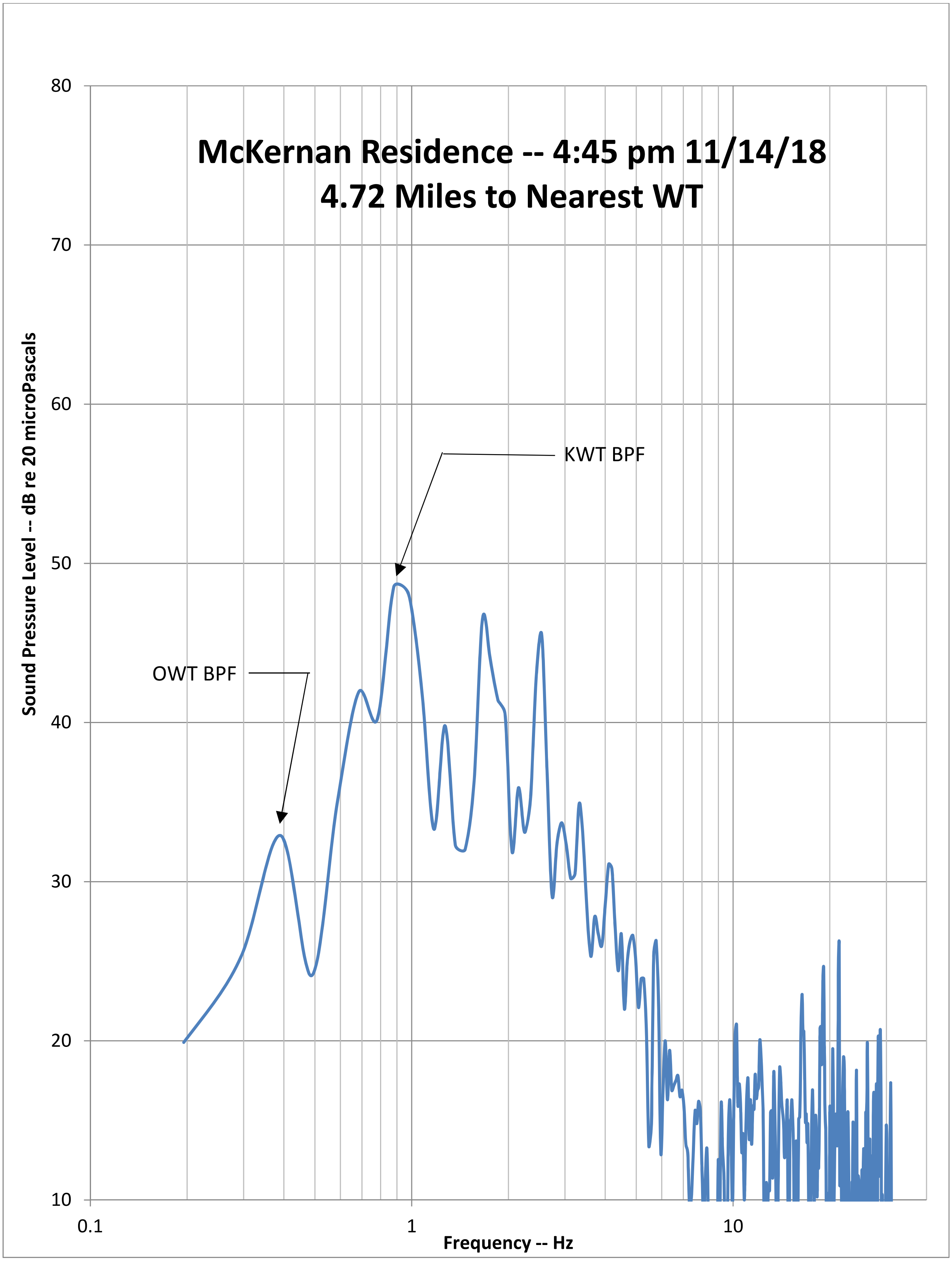

Figure C - 11 McKernan Residence

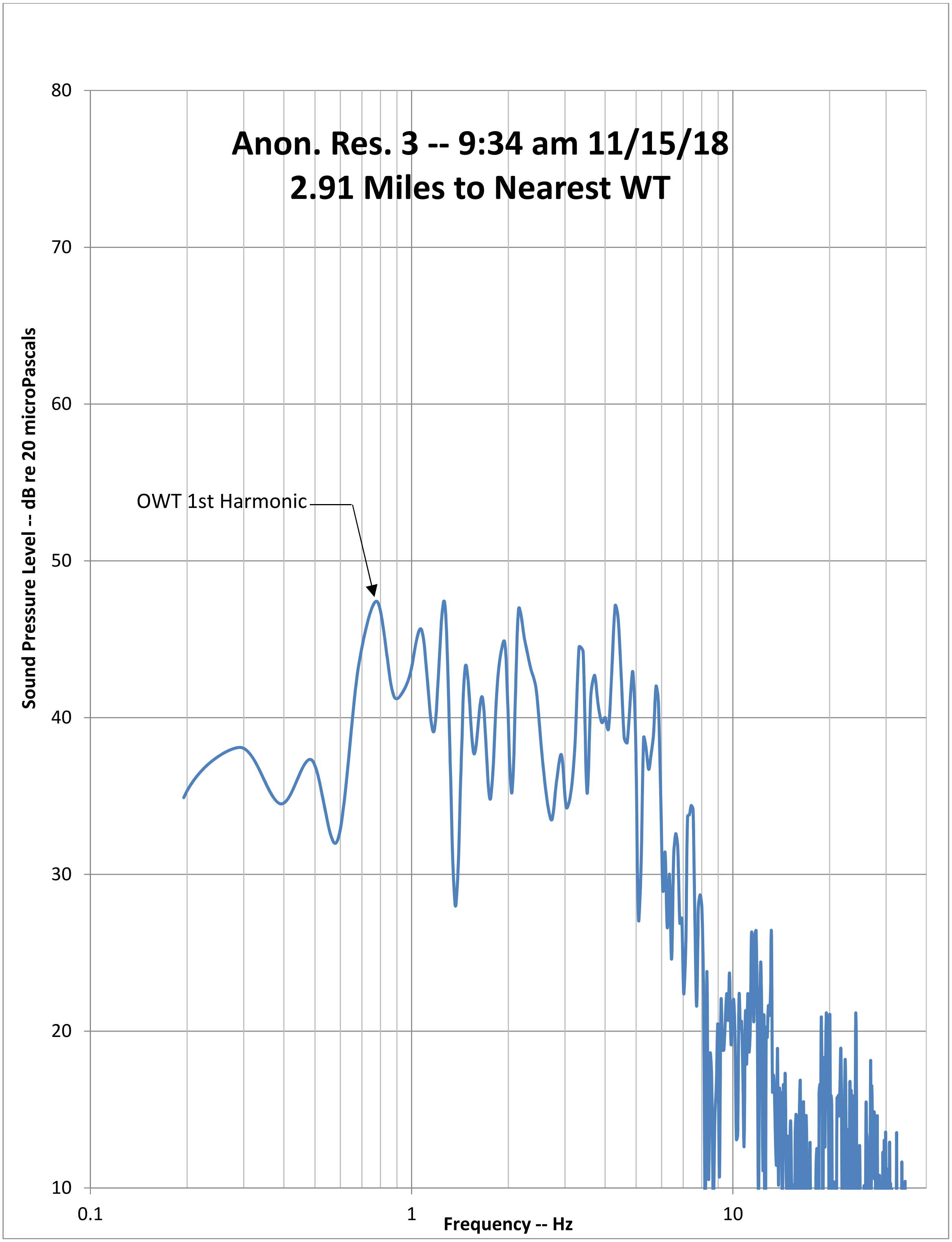

Figure C - 12 Anonymous Residence 3

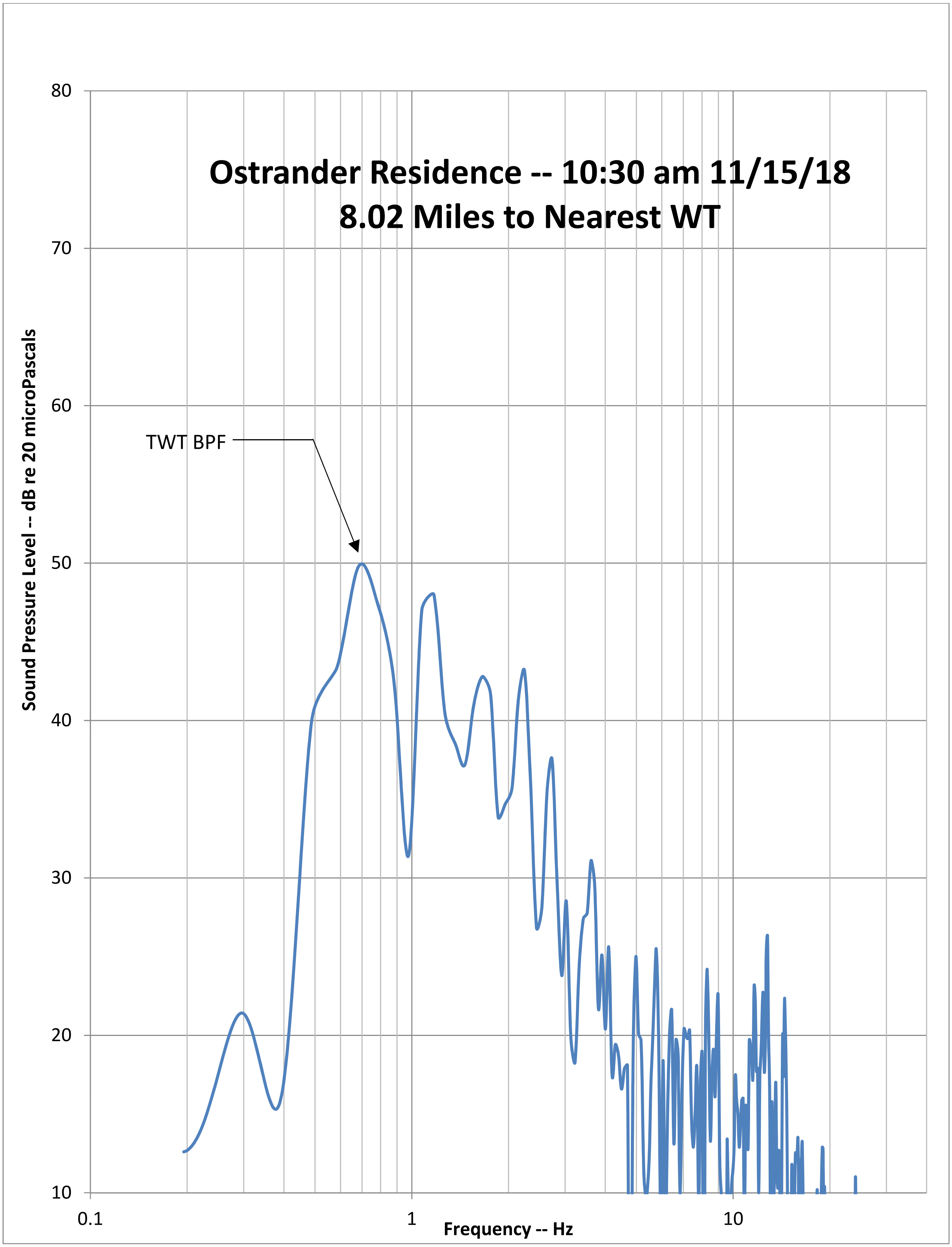

Figure C - 13 Ostrander Residence

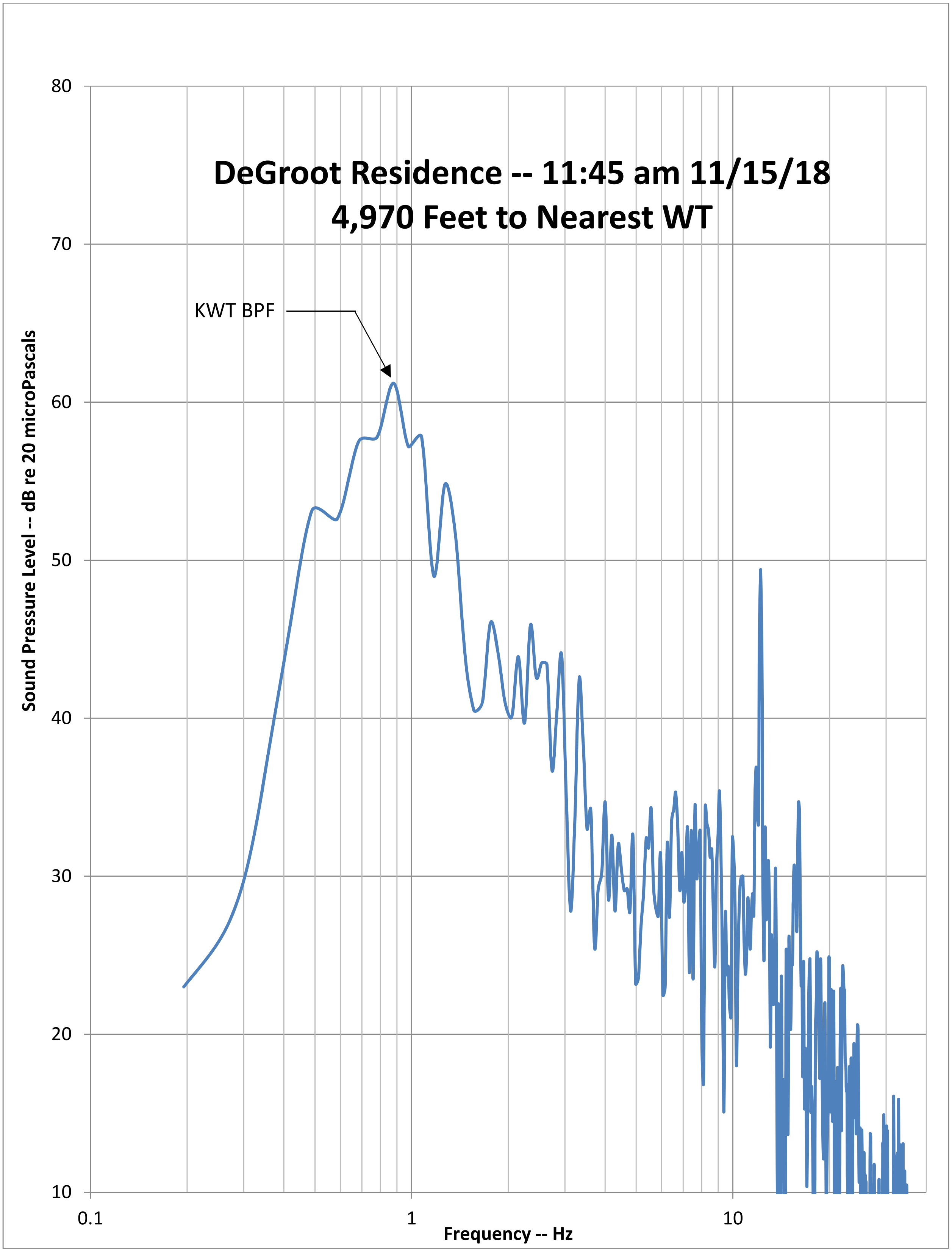

Figure C - 14 DeGroot Residence

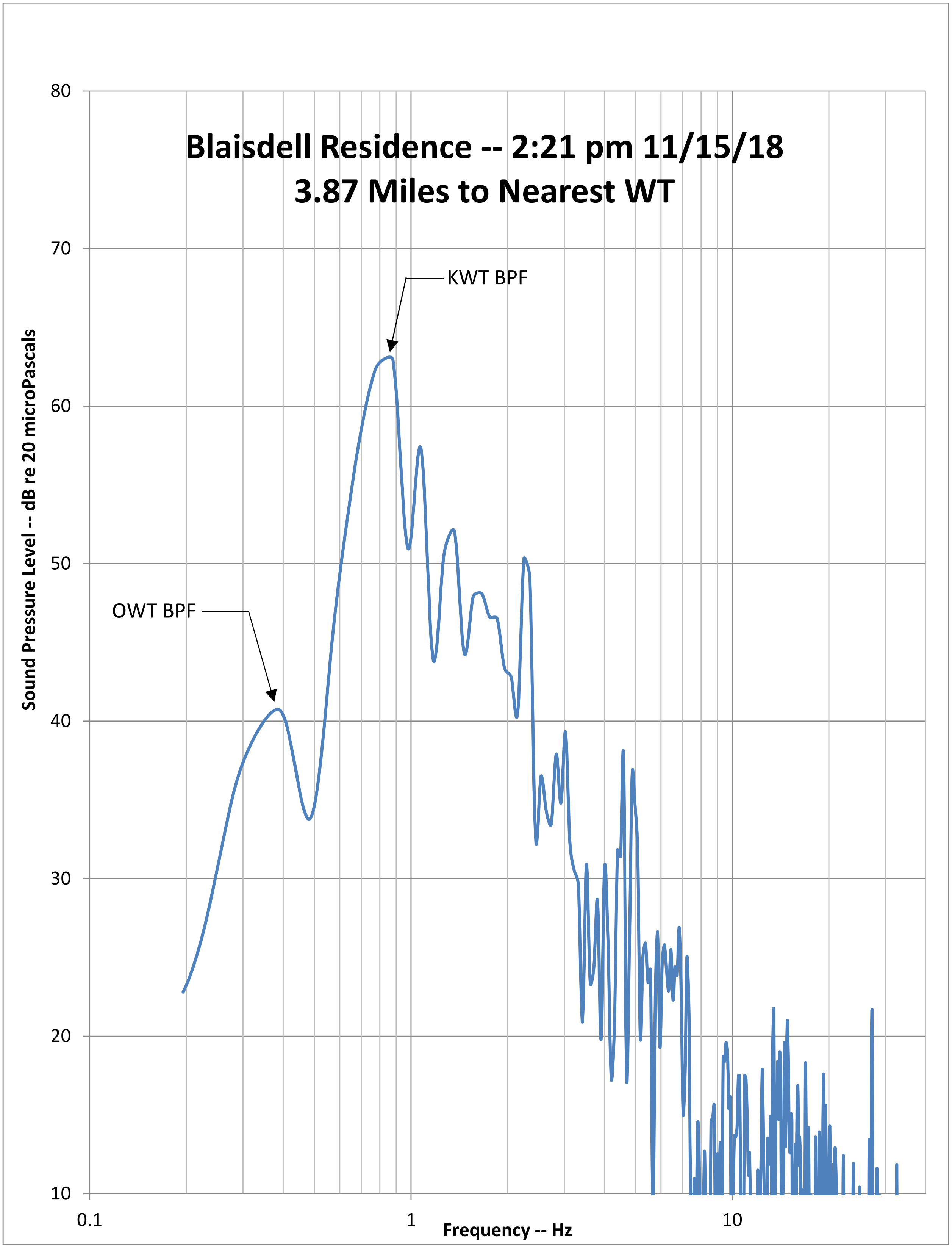

Figure C - 15 Blaisdell Residence

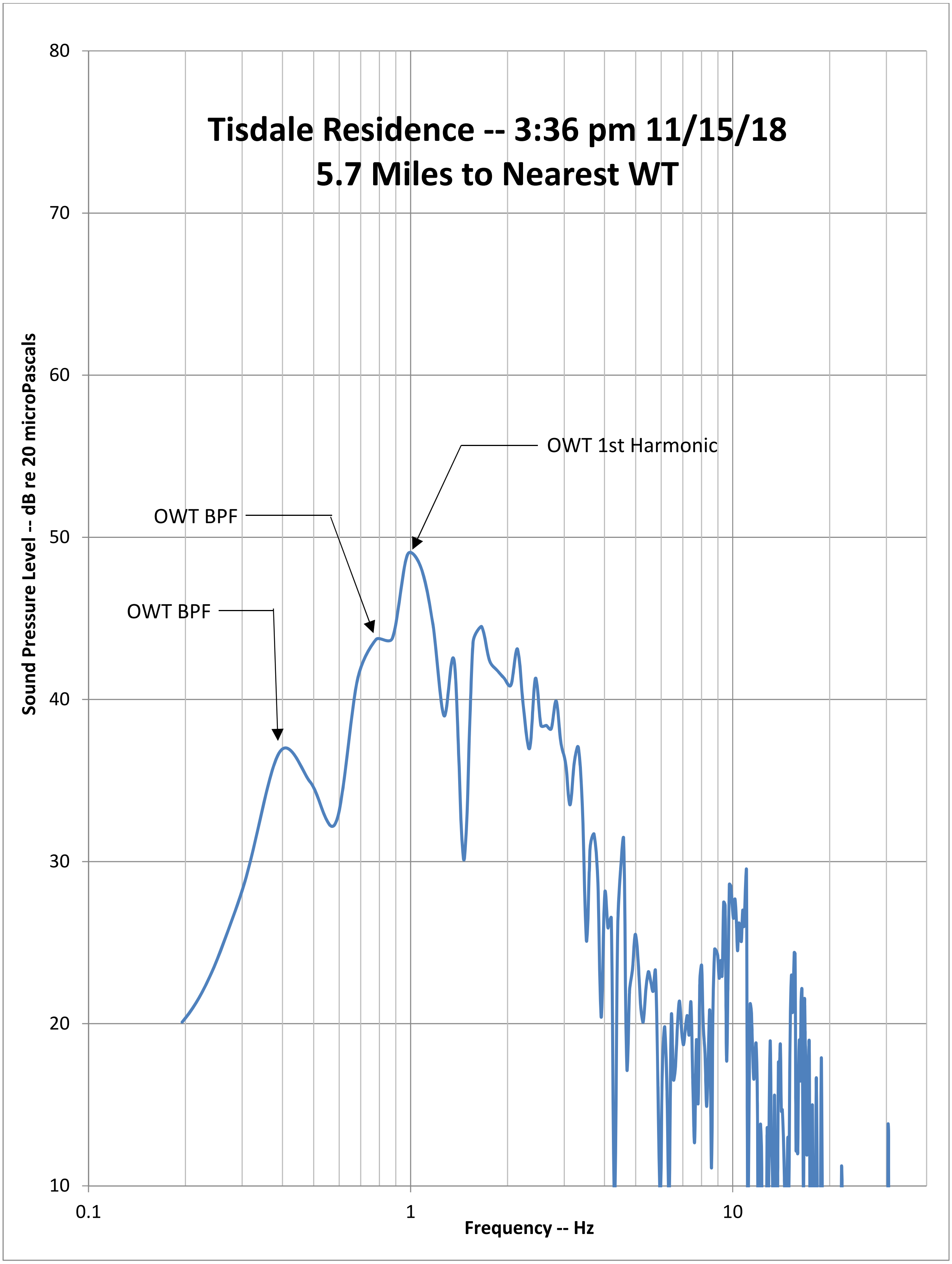

Figure C - 16 Tisdale Residence

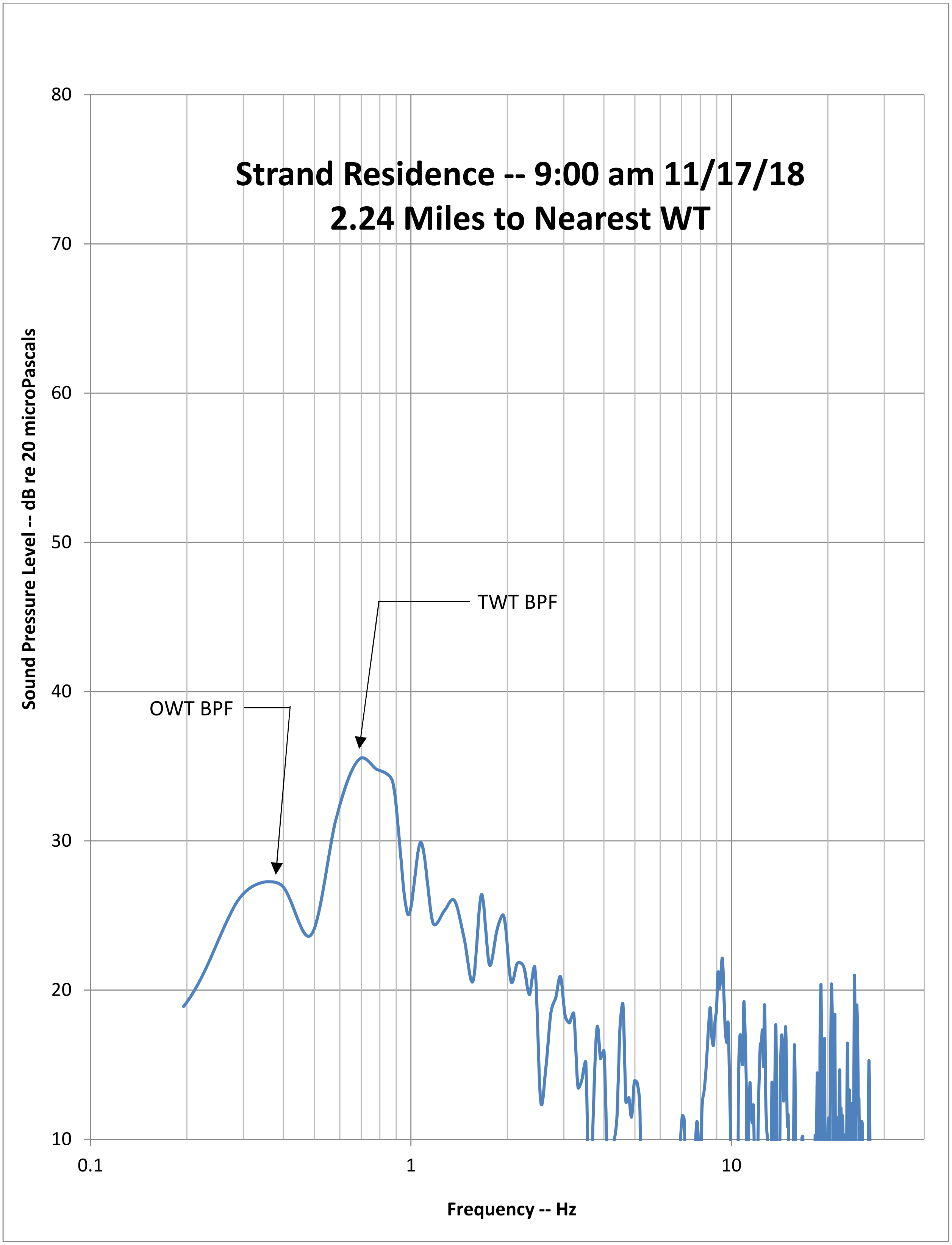

Figure C - 17 Strand Residence

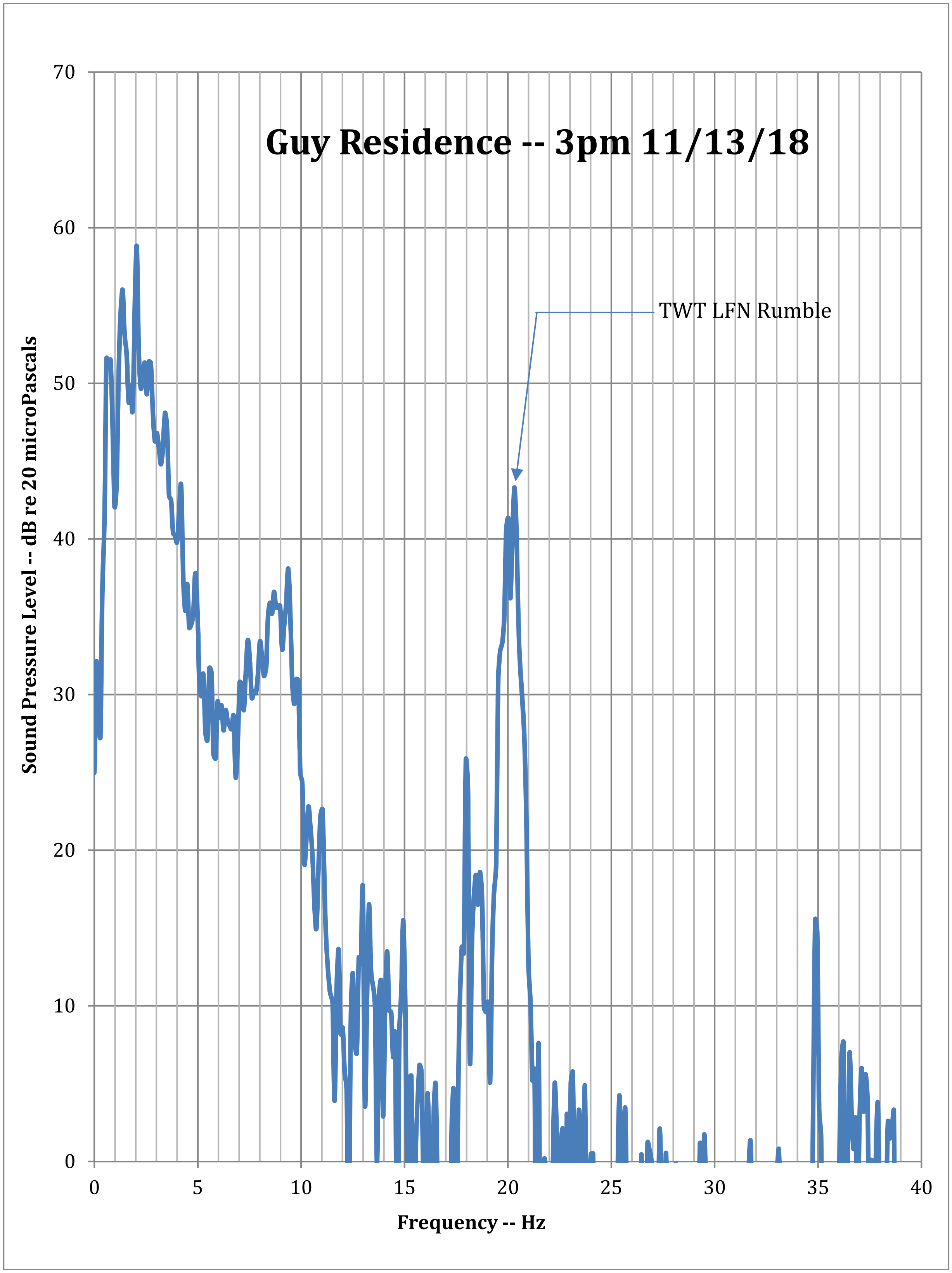

Figure C - 18 LFN at Guy Residence

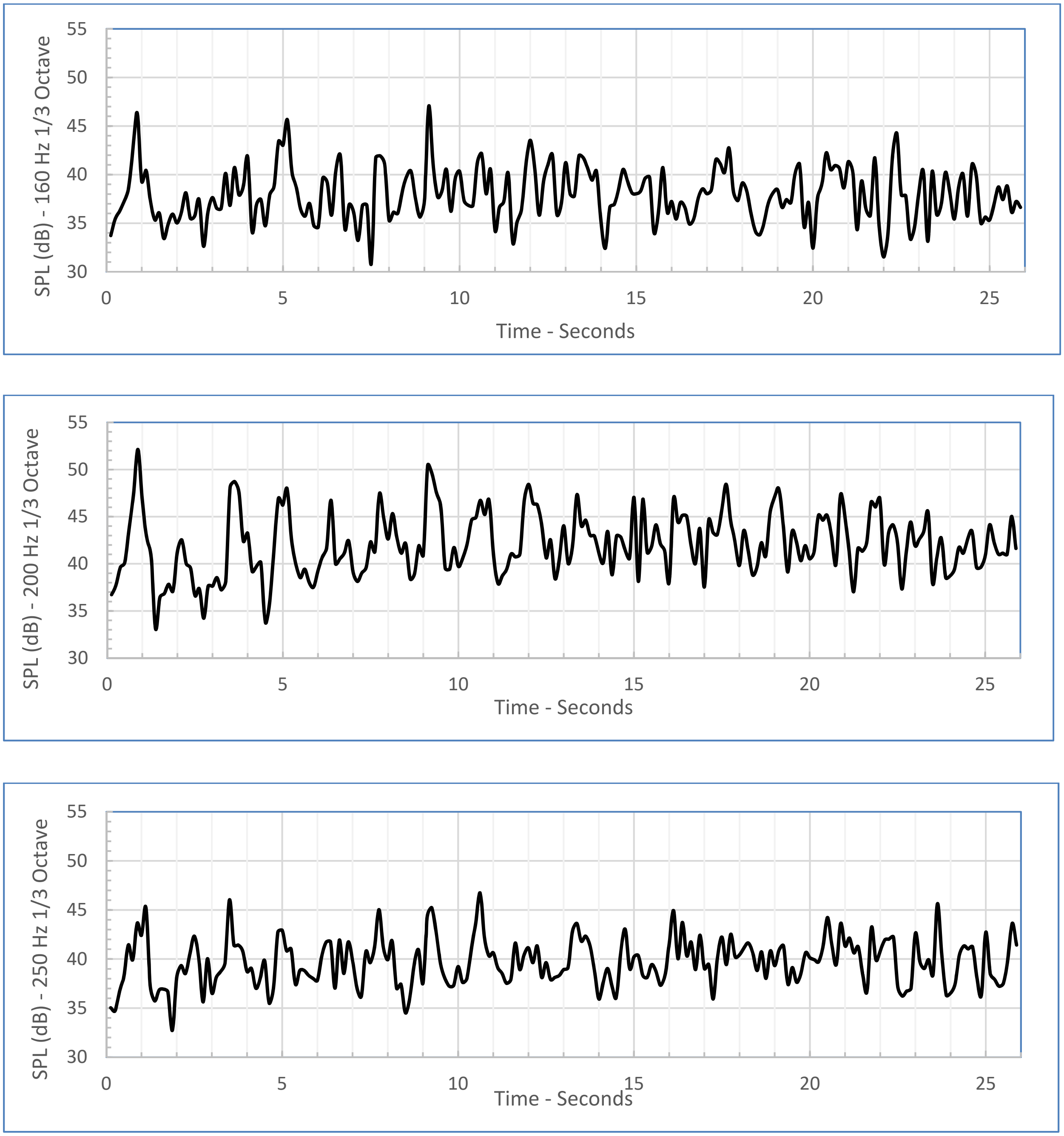

Figure C - 19 Frequency Filtered Samples of Amplitude Modulated WT Noise (Guy Res.)

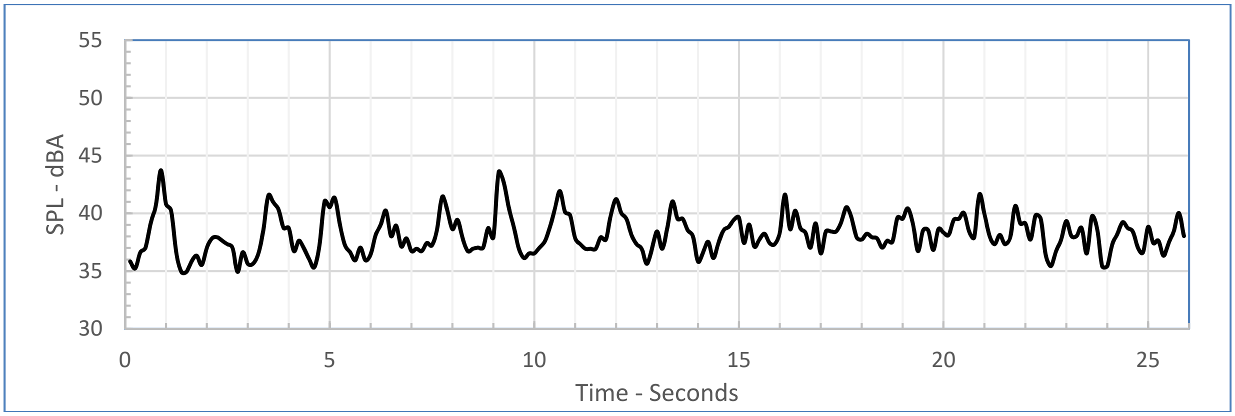

Figure C - 20 A-wtd Sample of Amplitude Modulated WT Noise (Guy Res.)

APPENDIX D – 2014 WILSON IHRIG REPORT

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KUMEYAAY AND OCOTILLO WIND TURBINE FACILITIES

NOISE MEASUREMENTS

28 February 2014

Submitted to:

Stephan C. Volker, Esq.

Law Offices of Stephan C. Volker

Submitted by:

Richard A. Carman, Ph.D., P.E.

Michael A. Amato

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EXECUTIVE SUMMARY

Noise measurements were obtained for wind turbines (WTs) at the Kumeyaay Wind Farm (Kumeyaay Wind) and Ocotillo Wind Energy Facility (Ocotillo Wind or OWEF) between April 28 and April 30, 2013. This report conclusively documents the presence of infrasound and low frequency noise (ILFN) generated by the two facilities' wind turbines at residential and other locations up to 6 miles from the wind turbines.

It is clear from the measured noise data obtained from Kumeyaay and Ocotillo facilities that there is significant wind turbine-generated ILFN. This was to be expected as it has been documented by others such as in the McPherson noise study, the Shirley Wind Turbine study, and by Epsilon Associates.[1] And indeed the measured ILFN levels near Kumeyaay and Ocotillo wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

Both the McPherson and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth, Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce ILFN, and whether that ILFN was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated ILFN at numerous nearby residences that correlated with residents' reported impacts.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then.

Recent research and investigations into human response to ILFN seem to provide strong evidence of a cause and effect relationship. In particular the work of Salt, et al.[2] has made a clear case for perception of ILFN below the threshold of hearing as defined by ISO 389-7 which is related to the response of the ear's inner hair cells (IHC). Salt has demonstrated that it is possible for the ears' outer hair cells (OHC) to respond to ILFN at sound pressure levels that are much lower than the IHC threshold. Salt has reported that ILFN levels (levels commonly generated by wind turbines nearby residences) can cause physiologic changes in the ear.[3] Salt and Kaltenbach "estimated that sound levels of 60 dBG will stimulate the OHC of the human ear."[4]

---

[1] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

[2] Alec Salt, and J. Lichtenhan, Perception based protection from low-frequency sounds may not be enough, Internoise 2012, August 2012.

[3] Alec Salt, and J.A. Kaltenbach, "Infrasound from Wind Turbines Could Affect Humans," Bulletin of Science, Technology and Society, 31(4), pp.296-302, September 12, 2011.

[4] Ibid., p. 300, "As discussed below, G-weighting (with values expressed in dBG) is one metric that is used to quantify environmental noise levels. While it is a more accurate measure of ILFN than most other metrics, G-weighting still de-emphasizes infrasound."

Furthermore, Matsumoto et al.[5] have demonstrated in a laboratory setting that humans can perceive ILFN at sound pressure levels below the IHC threshold when the noise is a complex spectrum (i.e. contains multiple frequency components). From this laboratory research it was clearly demonstrated that humans can perceive sound pressure levels that are from 10 to 45 decibels (dB) less than the OHC threshold in the ILFN range. In fact, the Matsumoto thresholds clearly follow the OHC threshold down to the frequency below which the two diverge. The Matsumoto thresholds are lower than the OHC thresholds at frequencies below the point at which they diverge.

These studies and more recent studies demonstrate that wind turbines (specifically wind turbine-generated ILFN) have the potential to not only annoy humans, but harm them physiologically.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay and Ocotillo facilities. Higher wind speeds generally produce higher noise levels in particular higher ILFN. This is clearly demonstrated in the Ocotillo data when comparing the daytime and nighttime levels.

INTRODUCTION

As requested, Wilson, Ihrig & Associates (WIA) performed noise measurements in the vicinity of the Kumeyaay Wind Farm, located on the Campo Indian Reservation near Boulevard, California. We also took similar measurements in the vicinity of the Ocotillo Wind Energy Facility located near Ocotillo, California. The purpose of the measurements was to determine whether, and at what levels and under what conditions, the Kumeyaay Wind and Ocotillo Wind turbines generate ILFN[6], and how far the ILFN is propagated. A subsidiary goal was to accurately show the pressure fluctuations in the sound, so as to allow an accurate and robust analysis of the human health and other environmental impacts of the ILFN generated.

Between April 28 and April 30, 2013, we recorded noise samples at numerous residential and reference locations near each wind turbine facility. The wind turbines at both facilities were operating the entire time during which we took our noise measurements. Although it would have been our preference to also measure ambient noise conditions with all wind turbines taken out of operation, turbine operation was out of our control. In any event, even without measurements of the ambient noise sans wind turbines, we successfully measured and isolated wind turbine-generated noise.

Through a spectral analysis of the noise recordings, we obtained sound pressure level data demonstrative of the wind turbine-generated ILFN. In this report, we discuss the manner in which the data were obtained and present and analyze the study results.

---

[5] Yasunao Matsumoto, et al, An investigation of the perception thresholds of band-limited low frequency noises; influence of bandwith, published in The Effects of Low-Frequency Noise and Vibration on People, Multi-Science Publishing Co. Ltd.

[6] Infrasound is defined as sound at frequencies less than 20 Hz. The focus of this report is frequencies less than 40 Hz, which includes low frequency sound as well.

WIND TURBINE DETAILS

Kumeyaay Wind Farm

Kumeyaay Wind is owned by Infigen Energy of Australia and operated by Bluarc Management of Texas, on 45 acres of land on the Campo Indian Reservation in southeastern San Diego County.[7] The nearest community outside of the tribal land is Boulevard, California. Currently there are 25 wind turbines operating at this facility. The wind turbines are located on a north-south ridge (Tecate Divide) at elevations ranging from 4,200 to 4,600 feet. The turbines started generating power in December 2005.

Kumeyaay Wind's turbines are Gamesa model G87X-2.0, with a rated power of 2.0 megawatts (MW). According to the manufacturer's published data, the G87X-2.0 has a hub height (height of the nacelle, which houses the gearbox, transmission and generator) that can vary from 217 to 325 feet depending on site conditions. The manufacturer also represents that the turbine has a rotor diameter of 283 feet, with three 138-foot-long, adjustable pitch blades. According to Councilman Miskwish the hub height of the Kumeyaay Wind turbines is typically 228 feet, and the blades are 145 feet long. Figure 1 shows some of the wind turbines.

The G87-2.0 model has a reported cut-in wind speed of 8.9 mph (5 mph according to former Campo tribal Councilman Miskwish, a.k.a. Michael Connolly) and achieves its rated (max) power generation at about 31 mph. The operational speed of the turbines is reported by the manufacturer to be in the range of 9 to 19 revolutions per minute (rpm) depending on wind conditions.

Figure 1 Wind Turbines at Kumeyaay Wind

[7] "Kumeyaay Wind Energy Project," PowerPoint presentation by Councilman Michael Connolly Miskwish, Campo Kumeyaay Nation, November 30, 2008., *available here:* http://www.certredearth.com/pdfs/Presentations/2007/KumeyaayWindEnergyProjectCampoKumeyaayNation.pdf

Ocotillo Wind Energy Facility

The Ocotillo Wind facility is owned and operated by Pattern Energy, on 10,200 acres of federal land located in southwestern Imperial County and managed by the United States Bureau of Land Management (BLM). Ocotillo Wind currently has 112 operating wind turbines. The wind turbines are located on the desert floor adjacent to the community of Ocotillo, California, at elevations ranging from approximately 300 to 1,400 feet above sea level. The Ocotillo Wind turbines are Siemens model SWT-2.3-108, with a rated power of 2.3 MW. Figure 2 shows some of Ocotillo Wind's turbines.

According to the manufacturer's published data, the SWT-2.3-108 model has a nominal hub height of 260 feet depending on site conditions, with a turbine rotor diameter of 351 feet and three 172-foot-long blades. The SWT-2.3-108 has a manufacturer-reported cut-in wind speed between 6.6 and 8.9 mph and achieves its rated power at wind speeds between 24 and 27 mph. The operational speed of the turbines reported by the manufacturer is in the range of 6 to 16 rpm depending on wind conditions.

Figure 2 Wind Turbines at Ocotillo Wind

MEASUREMENT LOCATIONS

Kumeyaay Wind-Area Residences

Both indoor and outdoor noise recordings were made at six residences in the Boulevard area near the Kumeyaay Wind turbines.

Table 1 lists the addresses of the residences at which the measurements were taken, along with the dates and times of the recordings. A map showing the Kumeyaay Wind-area measurement locations is provided in Appendix A.

Table 1 Addresses of Residences Used in Kumeyaay Measurements

Resident/Owner	Address	Distance to Closest Wind Turbine	Date	Recording Start Time	Recording End Time[1]
D. Elliott	Off of Crestwood, Campo Indian Reservation	2,960 feet	April 28	16:02	16:22
			April 30	11:00	11:20
G. Thompson	33 Blackwood Road, Manzanita Indian Reservation	2,880 feet	April 28	18:47	19:07
R. Elliott	25 Crestwood Road, Manzanita Indian Reservation	4,330 feet	April 28	17:30	17:50
D. Bonfiglio	40123 Ribbonwood Road, Boulevard	2.9 miles	April 29	9:15	9:35
K. Oppenheimer	39544 Clements Street, Boulevard	1.6 miles	April 30	15:11	15:31
M. Morgan	2912 Ribbonwood Road, Boulevard	1.7 miles	April 30	16:15	16:35
D. Tisdale	Morning Star Ranch, San Diego Co.	5.7 miles	April 30	13:45	14:05

[1] Recordings were nominally 20 minutes long

The Kumeyaay Wind-area residences at which we took measurements are located at distances of 2,880 feet to 5.7 miles from the nearest wind turbine at Kumeyaay Wind Farm. Additional recordings were made at two reference locations, which were closer to the wind turbines than the residential locations, as shown below in Table 2.

A recording was also obtained at the Tisdale ranch located 5.7 miles from the nearest wind turbine (see Table 1 above). The purpose of this recording was primarily to document existing ambient conditions; however, even at that great distance, analysis of the data indicates the presence of noise generated by the existing turbines.

A recording was also made at one of the guest cabins at the Live Oak Springs Resort. The purpose of this latter measurement was to obtain noise recordings in a condition with essentially no "local wind." By no local wind, it is meant that the wind at the microphone was either very light or non-existent even though there was wind at the wind turbine level, which was confirmed by observing the closest wind turbine rotating, thus providing a sample of wind turbine noise that was minimally affected by wind on the microphone. This latter recording was made at 10:10 pm on April 28. Cabin #2 at Live Oak Springs Resort is 5,950 feet from the nearest wind turbine.

Kumeyaay Reference Noise Measurements

To more fully document wind turbine-generated noise levels and spectra, we took noise measurements at locations closer to the subject wind turbines than the residences used in this study. Two reference locations were used near Kumeyaay Wind. Table 2 indicates the locations, distances to the closest wind turbine, dates and times of the reference recordings.

Table 2 Reference Locations for Kumeyaay Wind

Location	Distance to Closest Wind Turbine (feet)	Date	Recording Start Time	Recording End Time[1]
Kumeyaay (K-R1)	2,040	April 28	15:58	16:18
Kumeyaay (K-R2)	930	April 30	11:00	11:20

[1] Recordings were nominally 20 minutes long

The recording on April 28 at 10:00 pm at Live Oak Springs Resort (K-LOSR) also serves as a reference measurement.

Ocotillo Wind-Area Residences

Recordings were made at three Ocotillo residences near the Ocotillo Wind turbines. Table 3 lists the addresses of the residences at which the measurements were taken, along with the dates and times of recordings. A map showing the Ocotillo Wind-area measurement locations is provided in Appendix A.

Table 3 Addresses of Residences Used in Ocotillo Measurements

Resident/Owner	Address	Distance to Closest Wind Turbine	Date	Recording Start Time	Recording End Time[1]
J. Pelly	1362 Shell Canyon Road, Imperial County	3,220 feet	April 29	11:22	11:42
				20:00	20:20
P. Ewing	98 Imperial Highway, Ocotillo	3,590 feet	April 29	12:32	12:52
				21:00	21:20

D. Tucker	1164 Seminole Avenue, Ocotillo	1.2 miles	April 29	13:42	14:02
				22:20	22:40

[1] Recordings were nominally 20 minutes long

The Ocotillo Wind-area residences at which we took measurements are located at distances of 3,220 feet to 1.2 miles from the closest wind turbine at Ocotillo Wind. We also made measurements at three reference locations closer to the wind turbines, as shown in Table 4 below.

Ocotillo Reference Noise Measurements

We used three reference locations near Ocotillo Wind. Table 4 lists the locations, distance to the closest wind turbine, dates and times of the reference recordings.

Table 4 Reference Locations for Ocotillo

Location	Distance to Closest Wind Turbine (feet)	Date	Recording Start Time	Recording End Time[1]
Ocotillo (O-R1)	1,540	April 29	11:19	11:39
			20:00	20:20
Ocotillo (O-R2)	1,470	April 29	13:44	14:04
			21:30	21:50
Ocotillo (O-R3)	2,100	April 29	22:08	22:28

[1] Recordings were nominally 20 minutes long

NOISE RECORDING METHODOLOGY

We made all of the noise recordings with Brüel and Kjaer (B&K) type-4193, ½-inch, pressure-field microphones, which are specifically designed for infrasound measurement and provide a linear response from 0.07 cycles per second (Hz) to 20,000 Hz. A B&K type-UC-0211 adapter was used to couple the microphones to a B&K type-2639 preamplifier, providing a linear frequency response down to 0.1 Hz for the microphone/adaptor/preamplifier system. All recordings were calibrated with B&K type-4230 calibrators, which are checked and adjusted with NIST traceable accuracy with a B&K type-4220 pistonphone in the WIA laboratory in Emeryville, California.

We recorded all the noise samples with a TEAC LX10, 16-channel digital recorder, which provides a linear frequency response (i.e., ±0.1% or less) to a lower frequency limit of essentially 0.1 Hz when used in the "AC mode" (which we did). Twenty minute (nominal) noise recordings were made at each location. Using two different microphones, recordings were made simultaneously both indoors and outdoors at each subject residence. This same approach was also used in the Shirley Wind Farm study[8].

Using a third microphone and another recorder (SONY PCM D-50 digital recorder), recordings were made at reference locations closer to the wind turbines while the residential recordings were in progress. The frequency response of this third system is linear down to a frequency of 1.4 Hz, being limited by the SONY recorder.

For several of the residential and reference locations, recordings were repeated at a different time and/or date. All measurement data reported herein are based on an analysis of the noise recordings played back in the WIA laboratory.

Residence Location Measurements

For measurements conducted at the residences, a microphone was set up inside each residence mounted on a tripod at 4.5 feet above the floor, typically in the middle of the room. The indoor recordings were made in either the living room (mostly) or dining room of the residences. Indoors, the microphone was oriented vertically and covered with a 7-inch-diameter wind screen. Figure 3 shows the microphone and windscreen mounted on a tripod inside one of the residences.

A second microphone was set up outside of each residence. Following IEC Standard 61400-11, the outside microphone was rested horizontally (i.e., flush mounted) on a ½-inch-thick plywood "ground board" that is 1 meter in diameter. The microphone was oriented in the direction of the nearest visible wind turbine and the ground board was placed in a flat location between the residence and the wind turbines.

Also following IEC 61400-11, wind effects on the outdoor microphone were reduced using both a hemispherical 7-inch-diameter primary windscreen placed directly over the microphone, and a hemispherical 20-inch-diameter secondary windscreen placed over the primary windscreen and mounted on the ground board. The microphone and primary windscreen were placed under the center of the secondary windscreen.

The primary windscreen was cut from a spherical, ACO-Pacific foam windscreen with a density of 80 pores per inch (ppi). The secondary windscreen was constructed by WIA using a wire frame covered with ½ inch open wire mesh. A one-inch-thick layer of open cell foam with a density of 30 ppi was attached to the wire mesh. Figure 4 shows the outdoor microphone, secondary windscreen, and ground board outside one of the residences.

Both microphones used at the residences were powered by B&K type-2804 power supplies, with signals amplified by a WIA type-228 multi-channel measurement amplifier, and recorded on a TEAC LX10 16-channel digital data recorder. Inside and outside noise signals were recorded simultaneously to allow for correlation of interior and exterior sound levels during analysis.

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[8] Channel Islands Acoustics, et al, A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin, Report No. 122412-1, December 24, 2012.

Figure 3 Microphone Inside Residence

Figure 4 Microphone Outside Residence

Reference Location Measurements

A third B&K 4193 microphone was used to obtain simultaneous reference measurements at locations closer to the wind turbines during each of the residential measurements. This third microphone was powered by a B&K type-5935 power supply and amplifier, with the signal recorded on a Sony type PCM D-50 recorder. The same windscreen and ground board configuration (i.e., primary and secondary windscreen) used for the residential recordings, was also used for the reference locations. Reference measurements were obtained at different locations at each of the two facilities. Figure 5 shows the microphone, ground board and secondary windscreen at one of the reference measurement locations in Ocotillo.

Figure 5 Reference Location O-R2 with Microphone, Ground Board and Windscreen

NOISE MEASUREMENT BACKGROUND

Purpose of Measurements

The primary purpose of making the wind turbine noise measurements reported herein was to determine whether, and at what levels and under what conditions, the Kumeyaay Wind and Ocotillo Wind turbines generate ILFN, and how far the ILFN is propagated. In light of increasing evidence in the literature that ILFN can affect and harm humans[9] [10] [11] [12] [13], along with numerous complaints of health impacts from both Boulevard- and Ocotillo-area residents[14] since the wind turbines near their respective residences began operating, we had a subsidiary goal to obtain measurements that accurately show the pressure fluctuations in the sound, so as to allow an accurate and robust analysis of the human health and environmental impacts of the ILFN generated.

Noise Measurements in Presence of Wind

Some atmospheric pressure fluctuations are oscillatory in nature, whereas others are not. An example of a non-oscillatory pressure fluctuation is a change in barometric pressure; a change that occurs over a much longer time scale (e.g., hours) than the fluctuations being measured in this study. Wind and, in particular, gusts of wind cause another form of non-oscillatory pressure fluctuation, though it occurs on a much shorter time scale (e.g., fraction of a second). Local wind can cause a pressure change affecting the human ear similar to the pressure change that occurs in an airplane as it ascends or descends during takeoff and landing, but this pressure change is not sound.

Sound, in contrast to non-oscillatory fluctuations, consists of regular oscillatory pressure fluctuations in the air due to traveling waves. Sound waves can propagate over long distances depending on many factors. In the case of noise generated by machinery, the pressure fluctuations can be highly periodic in nature (i.e., regular oscillations). Sound that is characterized by discrete frequencies is referred to as being tonal. Although wind can generate sound due to turbulence around objects (e.g., trees, buildings), this sound is generally random in nature, lacks periodicity and is usually not in the infrasound range of frequencies.

However, the sound measurements we were interested in for this study (i.e. periodic wind turbine-generated ILFN) can be greatly impacted by non-oscillatory pressure fluctuations and extraneous noise caused by, for example, wind turbulence due to steady wind and particularly during gusts. The microphones we used in these measurements are highly sensitive instruments, with pressure sensor diaphragms that will respond to any rapid enough pressure change in the air regardless of the cause. To minimize the artificial (i.e. unrelated to the noise source being measured) noise or "pseudo sound" caused by wind gusts and other pressure fluctuations not associated with the wind turbine-generated noise itself, we employed special procedures. The

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[9] Salt, A.N., T.E. Hullar, Responses of the ear to low frequency sounds, infrasound and wind turbines, Hearing Research, 16 June 2010.

[10] Salt, A.N., J.T. Lichtenhan, Reponses of the Inner Ear to Infrasound, Fourth International Meeting on Wind Turbine Noise, Rome, Italy, April 2011.

[11] Salt, A.N., J.A. Kaltenbach, Infrasound from Wind Turbines Could Affect Humans, Bulletin of Science, Technology & Society, 31, 296-302, 2011.

[12] Salt, A.N., J.T. Lichtenhan, Perception-based protection from low-frequency sounds may not be enough, Inter-Noise 2012, New York, New York, August 2012.

[13] Lichtenhan, J.T., A.N. Salt, Amplitude Modulation of Audible Sounds by Non-Audible Sounds: Understanding the Effects of Wind-Turbine Noise, Proceedings of JASA, 2013.

[14] San Diego Reader, Volume 42, Number 34, August 22, 2013.

main sources of artificial noise and the procedures we used to minimize its impact are discussed more fully below.

Artificial Noise due to Turbulence at the Microphone

One source of artificial noise caused by wind on the microphone – and the most commonly encountered artificial noise source in outdoor noise measurements – is the turbulence caused by wind blowing over the microphone. To minimize this effect of wind when conducting environmental noise measurements outdoors, it is standard practice to use a windscreen,[15] the size of which is usually selected based on the magnitude of the wind encountered. The higher the wind speed generally the larger the windscreen required to minimize artificial noise caused by air turbulence at the microphone.

The windscreen used must be porous enough so as not to significantly diminish the pressure fluctuations associated with the noise being measured, which is to say that the wind screen must be acoustically transparent. As indicated above, the measurements reported herein followed procedures on windscreen design and usage as recommended by IEC 64100-11.

Artificial Noise due to Air Gusts

There is another – and more problematic – source of artificial wind-based noise. This one is caused by non-oscillatory pressure fluctuations associated with wind gusts as well as the pressure associated with the air flow in a steady wind. Air gusts can have an effect on a microphone signal in two ways. Outdoors, the microphone diaphragm will respond to the direct change in pressure associated with air flow; whereas indoors, the microphone will respond to the indirect change in pressure associated with wind and particularly gusts of wind that pressurize the interior of the building. These wind effects induce artificial noise that appears in the electrical signal generated by the microphone that is in the ILFN frequency range. This pseudo noise can, in turn, affect the spectral analysis of the recorded data. This form of pseudo noise (i.e., pressure changes due to air flow) is not substantially reduced by the use of a windscreen or even multiple windscreens generally regardless of their size.

Here, as discussed more fully in the Method of Analysis of Recorded Data section below, we analyzed the sound recordings in this study using a fast Fourier transform (FFT) technique to resolve low frequency and infrasound data. The primary range of interest in these measurements was in frequencies between 0.1 and 40 Hz. An FFT analysis produces a constant bandwidth (B). A 400-line FFT was used in the analysis, which means the bandwidth was $B = 0.1$ Hz. This allows resolution of frequency components to fractions of one Hz.

When using a very narrow bandwidth (e.g., 0.1 Hz), the time required for filtering is long in order to obtain the frequency resolution. The FFT analysis time T required for a specific bandwith B is given by: $T = 1/B$. For a 0.1 Hz bandwidth the time required is 10 sec. At this time scale, the effects of air pressure changes due to air movement tend to linger in the filtering process as discussed in the Method of Analysis of Recorded Data section below.

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[15] ANSI S12.9-2013/Part 3, Quantities and Procedures for Description and Measurement of Environmental Sound, Part 3: Short-Term Measurements with an Observer Present, American National Standards Institute, 2013.

To reduce the wind gust-induced artificial noise that manifests in the data with such long filtering times, both physical means during recording and analytical post-recording methods can be employed to minimize this artificial noise. The most effective pre-measurement technique is to dig a hole in the ground and put the microphone into it.[16] If two pits and microphones are used, then a cross-spectral analysis is also possible. In this study, however, it was impractical and, in some cases, impossible to dig microphone pits at the 15 total measurement locations. We thus relied on post-measurement analytical methods to filter out the pseudo noise as much as possible.

Each of the two most effective analytical techniques takes advantage of the fact that wind turbines and other large rotating machinery with blades (e.g., building ventilation fans and helicopters) produce very regular, oscillatory pressure fluctuations that are highly deterministic,[17] whereas pressure changes due to air movement associated with local wind gusts are essentially random in nature. The sound produced by wind turbines is tonal in nature, meaning that it has a spectrum with discrete frequencies that, in this case, are interrelated (i.e., harmonics of the blade passage frequency). This difference between the random wind noise and the wind turbine noise provides a means to minimize the latter in the signal processing of the recorded data. It has been posited that it is the tonal nature of wind turbine infrasound that may have some influence on residents in the vicinity of large wind turbines[18].

The artificial noise associated with pressure changes at the microphone due to local wind gusts can be minimized in two ways when analyzing the recorded signal. The first technique is to average the noise measurements over a longer time period. This tends to reduce the effect of pseudo noise associated with random air pressure transients during wind gusts, but does not affect the very regular, periodic pressure fluctuations generated by wind turbines.

When averaging over time is not sufficient, a second technique can be used to further minimize the effect of random pressure fluctuations associated with local wind. This second technique uses "coherent output power," a cross-spectral process. Both time averaging and coherent output power are discussed below under the method of analysis of recorded data.

WIND TURBINE OPERATION DURING MEASUREMENTS

Video recordings were made several times during the study period to document the operation of the wind turbines. Using the video recordings, we determined both the rotational speed of the wind turbine rotors (Ω in rpm) and the so-called "blade passage frequency" (f_0, also referred to as "blade passing frequency" or BPF), which is calculated in cycles per second, where $f_0 = N \times \Omega /60$, and N is the number of blades. For a three-bladed rotor ($N = 3$) the blade passage frequency is given by the equation:

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[16] Betke, L. and H. Remmers, Messung and Bewertung von tieffrequentem Schall, Proceedings of DAGA 1998 (in German)

[17] Johnson, Wayne, Helicopter Theory, Dover Publications, New York, 1980.

[18] Hessler, G., P. Schomer, Criteria for Wind-turbine Noise Immissions, Proceedings of the Meetings on Acoustics ICA 2013, Montreal, 2-7 June 2013, Acoustical Society of America, Vol. 19, 040152 (2013).

$$f_0 = \frac{\Omega}{20} .$$

Associated with the blade passage frequency are harmonics, which are integer multiples of the blade passage frequency. In this study, we typically observed at least five discrete harmonics in the measurement data. This pattern was also observed in the aforementioned Shirley Wind Farm study.

The harmonic frequencies are given by:

$$f_n = (n + 1) \times f_0 , where\ n \geq 1 .$$

For example, if Ω = 17 rpm, then f_0 = 0.85 Hz and the frequencies of the first six harmonics (n = 1 through 6) are: 1.7, 2.6, 3.4, 4.3, 5.1 and 6.0 Hz.

Table 5 summarizes a selection of the wind turbine speeds observed during the recordings. We note that the turbine speed of 16.2 rpm observed in Ocotillo at 19:51 on April 29 is the maximum rated speed for the Siemens SWT-2.3-108.

Table 5 Rotational Speeds Observed for Nearest Wind Turbines

Facility	Date	Location[1]	Time	Speed (rpm)	BPF (Hz)
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	April 28	D. Elliott	14:14	17.3	0.87
			15:05	17.1	0.86
			16:29	16.8	0.84
			16:30	16.3	0.81
		R. Elliott	17:28	16.7	0.83
		Thompson	19:32	17.2	0.86
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	April 29	Bonfiglio	9.37	12.2	0.61

Ocotillo Wind (Siemens Turbines – rated speed of 6 to 16 rpm)	April 29	O-R1	11:26	9.8	0.49
			11:29	7.4	0.37
			11:32	6.5	0.32
		O-R2	12:40	13.3	0.67
			13:54	15.0	0.75
			14:02	12.5	0.63
		O-R1	19:51	16.2	0.81
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	April 30	D. Elliott	10:33	15.6	0.78
		K-R2	11:22	16.7	0.83
			11:24	13.6	0.68
		Tisdale	13:45	14 to 16.6[2]	0.7 to 0.83[2]
		Oppenheimer	14:50	16.7	0.83
			15:17	17.1	0.86
			15:27	16.7	0.83
		Morgan	16:12	17.1	0.86
			16:18	16.2	0.81
			16:28	17.1	0.86

[1] Locations refer to where video was recorded

[2] Based on observed rotor speeds before and after recording

METEOROLOGICAL DATA

Weather Underground provides publicly available weather data for the two measurement areas (Boulevard and Ocotillo) on its website (wunderground.com). Among other things, this data includes wind speed, wind direction, temperature, and pressure. Weather Underground reports that it measures the meteorological conditions for Boulevard and Ocotillo at respective elevations of 4,113 feet and 694 feet above sea level. The relevant Weather Underground weather data for the Boulevard and Ocotillo areas is provided in Appendix B and summarized below.

Meteorological Data for the Kumeyaay Wind-Area Noise Measurements

We obtained noise measurements in the vicinity of the Kumeyaay Wind turbines on two different days. We took measurements on April 28, 2013, in the mid-afternoon to early evening. On April 30, we took measurements from mid-morning to mid-afternoon.

April 28, 2013

The Weather Underground data for this date show wind from the northwest in the morning, shifting to the west in the afternoon when the noise recordings were made. Average wind speeds between 1pm and 7pm were approximately 15 mph, with some gusts reaching 25 mph.

April 29, 2013

The Weather Underground data for this date show that wind speeds were considerably lower than on April 28, typically averaging between 5 and 8 mph, with some gusts reaching 10 mph. The wind direction between 9 am and 10 am, when the lone Kumeyaay Wind-area noise recording on this date was made, was from west south west.

April 30, 2013

The Weather Underground data for this date show that the wind direction in the morning was from the west, with average wind speeds that were 5 mph or less during the second recording at Mr. Elliott's residence. In the afternoon, during recordings at the Oppenheimer, Morgan and Tisdale residences, the wind was from the southwest, with average wind speeds between 10 and 17 mph and gusts up to 25 mph.

Meteorological Data for the Ocotillo Wind-Area Noise Measurements

We took noise measurements only on April 29, 2013, for the Ocotillo Wind Energy Facility. We took measurements from mid-morning to mid-afternoon, and then again from early evening to late evening.

April 29, 2013

The Weather Underground data for this date show that between 11am and 2 pm the wind direction was from the southwest with average wind speeds between 10 and 15 mph, with gusts from 15 to 20 mph. In the evening, the wind was also from the southwest, but was much stronger, with average wind speeds between 15 and 25 mph and gusts up to 35 mph.

METHOD OF ANALYSIS OF RECORDED DATA

We analyzed the 20 minute (nominal) recordings in the WIA laboratory with a Larson Davis type-2900 2-channel FFT analyzer. We first viewed each recorded sample in digital strip chart format to visually locate periods of lower local wind gusts to minimize low-frequency wind pressure transient effects on the data. We set the FFT analyzer for 40-Hz bandwidth, with 400-line and 0.1-Hz resolution. We used linear averaging. A Hanning window was used during a one- to two-minute, low-wind period to obtain an "energy average" with maximum sampling overlap. We stored the results for each sample, including autospectra, coherence, and coherent output power for both channels of data at the residential locations (i.e., indoors and outdoors). We also obtained autospectra for the reference locations.

Autospectra and Coherent Output Power

One of the strengths of our indoor-outdoor sampling design is that it made possible the use of what is called the "coherent output power" to filter out of the data the effect of the low-frequency wind pressure transients caused by local wind gusts. If two closely correlated signals are available (such as we have here, with the indoor and outdoor measurements for each residential study location), it is possible to use the coherent output power to reduce the effects of uncorrelated or weakly correlated phenomenon associated with wind gusts.

Coherent output power is based on use of the coherence between two signals to weight the spectra of one of the signals based on coherent frequency components common to the two simultaneously recorded signals. Where, as here, the wind turbine-generated noise remains at fairly consistent frequencies over the recording periods, the effects on the recorded signal of the essentially random, non-oscillatory pressure fluctuations caused by wind gusts should be reduced using this analysis procedure. The result is sometimes referred to as the coherent output spectrum.[19] For an example of previous studies that have used coherent output power to obtain wind turbine noise spectra, see Kelley, et al. (1985).[20]

In discussing coherent output power we use standard signal processing terminology. Obviously, all of the terms are functions of frequency.

For two signals (signal 1 and signal 2), the coherent output power for signal 2 (i.e., G_2) is defined as:

$$G_2 = {\gamma_{12}}^2 G_{22} \ .$$

The term ${\gamma_{12}}^2$ is the coherence (also referred to as spectral coherence) between the two signals and the term $G_{22}$is the autospectral density of the second signal. The value of the coherence lies in the range of $0 \leq {\gamma_{12}}^2 \leq 1$. A value of ${\gamma_{12}}^2 = 1$ indicates there is a one-to-one correlation between the two signals, which could only occur within an ideal system. In practice, ${\gamma_{12}}^2$ will generally be less than 1.

The coherence is defined as:

$${\gamma_{12}}^2 = \frac{|G_{12}|^2}{G_{11}G_{22}}$$

The term autospectral density used here has the same meaning as sound pressure level spectrum, the units of which are dB (re: 20 µPa). The term G_{11} is the autospectral density of the first signal.

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[19] Bendat, J. and A. Piersol, Random Data – Analysis and Measurement Procedures, 2nd Edition, John Wiley & Sons, 1986.

[20] Kelley, N.D., et al., Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact and Control, SERI/TR-635-1166 report prepared for U.S. Department of Energy, Solar Energy Research Institute, February 1985.

The term G_{12} is the cross-spectral density between the two signals, and the term $|G_{12}|^2$ is the square of the magnitude of the cross-spectral density.

For two recorded signals, it is possible to determine the coherence of the first with respect to the second (γ_{12}) and switch the two and determine the coherence of the second with respect to the first (γ_{21}). Consequently it is possible to obtain an inside coherent output power spectrum and an outdoor coherent output power spectrum. The measurement data presented herein indicate when the data are the autospectra, and when they are determined from the coherent output power. Where coherence data are presented, it is the coherence of the indoor signal with respect to that of the outdoor signal.

Sound Level Corrections Due to Use of Ground Board

Placing an outdoor microphone on a ground board, as was done in this study, results in higher sound pressure levels (up to 3 dB greater) for frequencies in the range of 50 to 20,000 Hz when compared to those measured at 4.5 to 5.5 feet above the ground, a standard height used to make environmental noise measurements as indicated in ANSI S12.9-2013/Part 3. Consequently corrections to the sound level data at frequencies greater than 50 Hz obtained using a ground board would be required.

However, for frequencies less than 50 Hz, the sound pressure level at the ground surface is essentially the same as that at a height of 5 feet. This is because a microphone on a tripod 5 feet above the ground is at a height less than one-fourth the wavelength of the sound at this frequency (i.e., $0.25 \times \lambda_{50\,Hz} = 0.25 \times \frac{1{,}100}{50} = 5.5\,feet$) and there is little difference at frequencies less than 50 Hz between the sound field at ground level and the sound field at 5 feet above the ground. This fact has been confirmed by other measurements[21].

Because the data presented herein are in the ILFN range with frequencies less than 40 Hz, no corrections to the sound level data are necessary, even though the measurements were made with a ground board.

NOISE MEASUREMENT RESULTS

Noise Data for Kumeyaay Wind

The noise spectra data from the Kumeyaay Wind-area measurements are provided in Appendix C. The turbine blade passage frequencies – in the range of 0.7 to 0.9 Hz (see Table 5) – and their harmonics up to 5 Hz are evident in the sound spectra from both recording days. Indeed, they align almost exactly with the predominant spectral peaks. This is a very strong indication that the wind turbines produced the ILFN at those frequencies.

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[21] Hansen, K., Z. Branko, C. Hansen, Evaluation of Secondary Windshield Designs for Outdoor Measurements of Low Frequency Noise and Infrasound, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

Data for Live Oak Springs Resort, Cabin #2 (K-LOSR)

It is instructive to first examine the spectra obtained at the Live Oak Springs Resort where there was virtually no local wind during the recording even though there was wind at the turbines as determined from observing the closest turbine rotating at the time. Live Oak Springs Resort is somewhat sheltered from wind, but has a direct line of sight to the closest wind turbine at a distance of 5,950 feet.

Looking at Figure C-1, it is evident in the autospectra for both indoor and outdoor measurements that the discrete frequencies predominating in the infrasound range correspond to the blade passage frequency of the nearest wind turbine (0.8 Hz) and its first five harmonics (1.6, 2.4, 3.2, 4.1 and 4.9 Hz). A blade passage frequency of 0.8 Hz corresponds to a rotational speed of 16 rpm. We note that the indoor levels at these frequencies are slightly higher than the outdoor levels, an indication of possible amplification associated with the building structure.

Figure C-2 presents the two coherent output power spectra and the coherence of the indoor to outdoor signals. At the blade passage frequency (0.8 Hz) and in the range of 1.6 to 5 Hz (including the first five blade passage frequency harmonics of 1.6, 2.4, 3.2, 4.1 and 4.9 Hz), the coherence is 0.75 or greater, indicating a strong correlation between indoor and outdoor sound levels.

A high coherence indicates that two signals are strongly correlated and contain the same frequency content. This is exactly what one would expect from a large rotating mechanical device such as a wind turbine that produces a steady, tonal (periodic) sound, whereas the effects of wind are very random in particular concerning signals from two different microphones, one of which is indoors. Hence, the correlation of the wind effects in the indoor and outdoor signals should be weak for the random effects of the wind. Thus there will be a low coherence associated with the wind and its effects on the two different signals. Averaging the total microphone signal over time and weighting the result by the coherence results in a diminished contribution from the wind, because of the low coherence of the wind effects.

Figure C-3 compares the autospectrum with the coherent output spectrum for the indoors measurement at Live Oak Springs Resort. It shows a very close match over the frequency range of 0.8 to 5 Hz at the discrete frequencies associated with the wind turbine ILFN.

Inside the guest cabin at Live Oak Springs Resort, sound pressure levels in the infrasound range measured between 45 and 49 dB. The outside sound pressure levels were somewhat lower in the ILFN range, seeming to indicate an amplification occurring from outside to inside, which became even more pronounced in the range of 5 to 8 Hz. There is also a strong peak at 26.4 Hz, which may be caused by an "amplitude modulation" similar to that identified in the Falmouth wind turbine study[22]. The coherence at this frequency is 0.95. Amplitude modulation occurs when a low frequency signal causes the level of a higher frequency signal to fluctuate. This fluctuation occurs at the frequency of the lower frequency signal. This has been the subject of many complaints concerning wind turbine noise[23] [24].

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[22] Ambrose, S. and R. Rand, The Bruce McPherson Infrasound and Low Frequency Noise Study, 14 December 2011.

[23] Gabriel, J., S. Vogl, T. Neumann, Amplitude Modulation and Complaints about Wind Turbine Noise, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

The ILFN levels at Live Oak Springs Resort's guest Cabin #2 would have been even greater if the cabin were closer to the nearest Kumeyaay Wind turbine than it is – 1.1 miles, or 5,950 feet. The ILFN levels would have also been greater under different wind conditions. According to the Weather Underground report for Boulevard, at the time we measured the noise at the guest cabin – starting at 10:10 pm on April 28 – the wind was blowing from the west with an average speed of approximately 7 mph and gusts up to 12 mph, which is at the lower end of the operating conditions for the Gamesa wind turbines. Because the closest wind turbine is north-northeast of the cabin, the cabin was crosswind and somewhat upwind of the turbine and thus receiving lower levels of turbine-generated noise than locations downwind of the turbines.

Data for Dave Elliott's Residence

Like the Live Oak Springs Resort guest cabin measurements, the April 30 (11 am) measurements at Dave Elliott's residence show pronounced peaks in the autospectra at frequencies corresponding to the blade passage frequency of the nearest wind turbine (0.78 Hz) and the first five harmonics. The inside level at 0.78 Hz was 54 dB. In this case, as displayed in Figure C-4, the sound levels were slightly higher inside than outside at 1.6 and 2.4 Hz. Above 3 Hz the inside levels were lower than outside. The maximum inside sound level of 59 dB occurred at 1.6 Hz (the first harmonic of the blade passage frequency).

Data for Ginger Thompson's Residence

As shown in the autospectrum in Figure C-5, the April 28 (6:50 pm) measurements at Ginger Thompson's residence demonstrate a similar discrete frequency pattern between 0 and 5.2 Hz that corresponds to the blade passage frequency of the nearest turbine (0.80 Hz) and the first three associated harmonics (1.6, 2.4, and 3.2 Hz), which corresponds to a rotational speed of 16.0 rpm. The lowest frequency peak in the spectrum occurs somewhat lower (i.e., at 0.78 Hz) than the blade passage frequency; a phenomenon seen in some of the other measurement data.

As also seen at Mr. Elliott's residence and at most other study sites, the measured ILFN levels at Ms. Thompson's residence were amplified indoors, with the inside levels higher than outside levels throughout the frequency range. The maximum inside sound level of 60 dB occurred at just below the blade passage frequency of 0.80 Hz.

Data for Rowena Elliott's Residence

In the April 28 (5:30 pm) measurement data from Rowena Elliott's residence, shown in Figure C-6, the autospectra peaks corresponding to WT infrasound from Kumeyaay protrude above the general wind noise spectrum. The inside coherent output power spectrum is also plotted in Figure C-6 with most of the same peaks that appear in the autospectrum. Also present in the spectrum is a peak at 1.0 Hz, which does not correspond to any of the harmonics of the BPF observed in Kumeyaay at that time. We suspect that this infrasound is coming from the wind turbines at Ocotillo Wind, which are 15 to 20 miles away. This peak would correspond to a BPF

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[24] Stigwood, M., S. Large, D. Stigwood, Audible Amplitude Modulation – Results of Field Measurements and Investigations Compared to Psycho-acoustical Assessment and Theoretical Research, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

of 0.5 Hz, which would be consistent with the somewhat slower rotational speeds for the WTs in Ocotillo. Detecting WT infrasound from 15 to 20 miles away is not surprising. Metelka[25] for example has measured WT infrasound at a distance of 77 miles from its source. The maximum inside sound level of 53 dB occurred at 1.6 Hz, the first harmonic of the Kumeyaay BPF (0.8 Hz).

Data for Kenny Oppenheimer's Residence

As with the data for the previously discussed measurement locations, the April 30 (3:11 pm) measurement data for Kenny Oppenheimer's residence, shown in Figure C- 7, reveal sound pressure level peaks at the blade passage frequency of the nearest wind turbine (0.9 Hz) and its first three harmonics (1.8, 2.7 and 3.6 Hz). There is also a strong peak both indoors and outdoors at 13.6 Hz whose source, in contrast to the wind turbine-generated ILFN peaks at the blade passage frequency and its first three harmonics, we have been unable to identify. In this case, however, the outside sound levels were much greater than those inside the residence. The highest outside sound level was 57 dB and occurred at the blade passage frequency of 0.9 Hz. By contrast, the highest indoor sound level in the coherent output power spectrum was 44 dB, also at 0.9 Hz.

We have estimated the WT infrasound inside at 0.9 Hz to be approximately 51 dB using the coherent output power spectrum level and correcting for the coherence at that frequency. This seems to indicate that the residence is attenuating the wind turbine infrasound more substantially than at some of the other residences investigated, which could be due to a much more tightly sealed building envelope and/or a more substantial exterior wall construction. This effect was also evident in the data for one of the Ocotillo residences.

As a result of this disparity, the coherence of the indoor and outdoor ILFN signals is not as great as with closer measurement locations, including the Live Oak Springs Resort guest cabin and the residences of Mr. Elliott, Ms. Thompson and Ms. Elliott. Nonetheless, the coherence of the two signals at the blade passage frequency and its first three harmonics is still relatively strong, at 0.5 or greater. This evinces a definite correlation between outdoor and indoor sound levels even at great distance from the wind turbine noise source. Also evident in the data is a peak at 13.7 Hz. The may be caused by amplitude modulation.

Data from Marie Morgan's Residence

The April 30 (4:20 pm) measurement data from Marie Morgan's residence, including the inside and outside coherent output power spectra, are shown in Figure C-8. Like the data measured at the residences of Mr. Elliott, and Ms. Thompson, the data at Ms. Morgan's residence show higher levels of ILFN indoors than outdoors.

And like the data measured at Ms. Elliott's residences, there appear to be multiple – in this case three – different BPFs in the data. The lowest BPF, similar to the data measured at Ms. Elliott's residence, appears to be infrasound coming from Ocotillo Wind (i.e., BPF1 of 0.39 Hz). Above that frequency there are two BPF which are associated with Kumeyaay WTs. Note that not all

[25] Metelka, A., Narrowband low frequency pressure and vibration inside homes in the proximity to wind farms, presentation at the 166th Meeting: Acoustical Society of America, San Francisco, 4 December 2013.

Kumeyaay WTs could be observed, and it is possible that some could be operating at a speed of 14 rpm and others at a speed of 18 rpm. The two BPF are at 0.68 Hz (BPF2) and 0.88 Hz (BPF3). A peak indoor level of 58 dB at the first harmonic of BPF 3 (1.7 Hz) was measured

In any event, the Morgan residence data demonstrate that under the right weather and topographical conditions, large wind turbines like those used at Kumeyaay Wind can produce high levels of ILFN inside buildings even miles away.

Data from Don Bonfiglio's Residence

As with the other Kumeyaay Wind-area study sites, the measurement data for Don Bonfiglio's residence, shown in Figure C- 9, display sound level peaks at the blade passage frequency of the nearest wind turbine (0.61 Hz) and the first three associated harmonics (1.2, 1.8 and 2.4 Hz). The sound levels, both indoors and outdoors, at these frequencies are in the range of 30 to 42 dB. The maximum inside level is 42 dB at 1.2 Hz (the frequency of the first harmonic of the blade passage frequency – BPF2).

While the coherence between the indoor and outdoor measurements is less than 0.5 at the blade passage frequency and associated harmonics, it is not surprising given the distance to the nearest wind turbine (2.9 miles, which is a greater distance than at any other Kumeyaay Wind-area study site except the Tisdale residence). Propagation effects (e.g., intervening terrain, atmospheric conditions) and interactions between infrasound from different wind turbines result in a more complex sound field at infrasound frequency as the distance increases. The wavelength of sound at 1 Hz is approximately 1,100 feet. At 2.9 miles the site is approximately 14 wavelengths from the sources of infrasound. Hence it is normal to witness declining coherence with increased distance due to this complexity. Also evident in the spectral data is a BPF peak at 0.39 Hz, which is most likely infrasound from Ocotillo Wind. There is also a harmonic at 0.78 Hz associated with the BPF.

Data from Donna Tisdale's Residence

The farthest (from a Kumeyaay Wind turbine) measurements we took were at the residence of Donna Tisdale, which is 5.7 miles from the nearest wind turbine. Yet even at that great distance, the data show as indicated in Figure C-10 peaks at the blade passage frequency (BPF2) of the nearest turbine (0.7 Hz) at Kumeyaay and its associated harmonics, albeit at lower sound pressure levels than observed at the closer study sites. The maximum measured indoor ILFN sound level was 43 dB at 0.7 Hz (the blade passage frequency). There is also a lower BPF at 0.39 Hz, which is most likely infrasound from Ocotillo Wind.

As similarly observed at the Bonfiglio residence, the coherence between the indoor and outdoor measurements at the Tisdale residence is mostly less than 0.5 for frequencies below 10 Hz. As indicated above, given the distance from the Tisdale residence to the nearest wind turbine (5.6 miles), this is not surprising. The Tisdale ranch is approximately 27 wavelengths from the wind turbines. The turbines are not visible from the ranch, because of intervening terrain. However the turbines are visible from some higher elevations of the ranch property.

Data from the Reference Sites

In contrast to the data for the Kumeyaay Wind-area residential measurement sites, the frequency and sound level data we present in the autospectra in Figures C-11 and C-12 for the two reference locations shows the autospectra values rather than the coherent output power. Because there was no option for making indoor sound measurements near the reference locations, we only used a single microphone to take measurements and thus did not measure a coherence or coherent output power. At both reference locations (K-R1 and K-R2), the data show clear sound level peaks at the blade passage frequency of the nearest turbine and the associated harmonics in the 0 to 5 Hz range. At K-R1, the sound levels of the peaks ranged from 53 dB to 60 dB (at the blade passage frequency, 0.84 Hz). At K-R2, which at 930 feet away was the measurement site closest to the Kumeyaay Wind turbines, the sound levels were even greater, between 60 dB and 70 dB for the spectral peaks below 3 Hz.

Tabulated Data

Table 6 lists the Kumeyaay Wind-area residential measurement locations, along with their distance from the nearest wind turbine, the highest measured indoor sound pressure levels, and the frequency of those peak sound pressure levels.

Table 6 Summary of Wind Turbine Noise for Kumeyaay Inside Residences

Residence	**Distance[1]**	**Highest Sound Pressure Spectrum Level Indoors[2,3,4]**	**Frequency (Hz) of Peak Spectrum Level**	**Rotor Rotational Component**
D. Elliott	2,960 feet	59 dB	1.6	1st harmonic
G. Thompson	2,880 feet	60 dB	0.8	BPF
R. Elliott	4,330 feet	53 dB	1.6	1st harmonic
K-LOSR	1.1 miles	48 dB	2.4	2nd harmonic
K. Oppenheimer	1.6 miles	51 dB	0.9	BPF
M. Morgan	1.7 miles	58 dB	1.7	1st harmonic
D. Bonfiglio	2.9 miles	42 dB	1.1	1st harmonic
D. Tisdale	5.7 miles	43 dB	1.4	1st harmonic

[1] Distance from closest wind turbine

[2] Decibels (re: 20 μPa)

[3] All but Live Oak Spring Resort, D. Elliott and G. Thompson data are coherent output power levels

[4] Oppenheimer data are estimated from coherent output power and correction for coherence

We note that while the Morgan residence data appears anomalous when compared with the trend of sound pressure levels as a function of distance from the wind turbines, it is not. Instead, the Morgan residence data demonstrates that under the right weather and topographical conditions, large wind turbines like those used at Kumeyaay Wind can produce high levels of ILFN inside buildings even miles away. It appears that one factor that contributed to the higher infrasound levels at the Morgan residence is the fact that this house was located downwind of multiple turbines, whereas the other residences except for Mr. Elliott's were either upwind of the turbines and/or had a more obscured line-of-sight to the full array of turbines compared to the Morgan's.

Noise Data for Ocotillo Wind

The noise spectra for the Ocotillo Wind-area measurements are displayed in Figures C-13 through C-21 in Appendix C. Table 7, below, summarizes much of the relevant data for the residential measurements.

In contrast to the relatively consistent wind conditions in the Kumeyaay Wind area throughout the measurement periods, the wind at the Ocotillo Wind Energy Facility varied greatly across the measurement periods. During the first recordings on the morning of April 29, the wind was generally light and the turbine blades were rotating slowly (less than 10 rpm). In the afternoon, however, the wind picked up considerably and the rotational speed of the turbine blades increased (e.g. 13 rpm). And later that night, when we took our last measurements, the wind speed had increased even more, causing the turbine blades to rotate even faster (i.e., 16 rpm observed at 7:51 pm just before dark). Between the first measurements in the morning and the last measurements at night, the turbines' average blade passage frequency increased from 0.5 Hz to 0.8 Hz.

The Ocotillo recordings were analyzed several different ways using cross-correlation, longer averaging times and 1/3-octave band filtering among other methods, without significantly changing the results. For the Ocotillo data, the coherence between the indoor and outdoor signals is low (i.e., less than 0.5). This, along with the spectral data, indicates a complex sound field with more than one BPF present, rather than a classical spectrum of tonal components including just one BPF and its harmonics. Note that it was only possible to observe a handful of turbines at a time out of the 112 turbines at Ocotillo Wind. Consequently, the BPF indicated in Table 5 for the Ocotillo recordings represent the BPF of the turbine or turbines closest to the reference location measurements and not the BPF for turbines in the entire facility.[26]

One possible explanation for low coherence is that Ocotillo Wind has so many turbines spread out over such a large area (with accompanying differences in wind speed and direction at each turbine), the ILFN produced by the turbines at Ocotillo has a greater probability of being less strongly synchronized as it is at Kumeyaay, for example, where the turbines are arrayed in a line on a ridge and experience a much more uniform wind configuration (i.e., speed and direction). At Ocotillo, it is much more likely that the wind turbines rotate at different speeds from one another. Thus where a residence or other receptor is exposed to ILFN from more than one

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[26] After dark (approximately 8 pm) on 30 April 2013 it was not possible to observe the rotational speed of turbines at Ocotillo Wind. However, it was possible to deduce the rotational speed of the turbines from the measured data.

turbine, which will usually be the case with most Ocotillo-area locations, it will experience a complex sound field with varying tonal components derived not only from the different turbines directly, but also possibly from the interaction of tonal components from a multitude of turbines.

Another possible factor contributing to the lower coherence between outdoor and indoor sound levels at Ocotillo could be that the residential structures alter the frequency of the WT noise just enough as the sound energy passes through them that the sound indoors is at a slightly different frequency than the sound outdoors. Although this effect is not as apparent in the Kumeyaay data, it is possible that the distributed pattern of the Ocotillo wind turbines makes it more apparent here.

Data for the Residential Sites

As evidenced by the data in Table 7 and by comparing the coherent output power spectra from the morning and night measurements at the Pelley residence (Figures C-13 and C-14), as well as the afternoon and night measurements at the Ewing residence (Figures C-15 and C-16), the ILFN sounds pressure level increased substantially as the wind speed picked up and the blade passage frequency of the turbines increased. This indicates not only that the Ocotillo Wind turbines produced much of the measured ILFN, but that the turbines can create very high ILFN sounds levels even at substantial distance. The Tucker residence data are shown in Figures C-17 and C-18.

Looking specifically at the Pelly residence data for the daytime measurement (Figure C-14) it would appear that there are two blade passage frequencies present (0.5 and 0.6 Hz). This is not surprising considering the distribution of turbines over a large area where different turbines see different wind conditions. The spectral peaks above the blade passage frequencies are consistent with this assessment. The two blade passage frequencies indicate corresponding rotational speeds of 10 and 12 rpm.

Two distinct blade passage frequencies (0.68 and 0.88 Hz) are also evident from the nighttime measurements at the Pelley residence. These blade passage frequencies are indicative of rotation speeds of 13.6 and 17.6 rpm respectively. Although the higher rotational speed is slightly above the reported, operational speed range (6 to 16 rpm) for the Siemens turbines, there is no other source for the infrasound in this area. Note that the outdoor coherent output power spectrum is omitted for clarity in Figure C-14.

The spectra from the Ewing residence likewise indicate two different blade passage frequencies during both the day and night. In Figure C-15 we see the same frequency of the second BPF of 0.88 Hz in the daytime data, confirming that in fact this is infrasound from the Ocotillo WTs. The nighttime data at the Ewing residence as shown in Figure C-16 indicates two BPF also (0.39 and 0.49 Hz) and their associated harmonics.

The data for the Tucker residence similarly contain two BPF during the day (0.6 and 0.8 Hz) and two in the nighttime (0.39 and 0.68 Hz), with the lower BPF reflected in the data at the Ewing residence at night.

Whereas the Pelly residence data indicates an amplification of sound level between inside and outside, the data for other two residences indicate the opposite. Apparently the Ewing residence is more tightly sealed. It also seemed to be of a more substantial construction. The Tucker residence data also shows a reduction from outside to inside. An explanation for this effect could be the shielding provided by neighboring structures, which are more closely spaced than at the Pelly residence. The Tucker residence may also be more tightly sealed.

That the Ocotillo Wind turbines generated much of the ILFN measured at the Pelley and Ewing residences is strongly supported by the fact that the recorded data for both residences show sound level peaks at the turbine blade passage frequencies and many of the associated harmonics. The reference location measurement data also demonstrate this pattern, although not as clearly.

Data for the Reference Sites

At reference location 1 for the Ocotillo Wind-area measurements (O-R1), the nighttime ILFN levels were quite high, with multiple peaks above 60 dB including at frequencies that correspond to many of the harmonics of the blade passage frequency of the nearest wind turbine. The overall peak sound level of 74 dB occurred at the blade passage frequency (0.8 Hz). At O-R2, which at 1,470 feet away was the measurement site closest to the Ocotillo Wind turbines, the peak sound level of 78 dB was even greater, and also occurred at the blade passage frequency of 0.8 Hz. Similarly, at O-R3, which was adjacent to the Ocotillo substation, the peak sound level was 77 dB and occurred at the blade passage frequency of 0.8 Hz. These data are shown in Figures C-19 through C-21.

Tabulated Data

Table 7 lists the Ocotillo Wind-area residential measurement locations, along with their distance from the nearest wind turbine, the highest measured indoor sound pressure levels, and the frequency of those peak sound pressure levels. As expected given higher wind speeds at night, nighttime, indoor noise levels range from 15 to 27 dB higher than those measured during the day.

Table 7 Summary of Wind Turbine Noise for Ocotillo Inside Residences

Residence	**Distance**[1]	**Time of Day**	**Highest Sound Pressure Spectrum Level Indoors**[2,3]	**Frequency (Hz) of Spectrum Peak Level**	**Rotor Rotational Component**
Pelley	3,220 feet	Day	42 dB	0.6	BPF2
			49 dB	1.0	1st of BPF1
		Night	67 dB	0.68	BPF1
			69 dB	0.88	BPF2
Ewing	3,590 feet	Day	48 dB	0.59	BPF1
			51 dB	0.88	BPF2
		Night	42 dB	0.39	BPF1

			59 dB	0.78	1st of BPF2
Tucker	1.2 miles	Day	42 dB	0.6	BPF1
			48 dB	0.8	BPF2
		Night	66 dB	0.68	BPF2
			69 dB	1.37	1st of BPF2

[1] Distance from closest wind turbine

[2] Decibels (re: 20 μPa)

[3] All are coherent output power spectrum levels

DISCUSSION OF RESULTS

It is clear from the measured noise data obtained from Kumeyaay and Ocotillo facilities that there is significant wind turbine-generated ILFN. This was to be expected as it has been documented by others such as in the McPherson noise study, the Shirley Wind Turbine study, and by Epsilon Associates.[27] And indeed the measured ILFN levels near Kumeyaay and Ocotillo wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

Both the McPherson and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth, Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce ILFN, and whether that ILFN was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated ILFN at numerous nearby residences that correlated with residents' reported impacts.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then.

Recent research and investigations into human response to ILFN have been conducted and seem to provide strong evidence of a cause and effect relationship. In particular the work of Salt, et al.[28] has made a clear case for perception of ILFN below the threshold of hearing as defined by ISO 389-7 which is related to the response of the ear's inner hair cells (IHC). Salt has demonstrated that it is possible for the ears' outer hair cells (OHC) to respond to ILFN at sound

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[27] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

[28] Alec Salt, and J. Lichtenhan, Perception based protection from low-frequency sounds may not be enough, Internoise 2012, August 2012.

pressure levels that are much lower than the IHC threshold. Salt has reported that ILFN levels (levels commonly generated by wind turbines nearby residences) can cause physiologic changes in the ear.[29] Salt and Kaltenbach "estimated that sound levels of 60 dBG will stimulate the OHC of the human ear."[30]

Furthermore, Matsumoto et al.[31] have demonstrated in a laboratory setting that humans can perceive ILFN at sound pressure levels below the IHC threshold when the noise is a complex spectrum (i.e. contains multiple frequency components). From this laboratory research it was clearly demonstrated that humans can perceive sound pressure levels that are from 10 to 45 decibels (dB) less than the OHC threshold in the ILFN range. In fact, the Matsumoto thresholds clearly follow the OHC threshold down to the frequency below which the two diverge. The Matsumoto thresholds are lower than the OHC thresholds at frequencies below the point at which they diverge.

These studies and more recent studies demonstrate that wind turbines (specifically wind turbine-generated ILFN) have the potential to not only annoy humans, but harm them physiologically.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay and Ocotillo facilities. Higher wind speeds generally produce higher noise levels in particular higher ILFN. This is clearly demonstrated in the Ocotillo data when comparing the daytime and nighttime levels.

NOISE METRICS FOR MEASURING ILFN

There are several noise metrics which are used to quantify environmental noise levels. The most common metric is A-weighting (A-wt). The A-wt curve is shown in Figure 6. The A-wt metric is intended to approximate the loudness sensitive of the human ear for common environmental sounds in the range of 20 to 20,000 Hz. A-wt at 1 Hz is -149 dB. Hence a noise limit based on A-wt would not be appropriate to address ILFN, a major component of which is sound below 20 Hz.

A noise metric sometimes used when there is low frequency noise is the C-weighting (C-wt). While the C-wt metric does attempt to address low frequency noise better than A-wt, it would also not be appropriate for quantifying infrasound, since it still strongly de-emphasizes sound at frequencies below 20 Hz as shown in Figure 6. C-wt at 1 Hz is -52.5 dB.

One noise metric recently used to quantify ILFN is G-weighting (G-wt). The G-wt measure has been used in Europe. G-wt would certainly be a more representative measure of ILFN than

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[29] Alec Salt, and J.A. Kaltenbach, "Infrasound from Wind Turbines Could Affect Humans," Bulletin of Science, Technology and Society, 31(4), pp.296-302, September 12, 2011.

[30] Ibid., p. 300, "As discussed below, G-weighting (with values expressed in dBG) is one metric that is used to quantify environmental noise levels. While it is a more accurate measure of ILFN than most other metrics, G-weighting still de-emphasizes infrasound."

[31] Yasunao Matsumoto, et al, An investigation of the perception thresholds of band-limited low frequency noises; influence of bandwith, published in The Effects of Low-Frequency Noise and Vibration on People, Multi-Science Publishing Co. Ltd.

either the A- wt or the C- wt metrics, but as shown in Figure 6 it too de-emphasizes the very low frequency infrasound by -40 dB at 1 Hz.

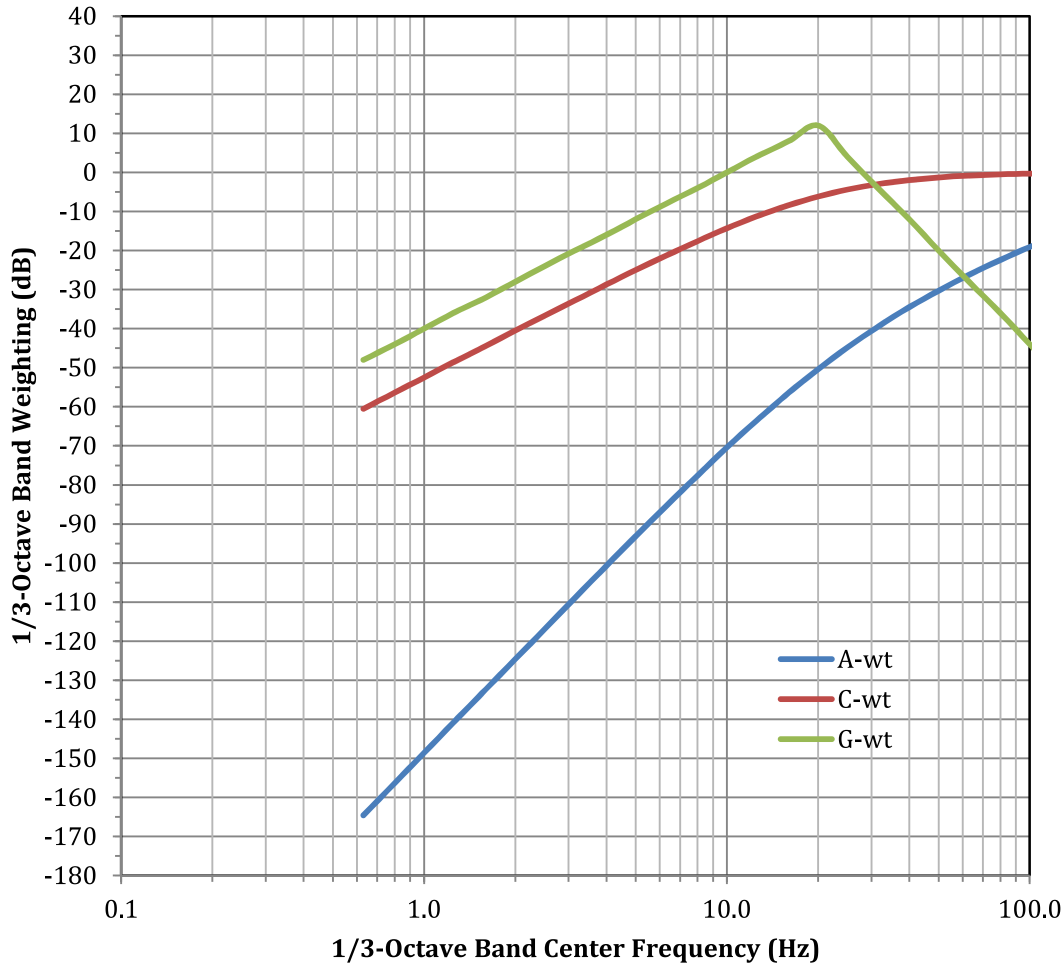


Figure 6 A, C and G Spectral Weighting Curves

CONCLUSION

The results of this study conclusively demonstrate that both the Kumeyaay and Ocotillo facilities' wind turbines generate ILFN at residential and other locations up to 15 miles away.

TERMINOLOGY

- Autospectrum: The autospectrum is the narrow band, energy average sound pressure level spectrum (in dB) measured for a specific time interval.
- Coherence: The spectral coherence is a statistic that can be used to examine the relation between two signals or data sets. It is commonly used to estimate the power transfer between input and output of a linear system. If the signals are ergodic, and the system function linear, it can be used to estimate the causality between the input and output.
- Cross-spectrum: In time series analysis, the cross-spectrum is used as part of a frequency domain analysis of the cross correlation or cross covariance between two time series.
- Cycles per second: A unit of frequency, same as hertz (Hz).
- Decibel (dB): A unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm (to the base 10) of this ratio. For sound, the reference sound pressure is 20 micro-Pascals.
- FFT (fast Fourier transform): An algorithm to compute the discrete Fourier transform and its inverse. A Fourier transform converts time to frequency and vice versa; an FFT rapidly computes such transformations.
- ILFN: Infrasound and low frequency noise.
- Infrasound: Sound at frequencies lower than 20 Hz.
- Low frequency noise: Noise at frequencies between 20 and 200 Hz.
- Noise level: The sound pressure energy measured in decibels.

APPENDIX A – MEASUREMENT LOCATIONS

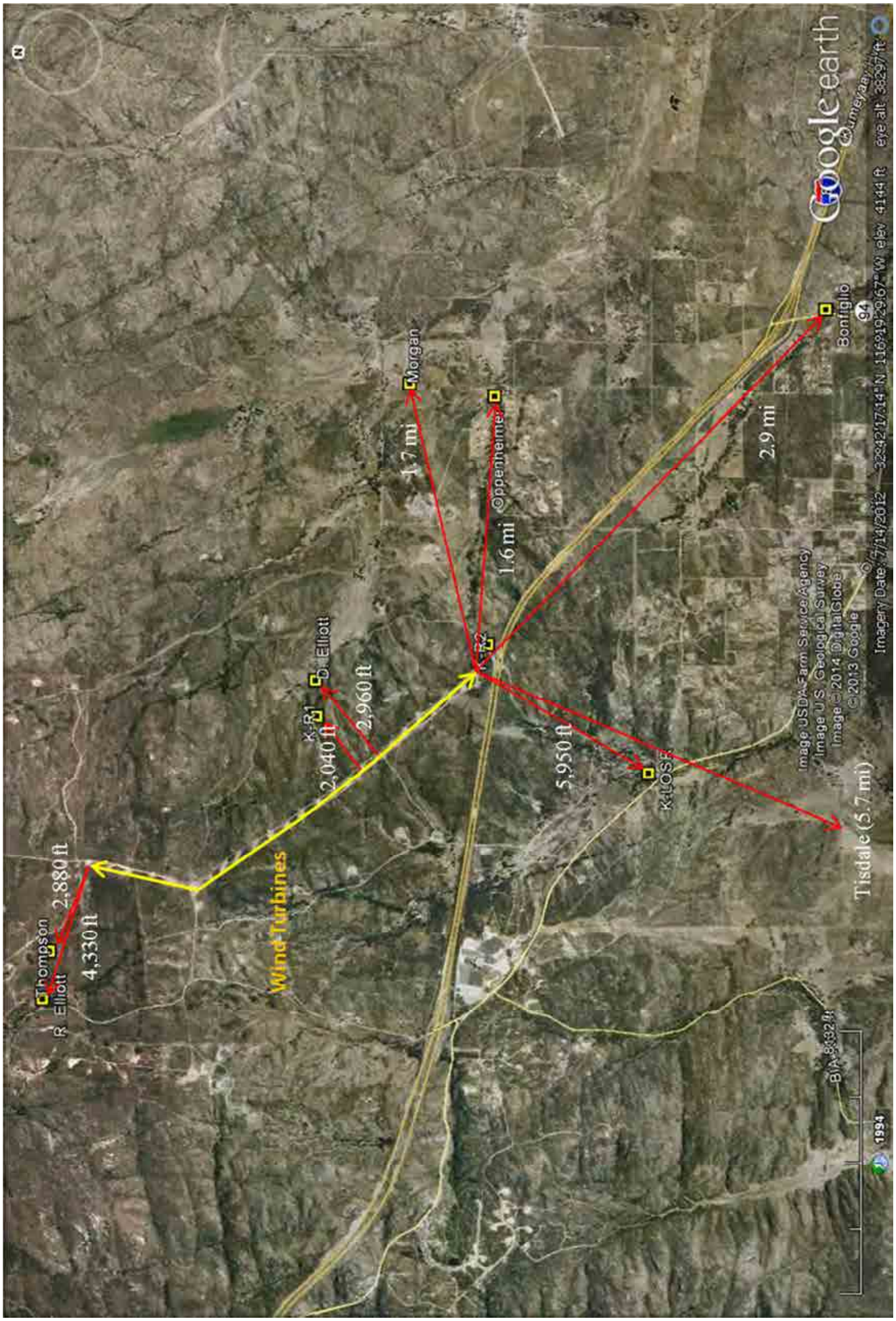


Figure A - 1 Kumeyaay Measurement Locations

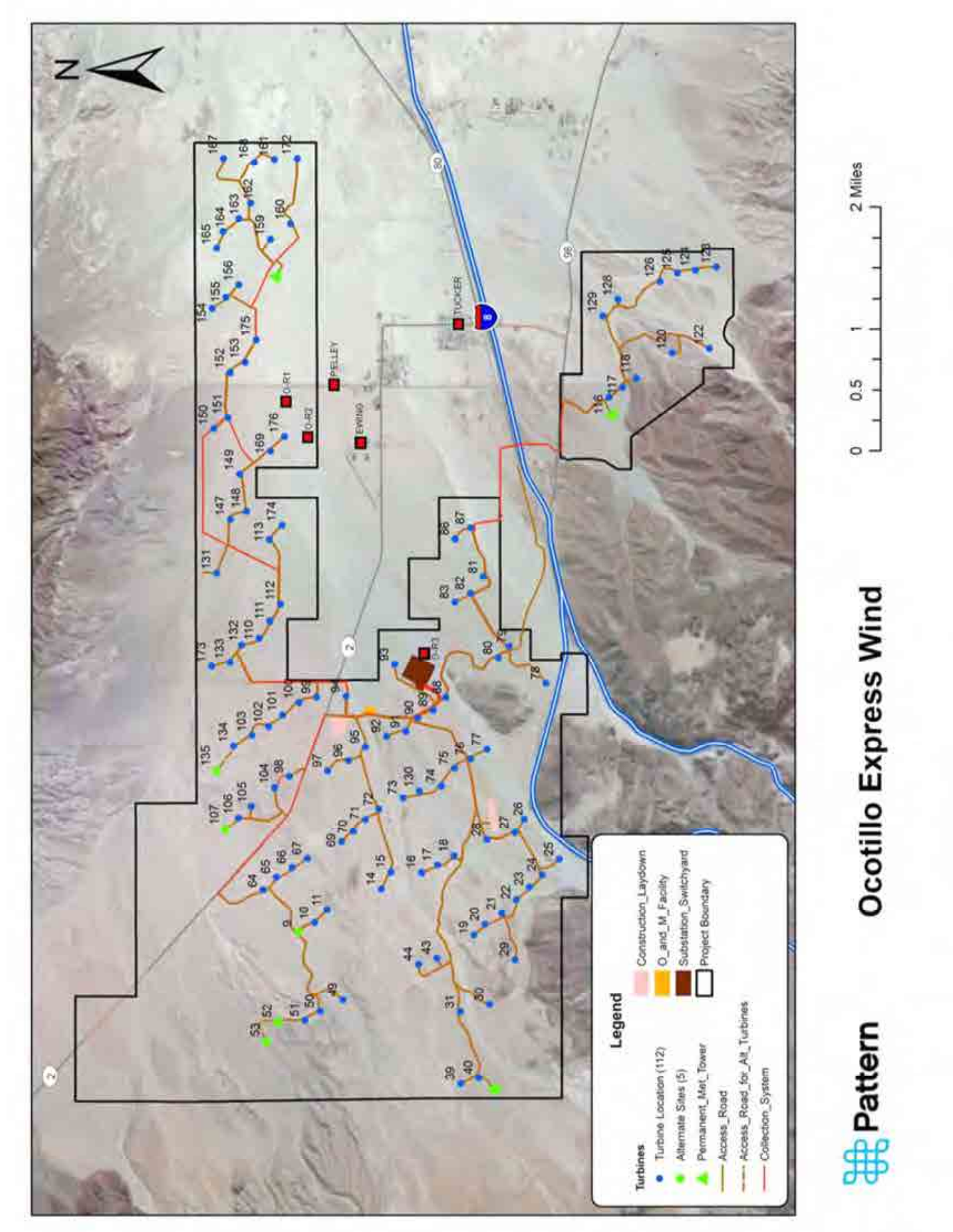


Figure A - 2 Ocotillo Measurement Locations

APPENDIX B – METEOROLOGICAL DATA

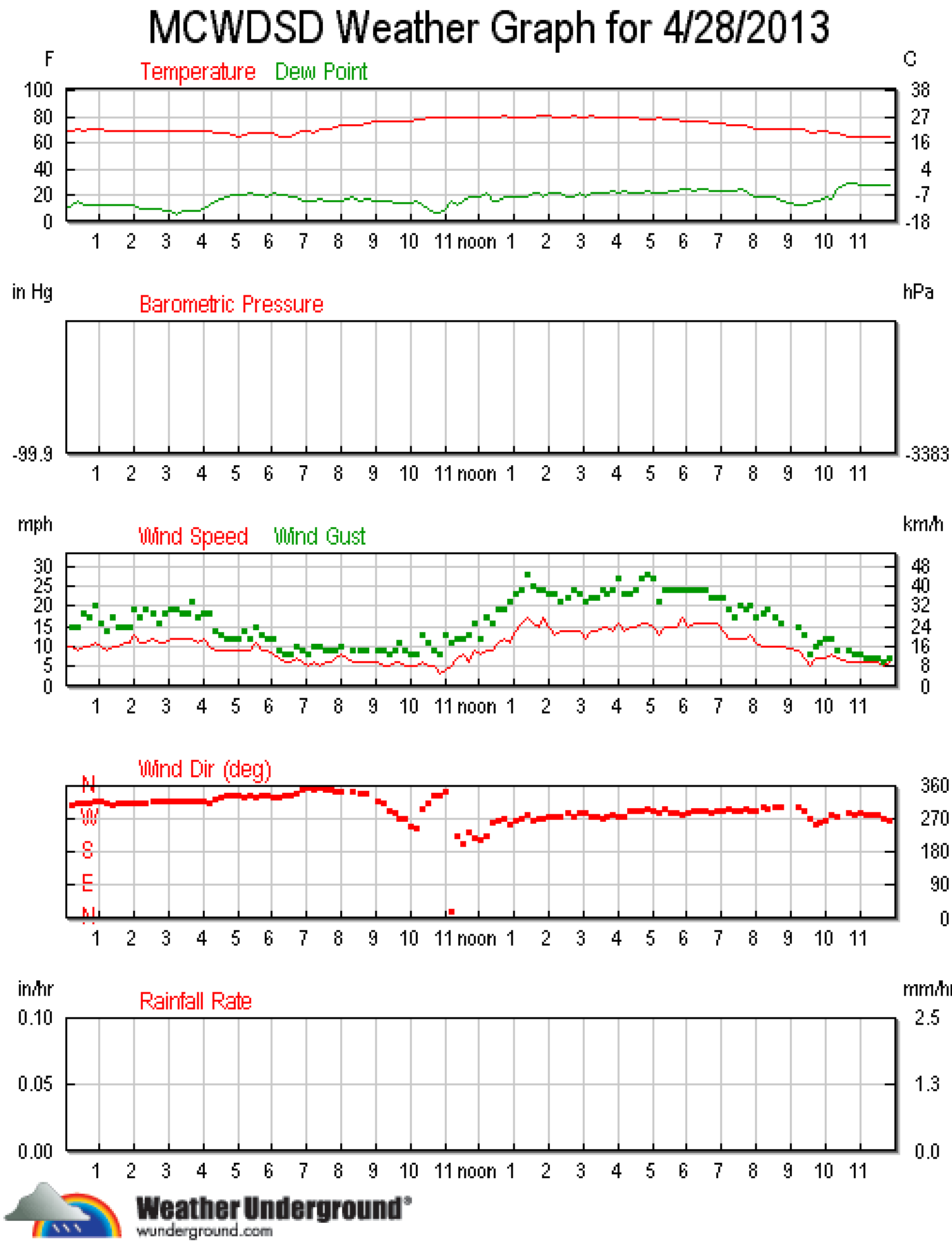


Figure B - 1 Weather Data for Kumeyaay 28 April 2013

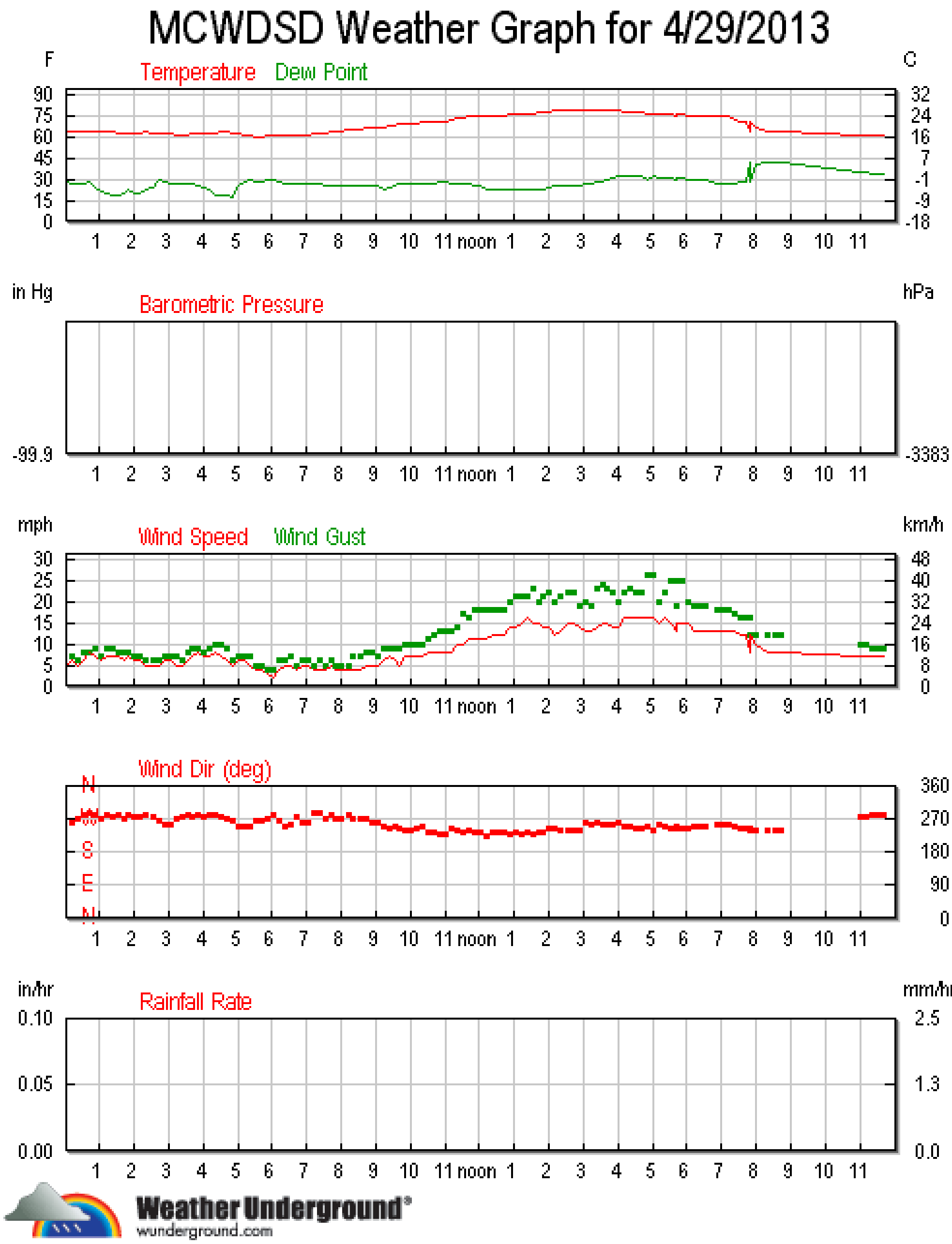


Figure B - 2 Weather Data for Kumeyaay April 29 2013

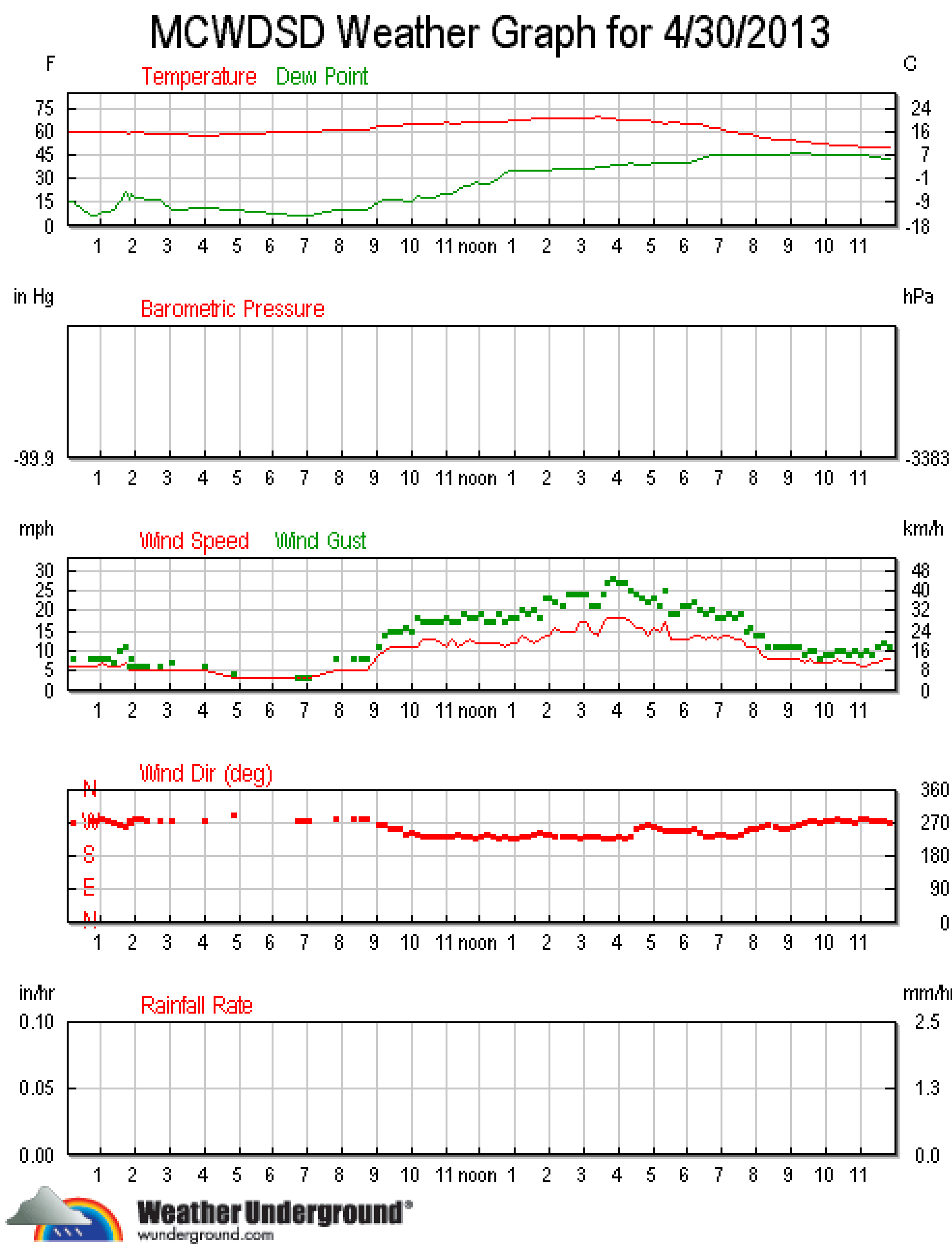


Figure B - 3 Weather Data for Kumeyaay 30 April 2013

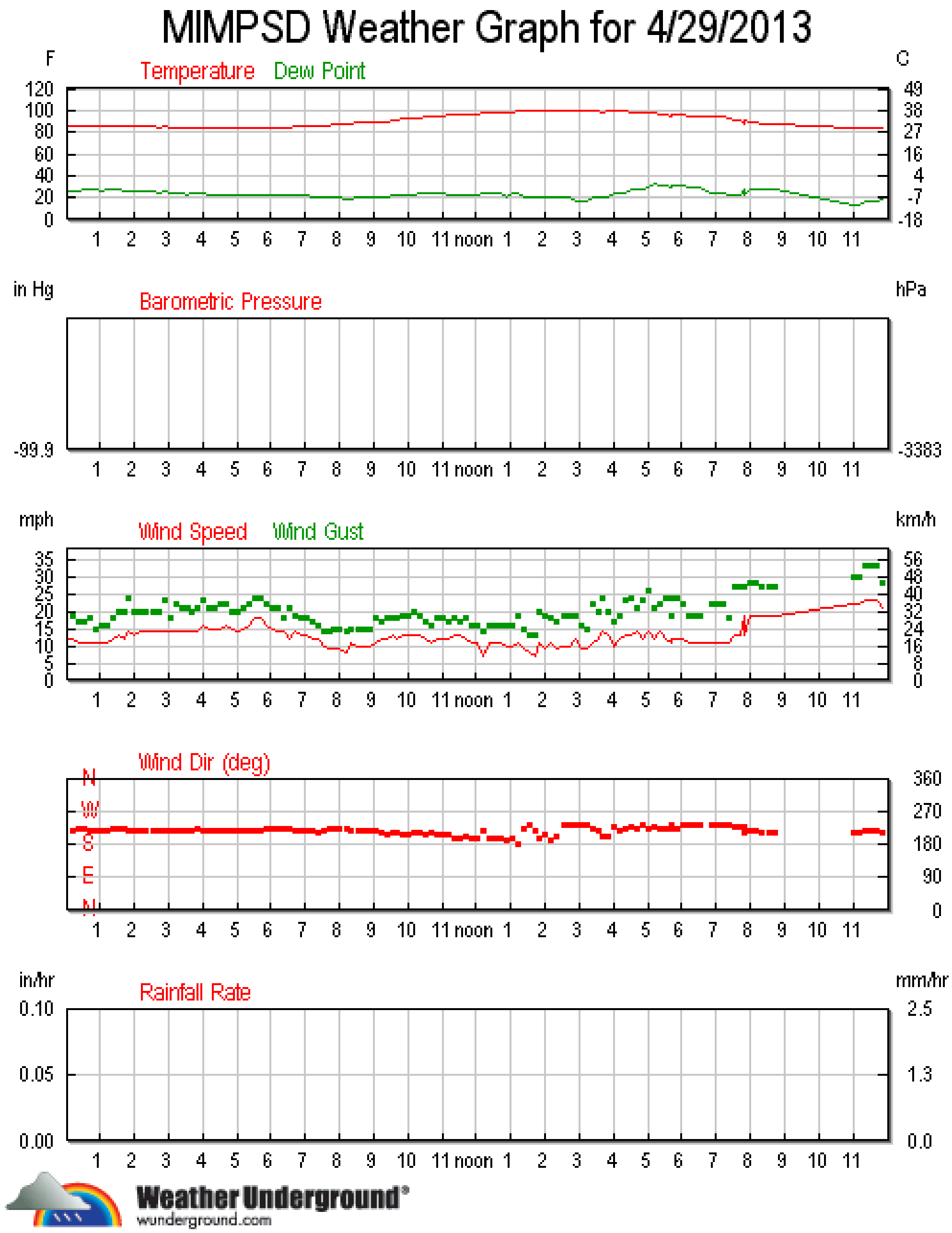


Figure B - 4 Weather Data for Ocotillo 29 April 2013

APPENDIX C – NOISE DATA

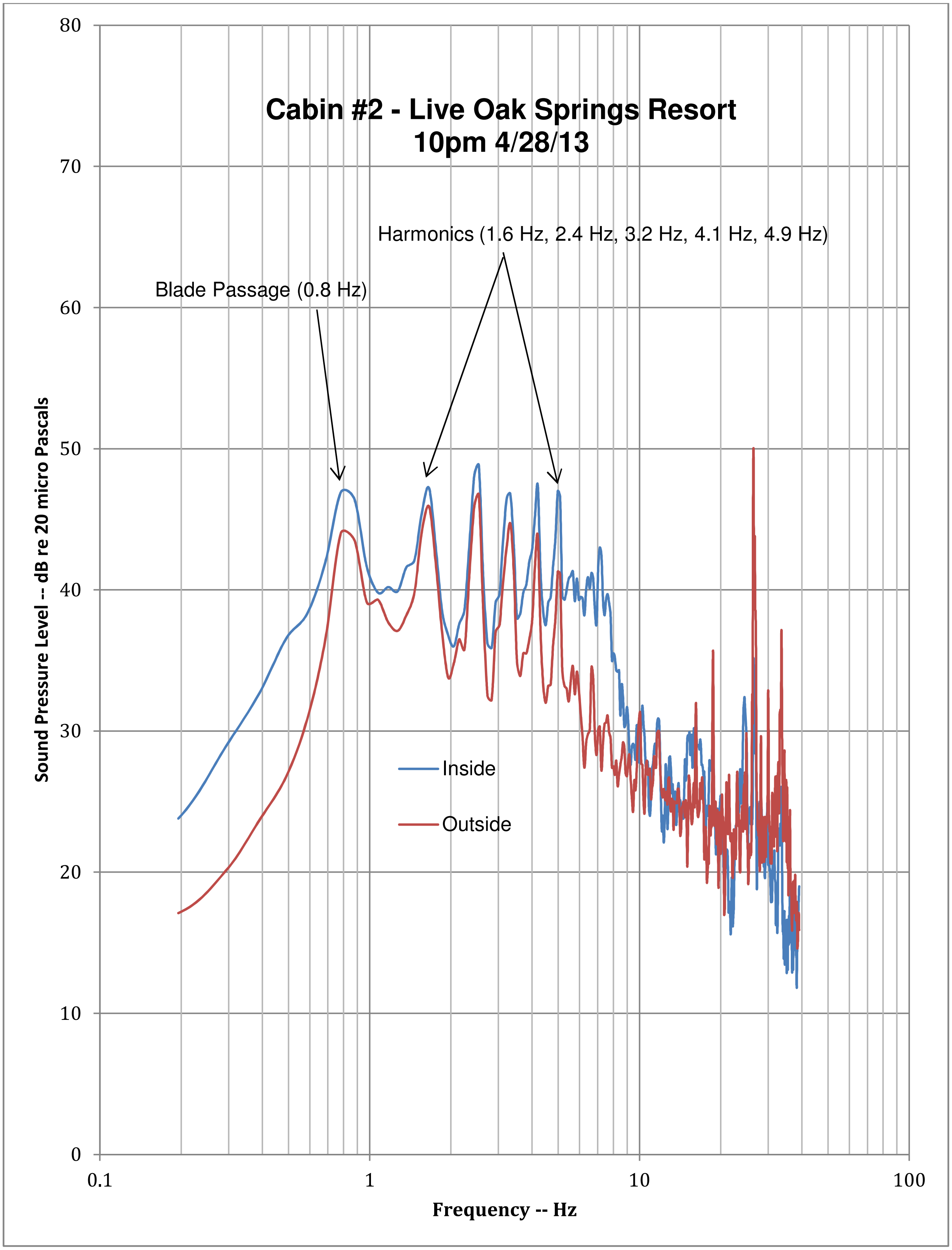
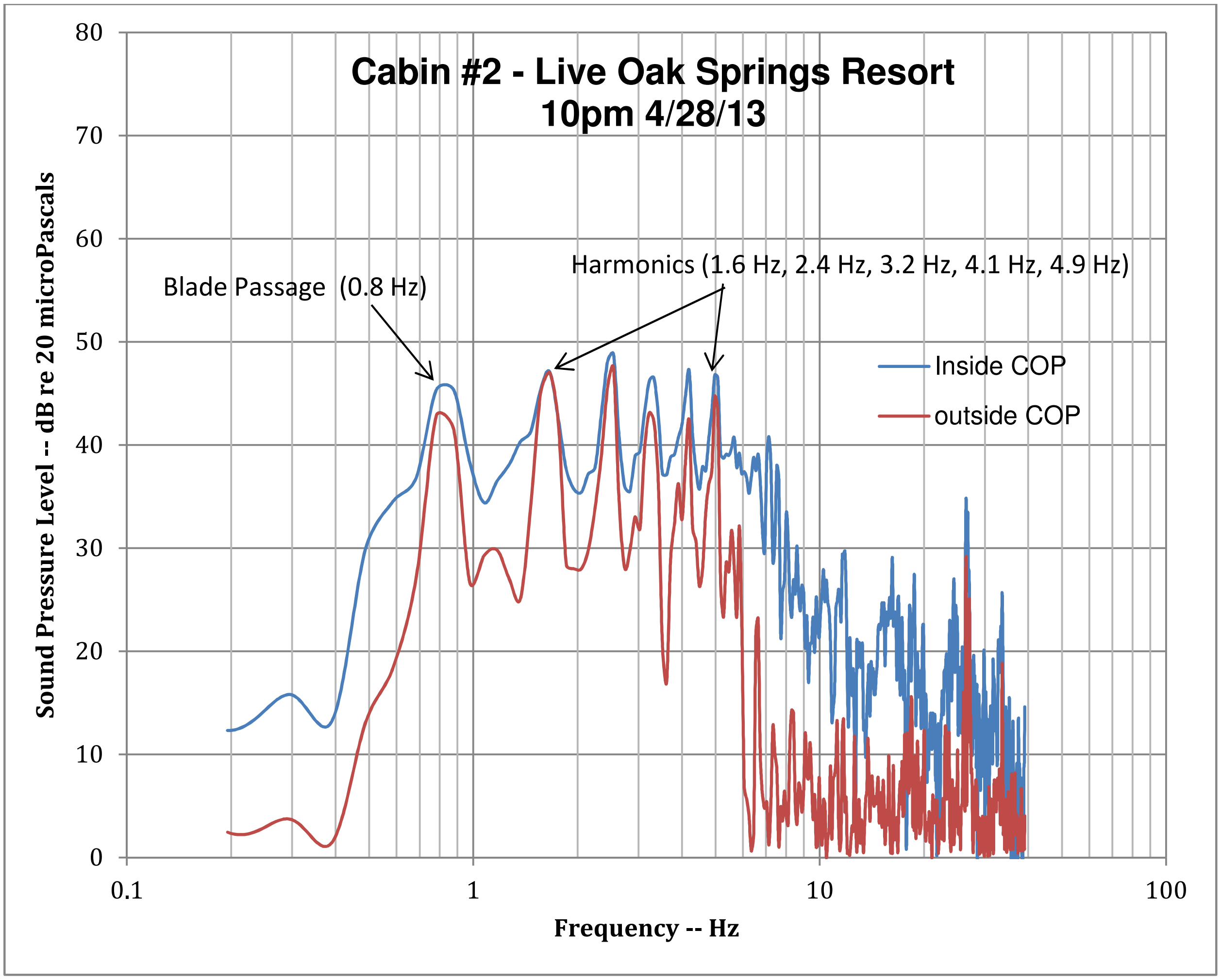


Figure C - 1 Live Oak Springs Resort – Cabin #2 – Autospectra



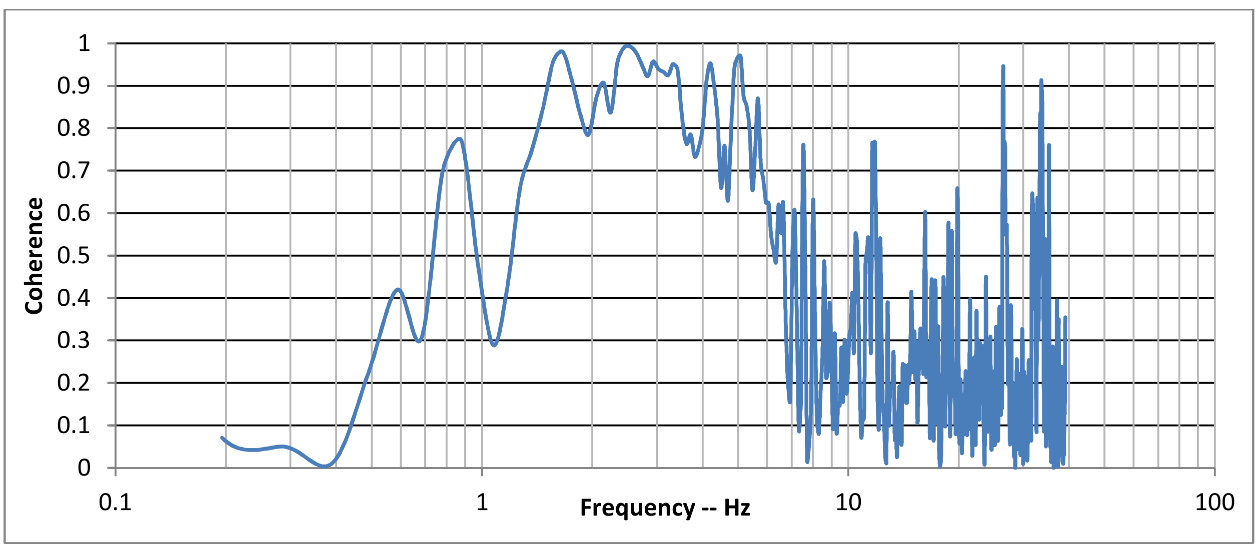


Figure C - 2 Live Oak Springs Resort – Cabin #2 – Coherent Output Power

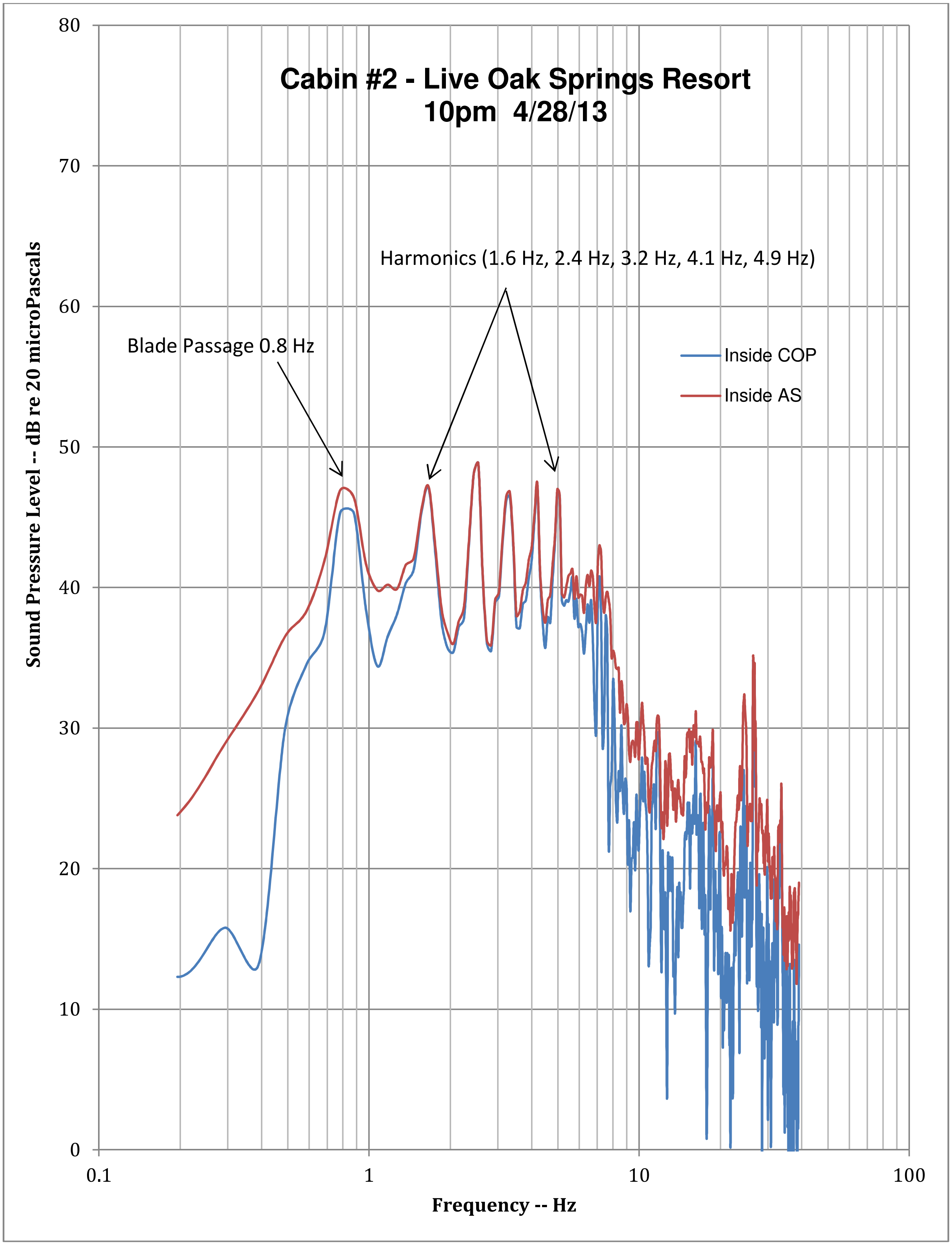


Figure C - 3 Live Oak Springs Resort – Cabin #2 – Comparison of Autospctrum and COP

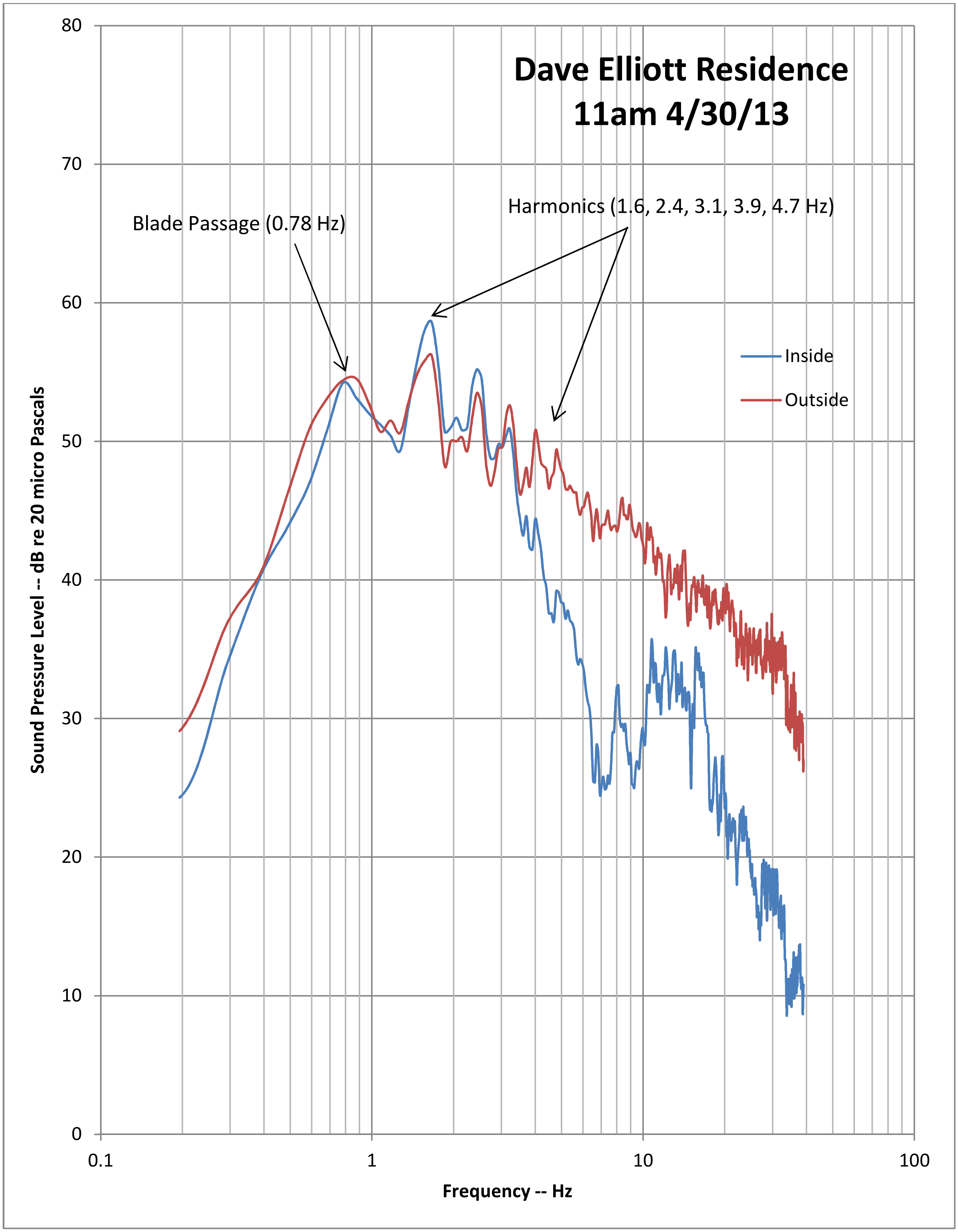


Figure C - 4 Dave Elliott Residence Autospectra

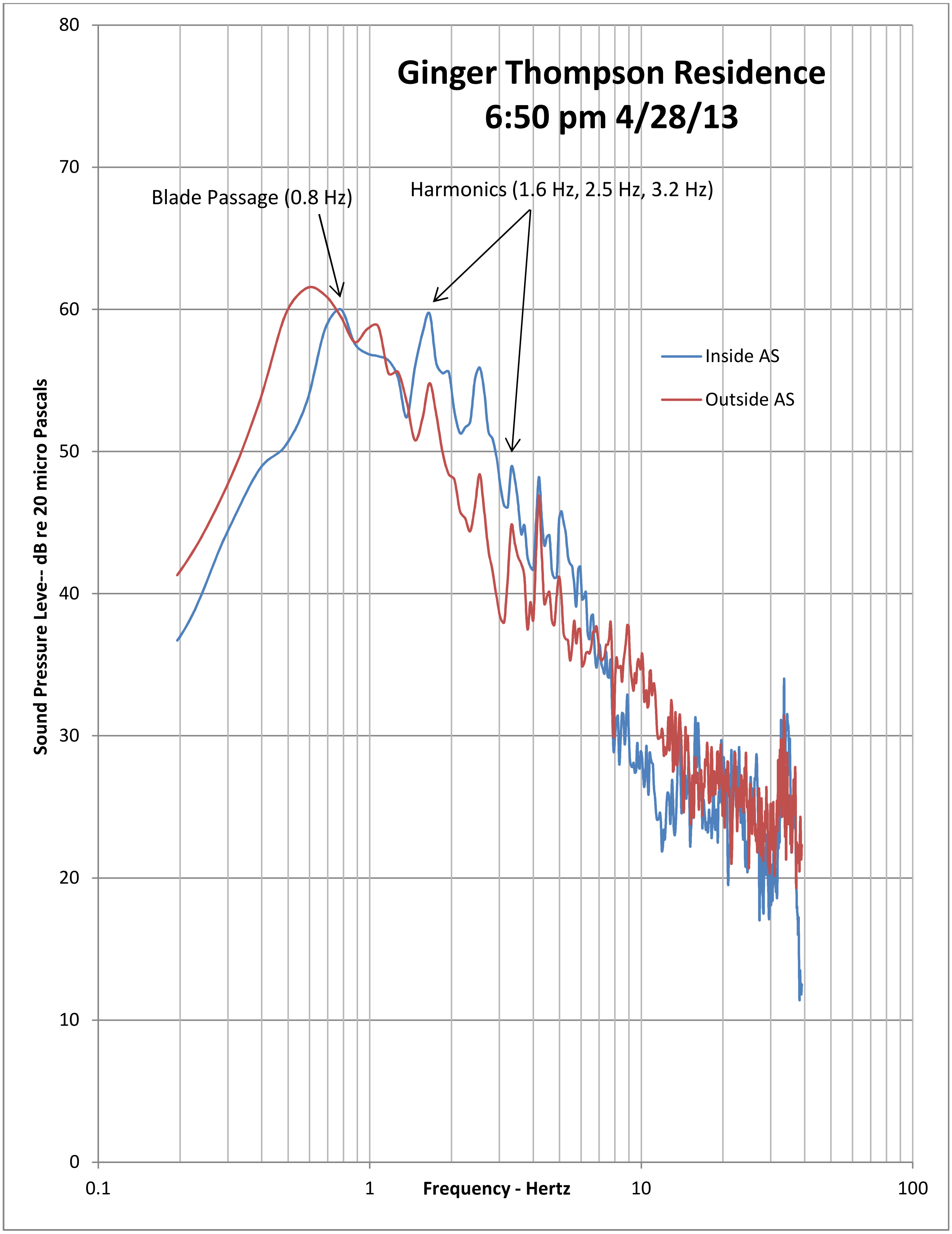


Figure C - 5 Ginger Thompson Residence Autospectra

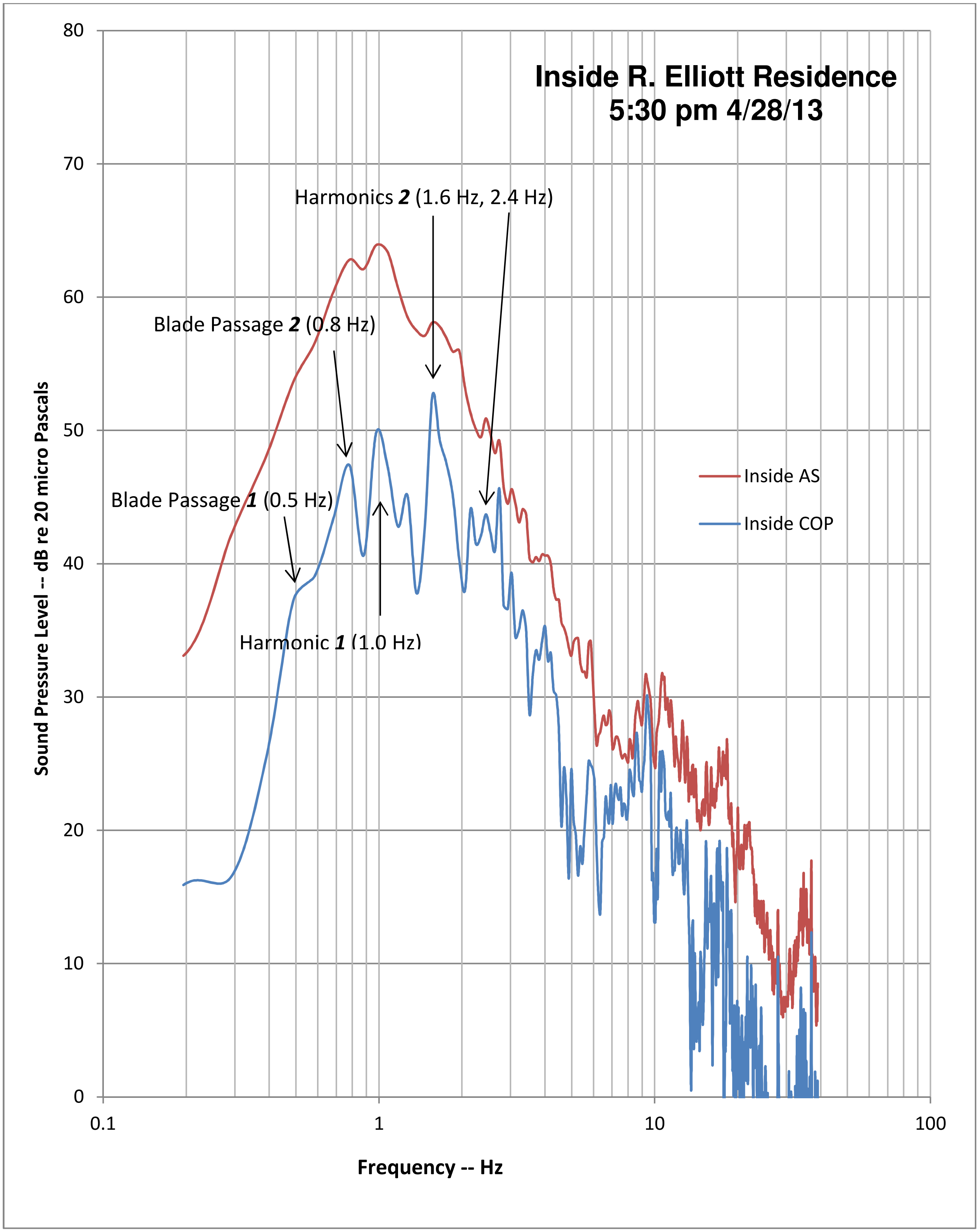


Figure C - 6 R. Elliott Residence Comparison of Autospectrum and Coherent Output Power

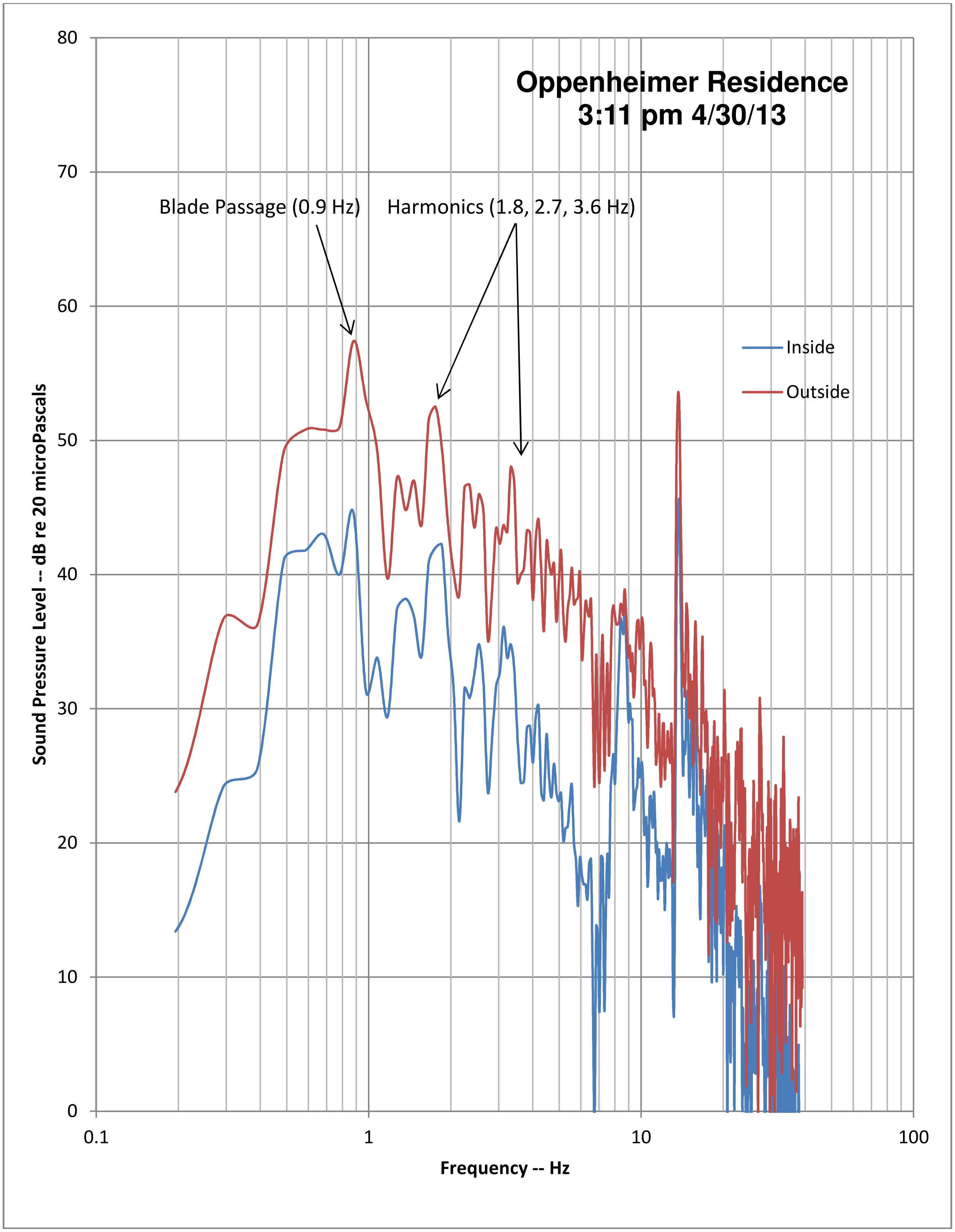


Figure C - 7 Ken Oppenheimer Residence during Day – Coherent Output Power

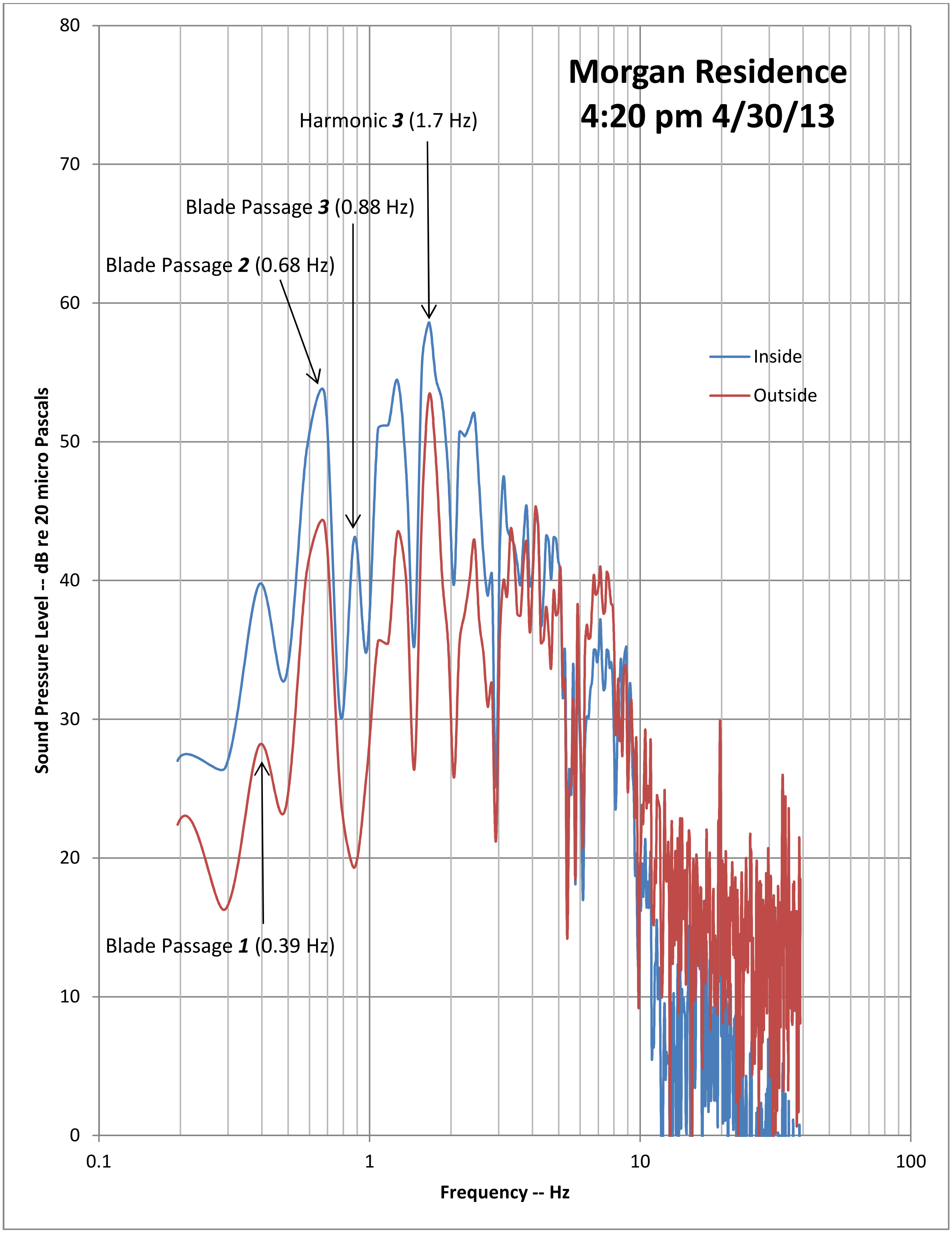


Figure C - 8 Marie Morgan Residence during Day – Coherent Output Power

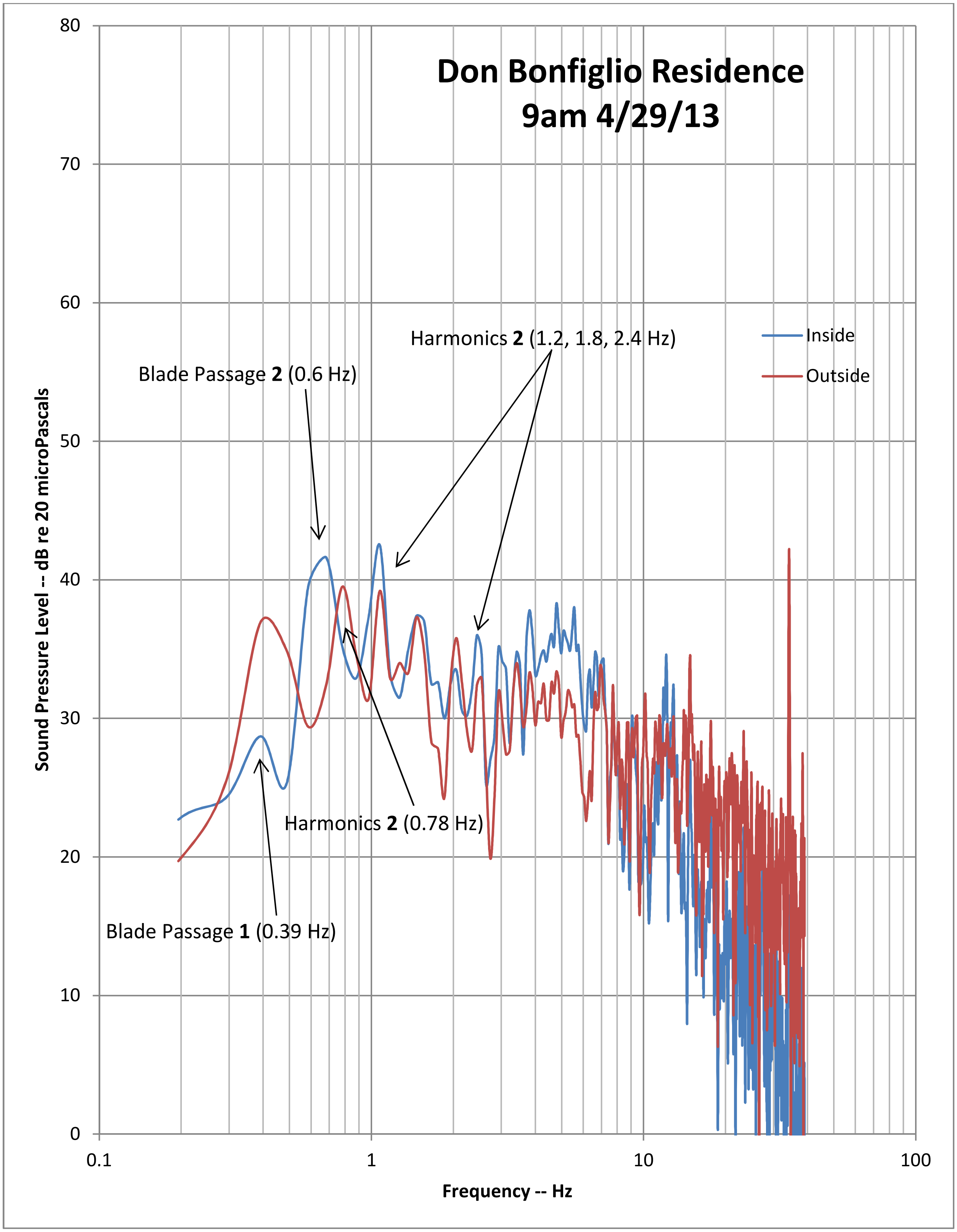


Figure C - 9 Don Bonfiglio Residence during Day – Coherent Output Power

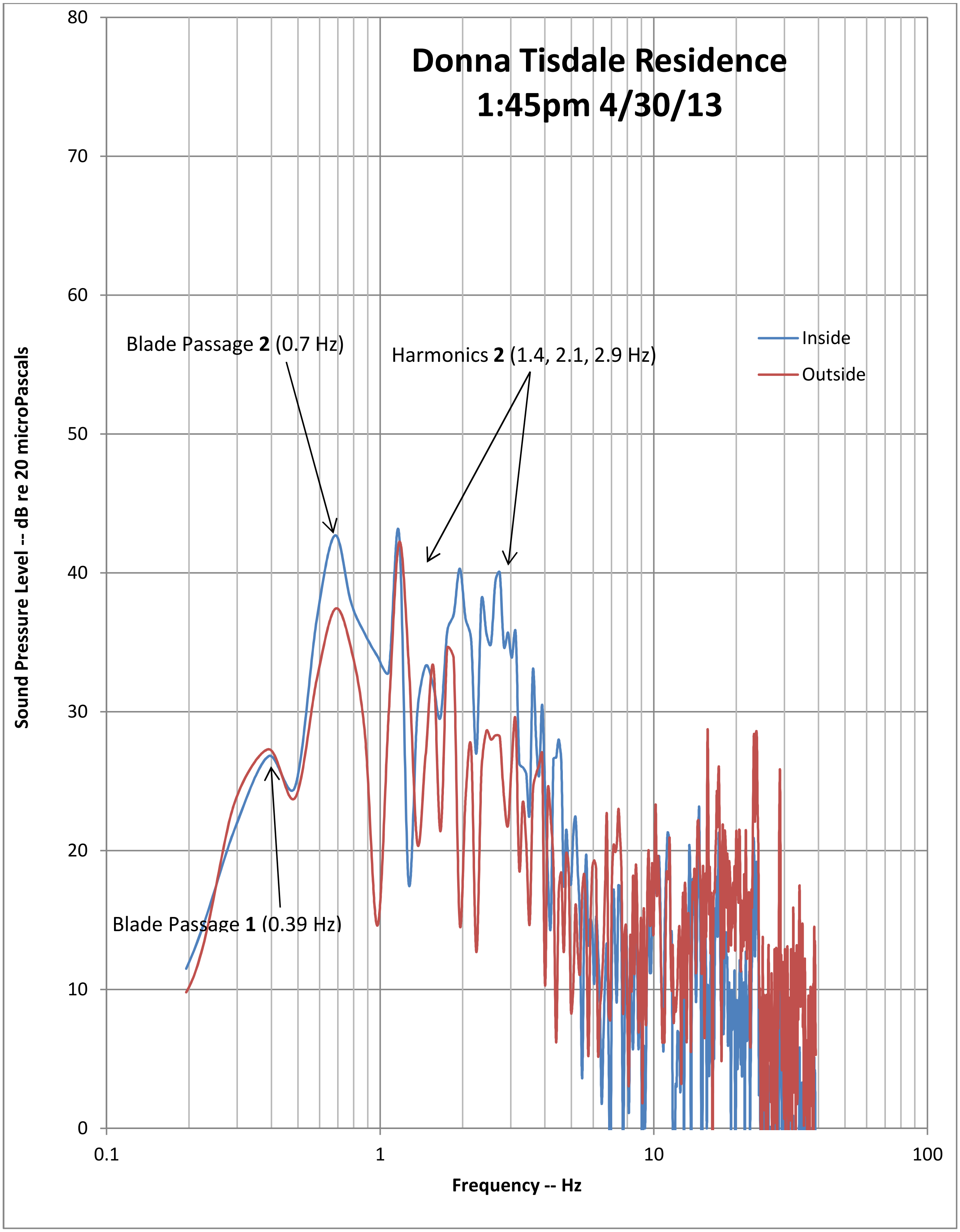


Figure C - 10 Donna Tisdale Residence during Day – Coherent Output Power

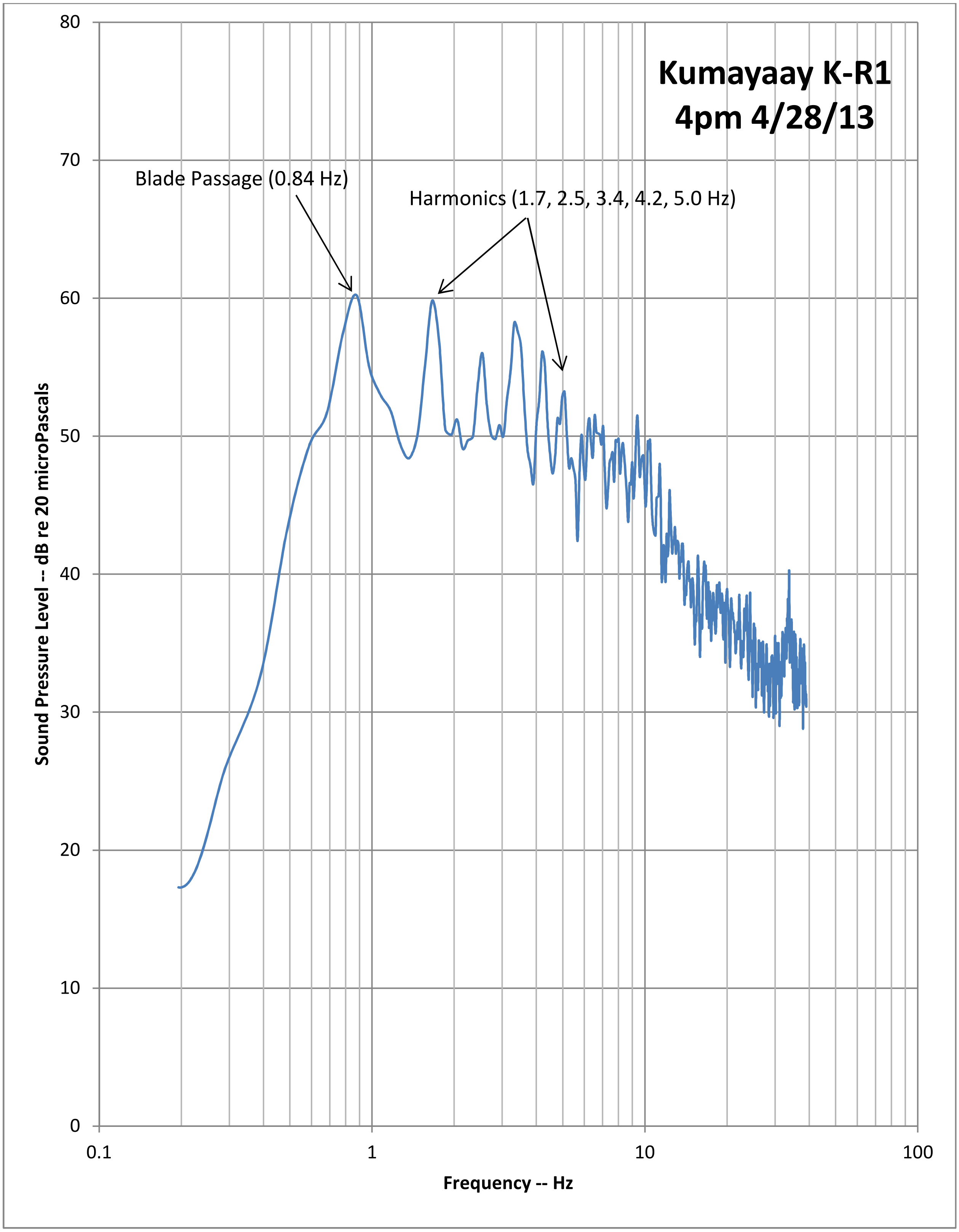


Figure C - 11 Kumeyaay Reference Location 1

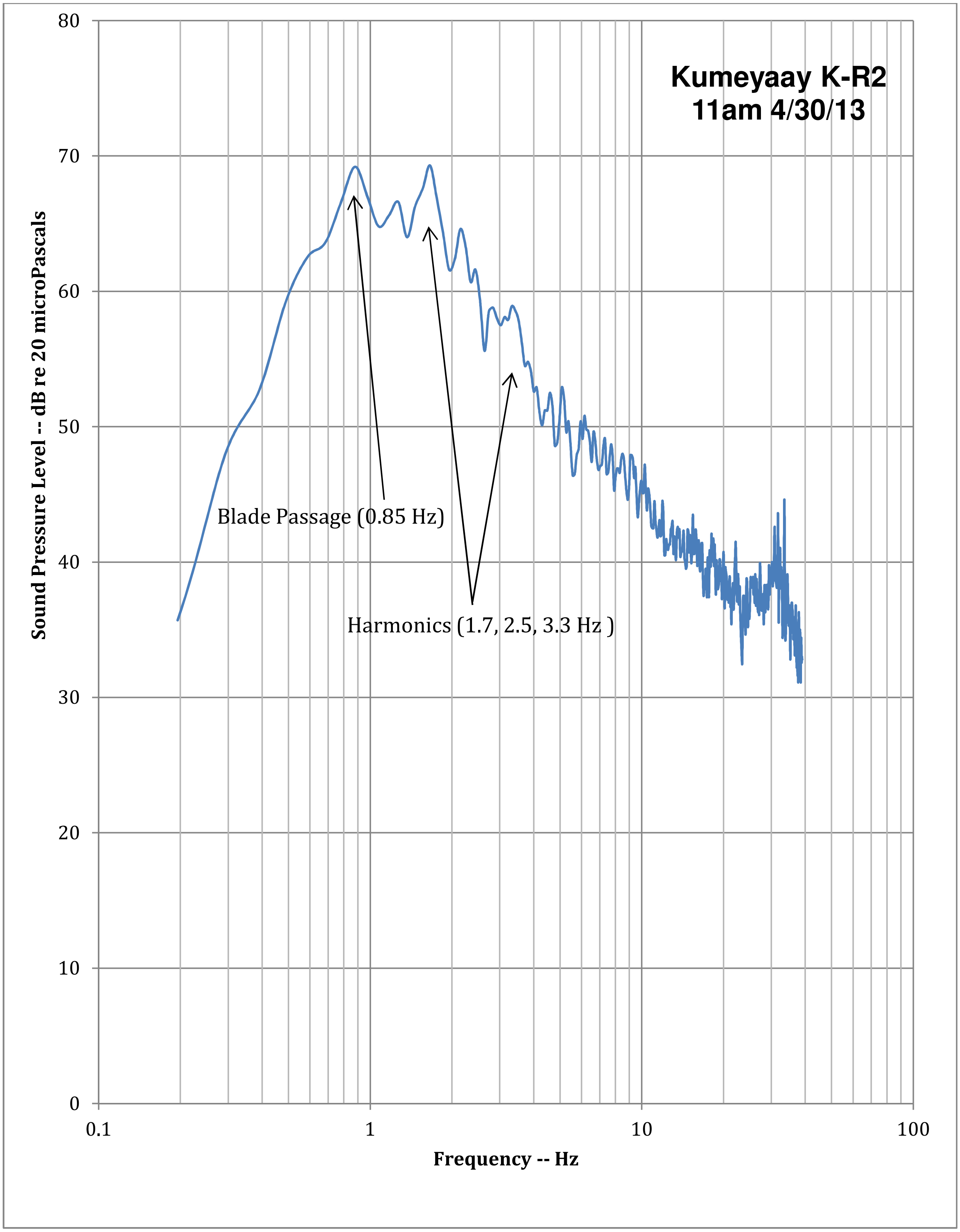


Figure C - 12 Kumeyaay Reference Location 2

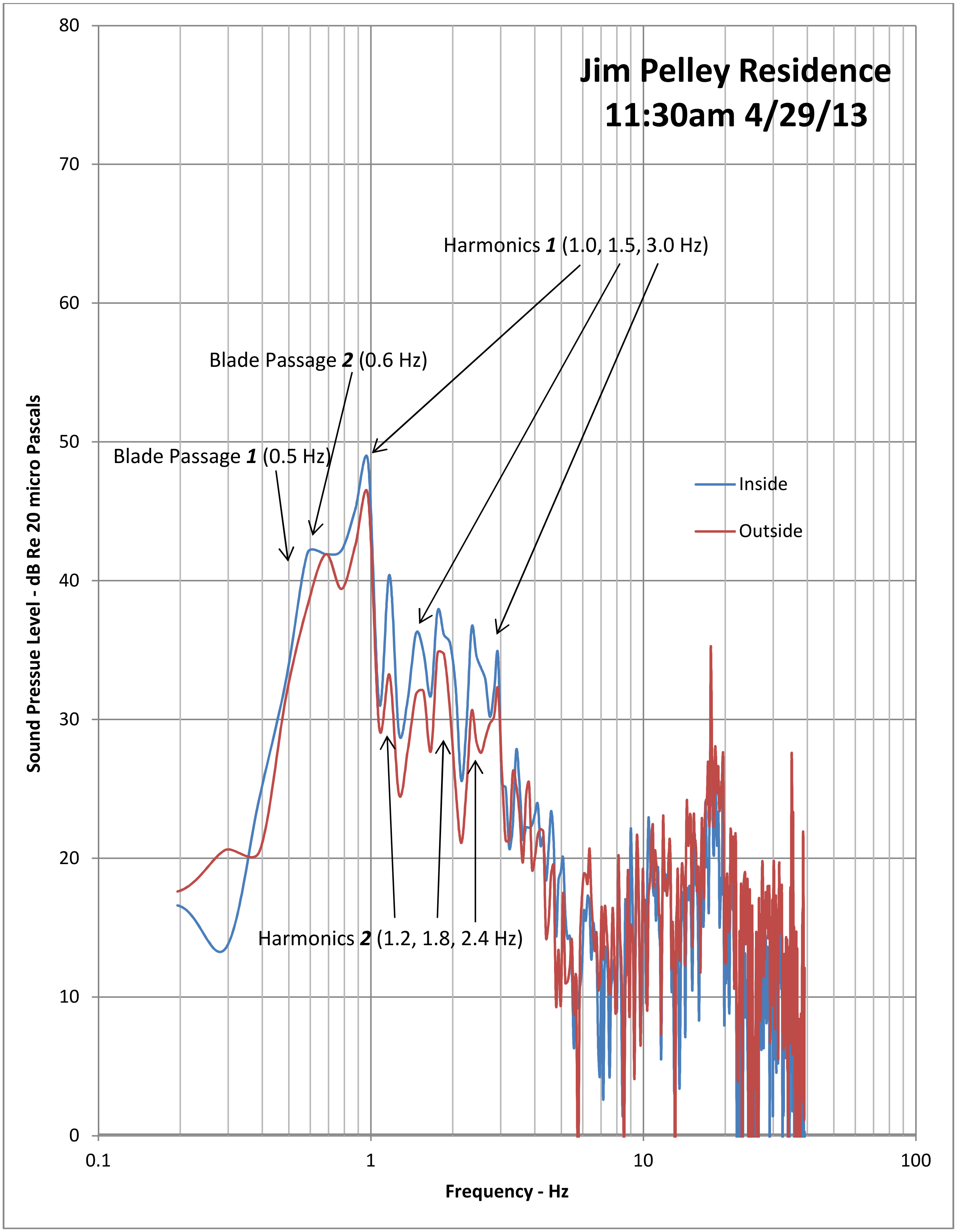


Figure C - 13 Jim Pelly Residence during Day – Coherent Output Power

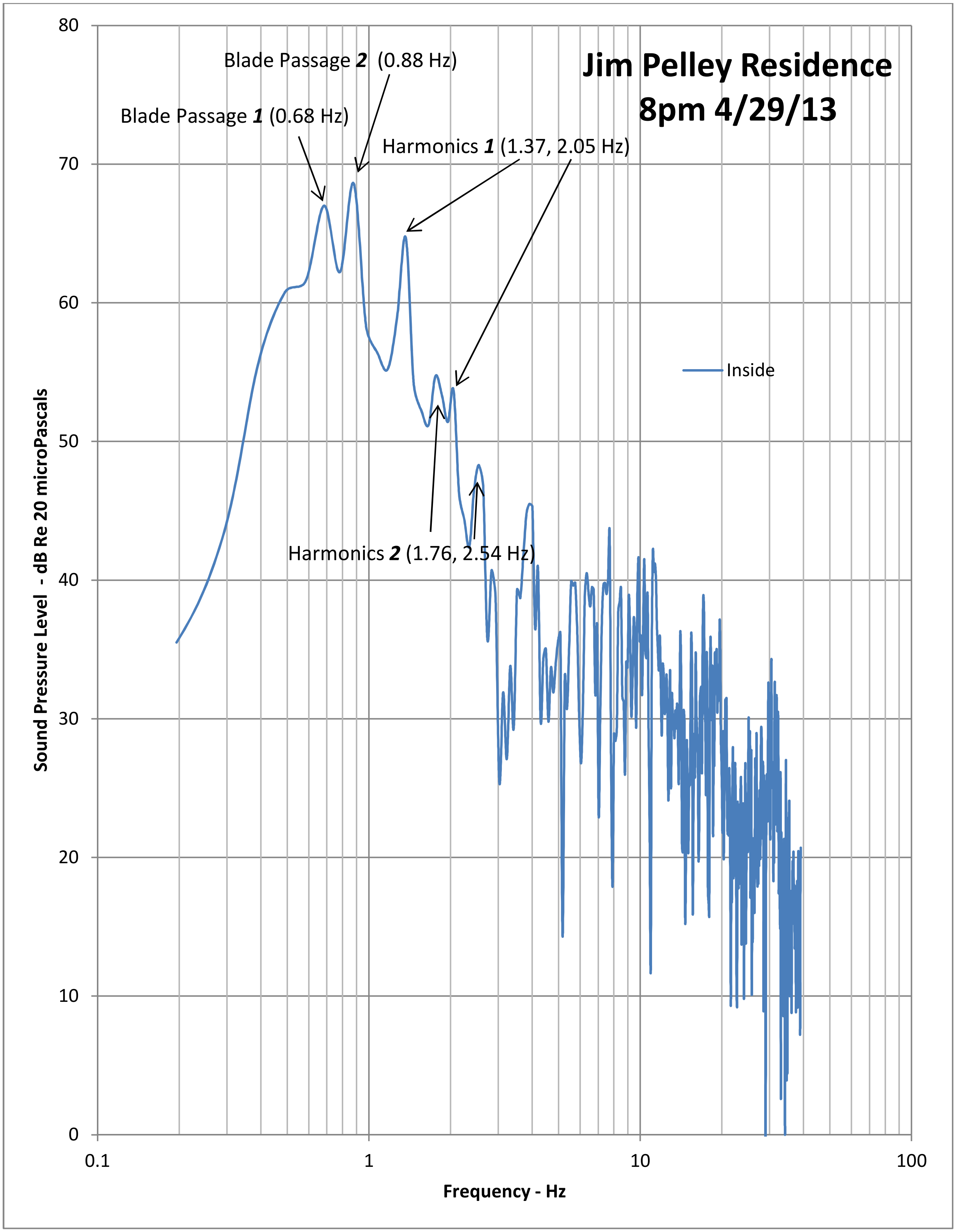


Figure C - 14 Jim Pelly Residence at Night – Coherent Output Power

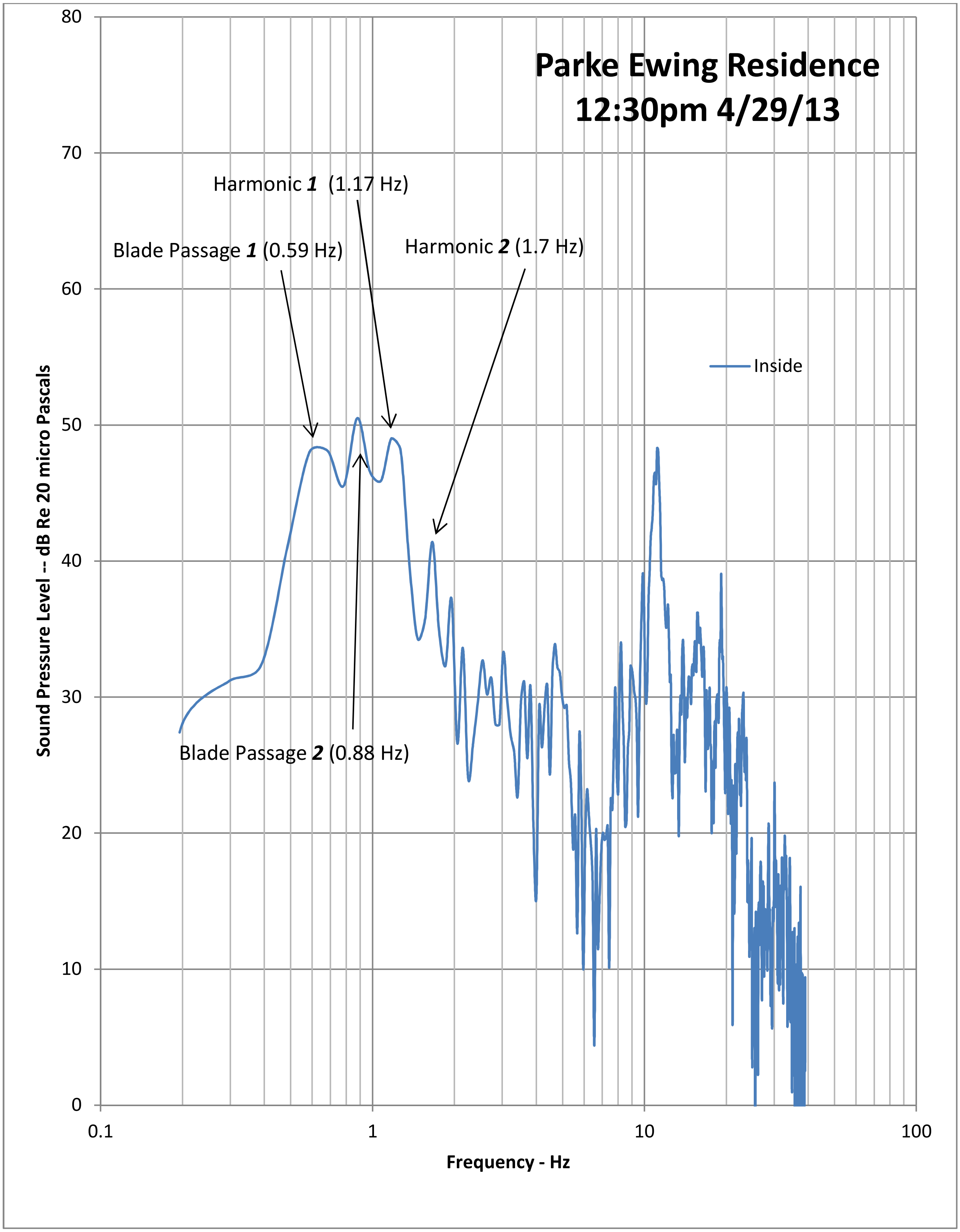


Figure C - 15 Parke Ewing Residence during Day – Coherent Output Power

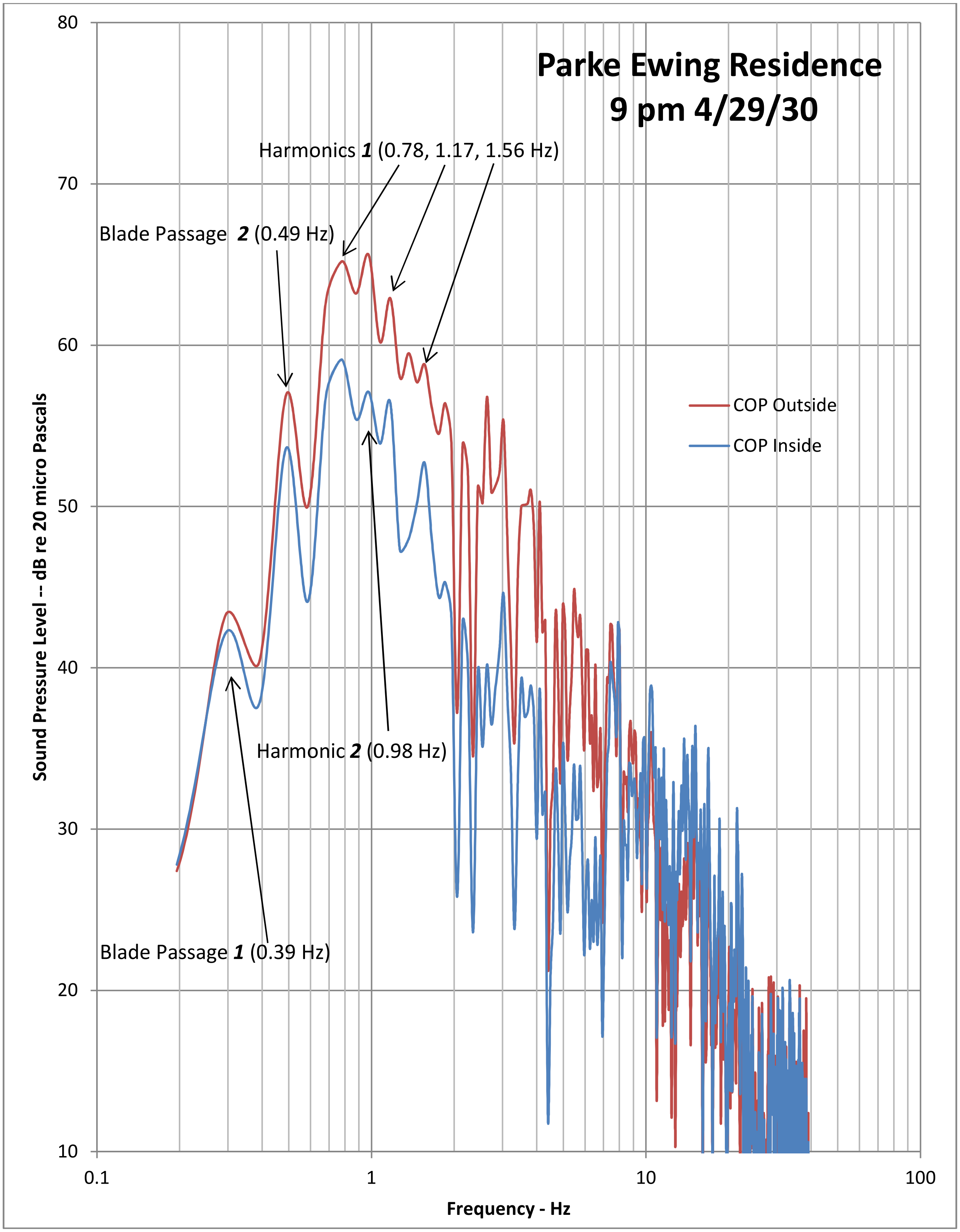


Figure C - 16 Parke Ewing Residence at Night – Coherent Output Power

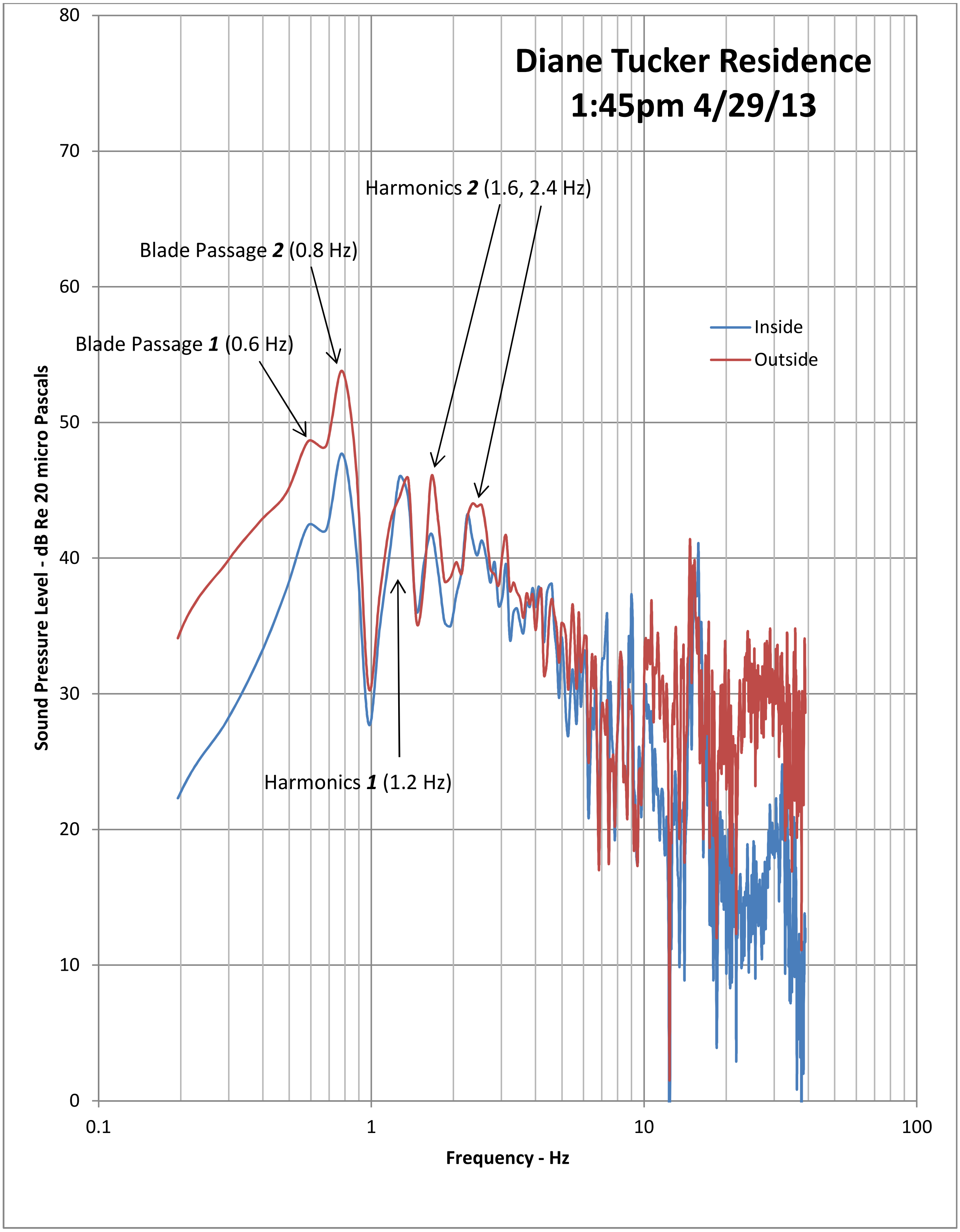


Figure C - 17 Diane Tucker Residence at Day – Coherent Output Power

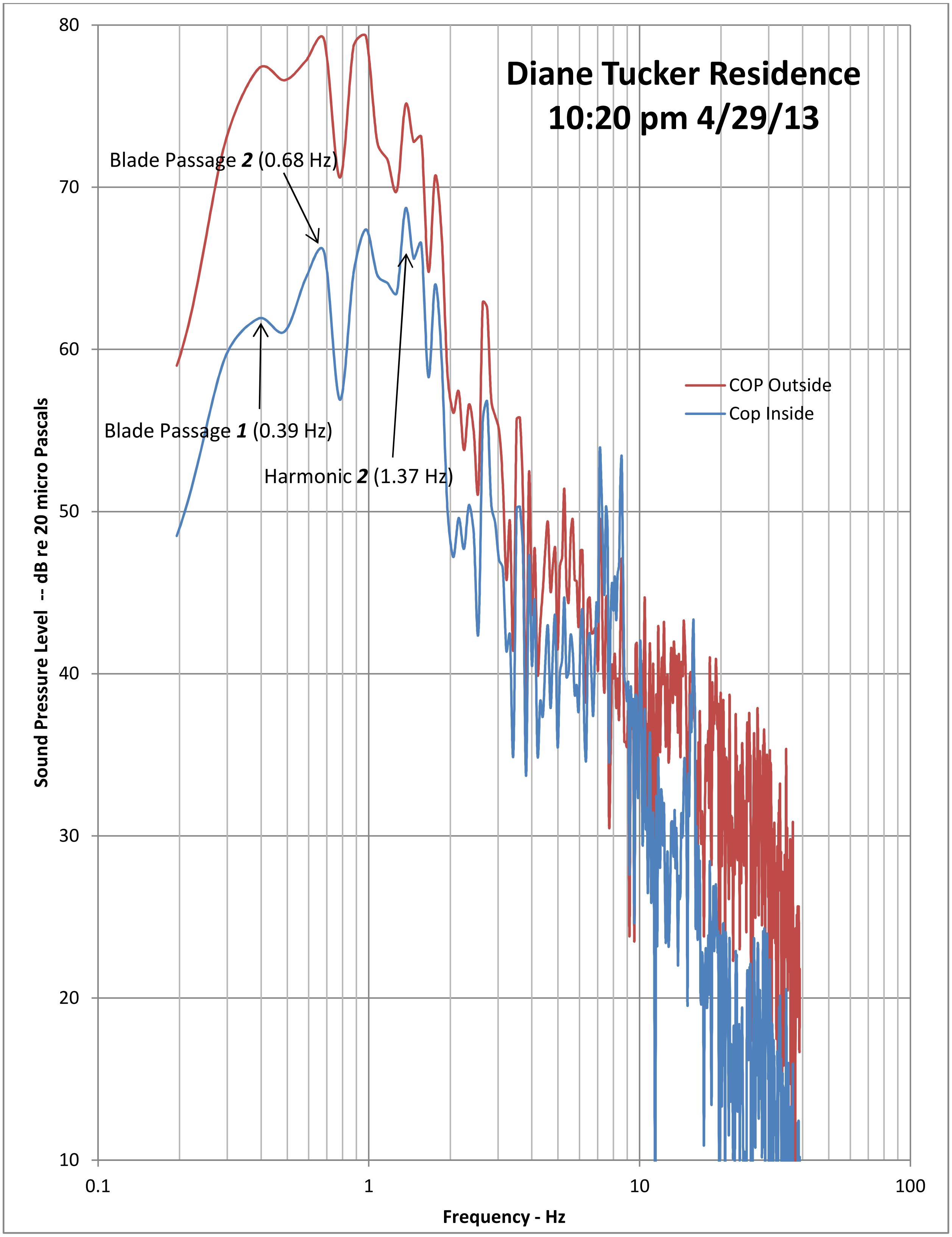


Figure C - 18 Diane Tucker Residence at Night – Coherent Output Power

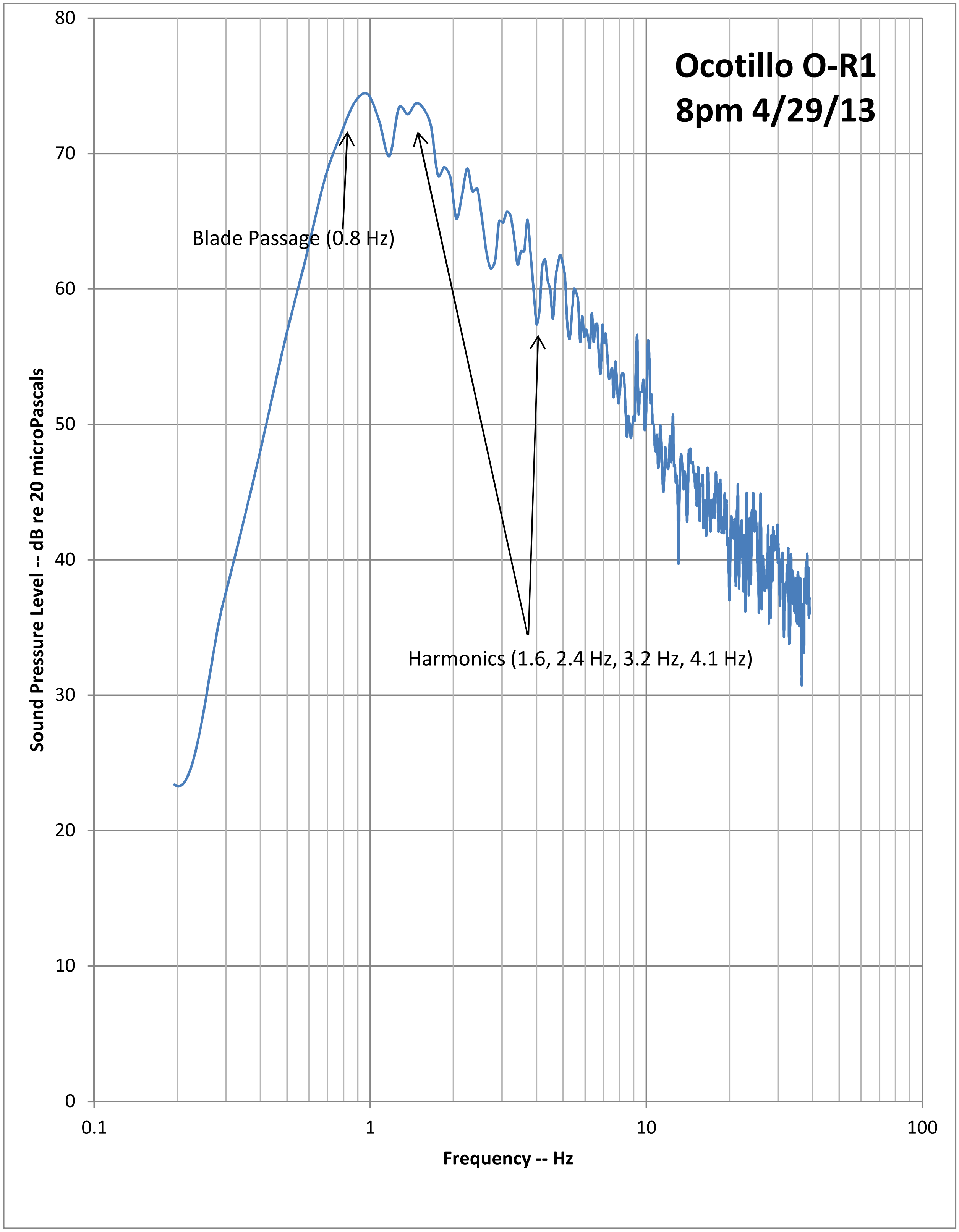


Figure C - 19 Ocotillo Reference Location 1 at Night

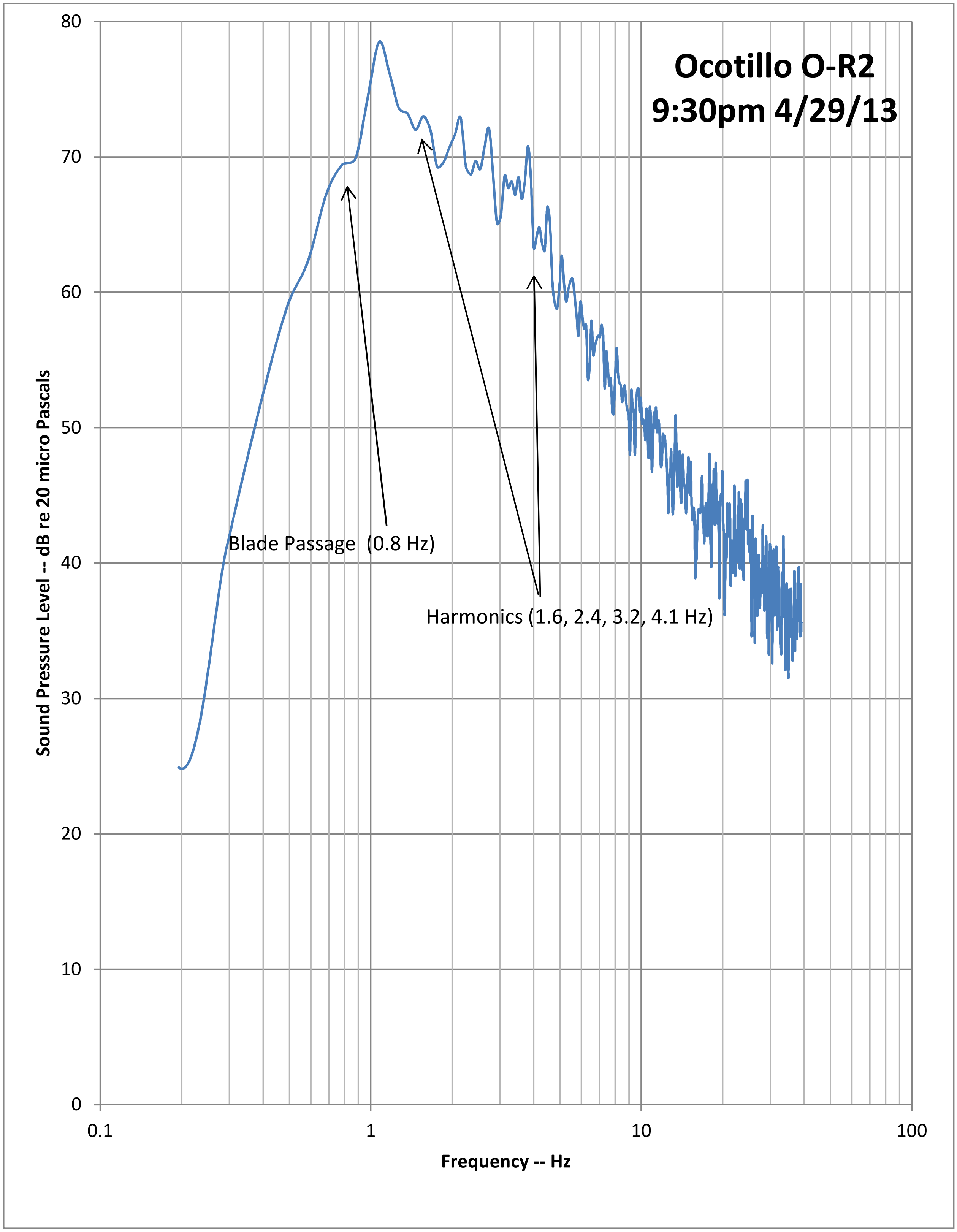


Figure C - 20 Ocotillo Reference Location 2 at Night

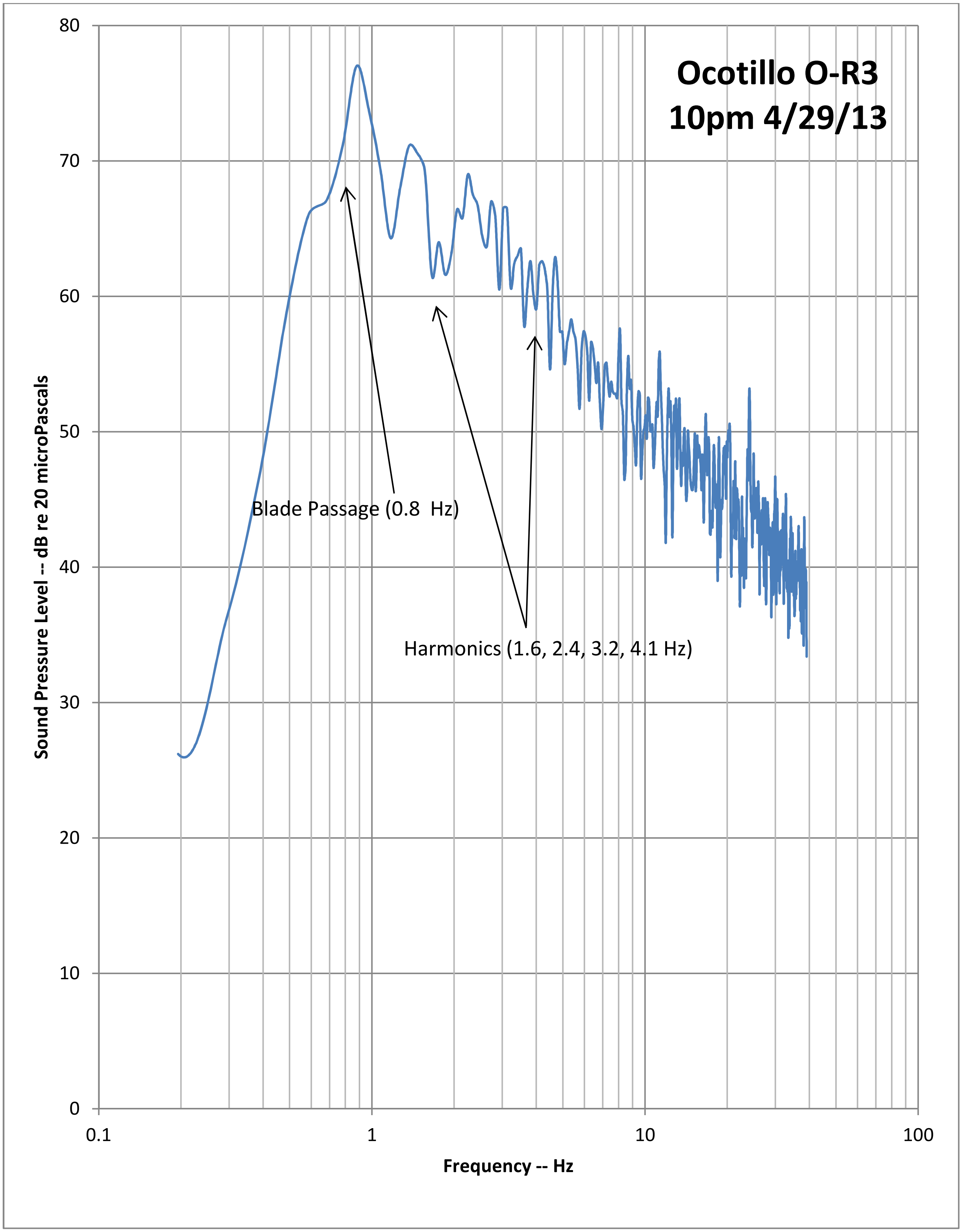
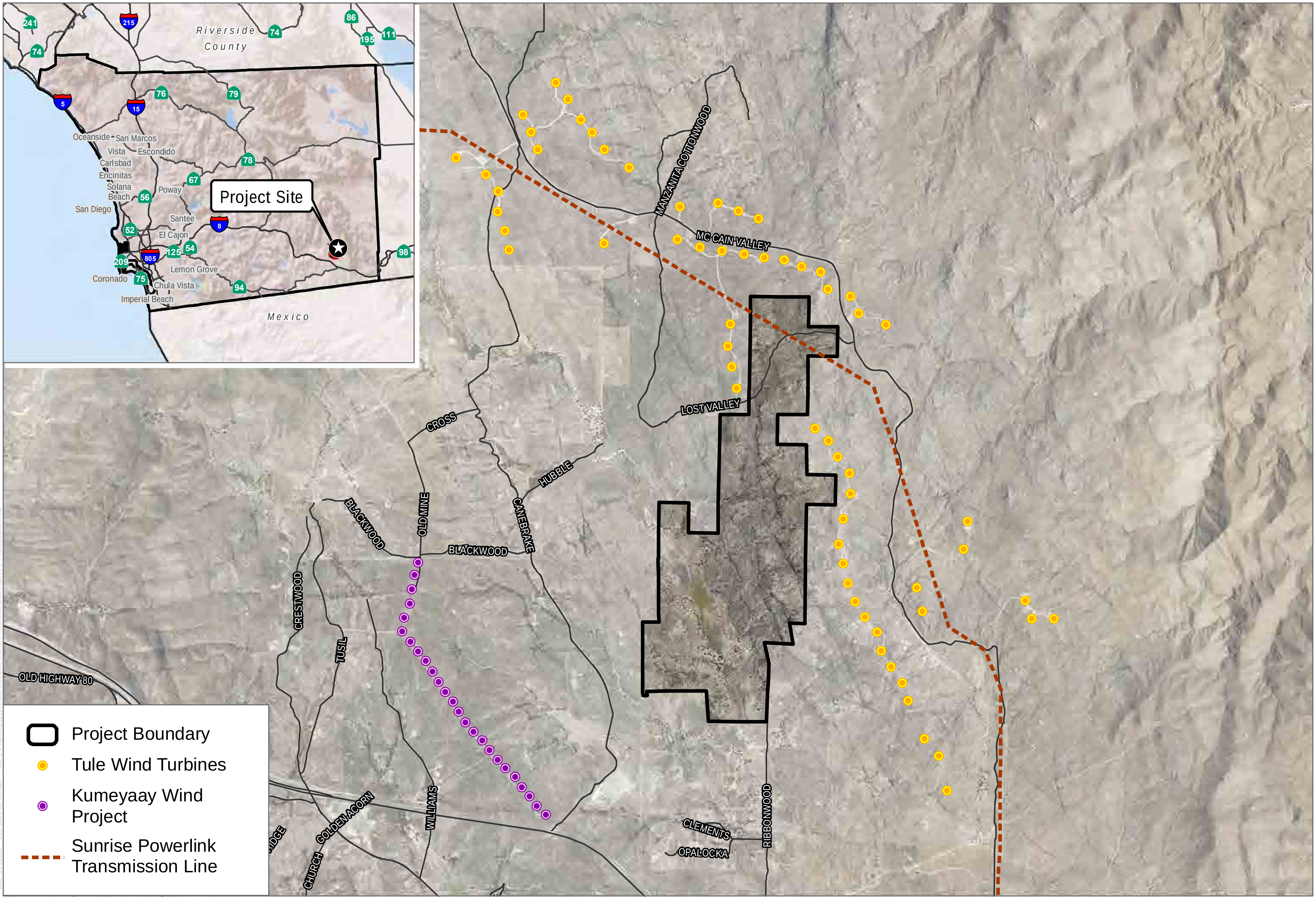


Figure C - 21 Ocotillo Reference Location 3 at Night

APPENDIX E – TORREY WIND MAP



SOURCE: SANGIS 2017

DUDEK

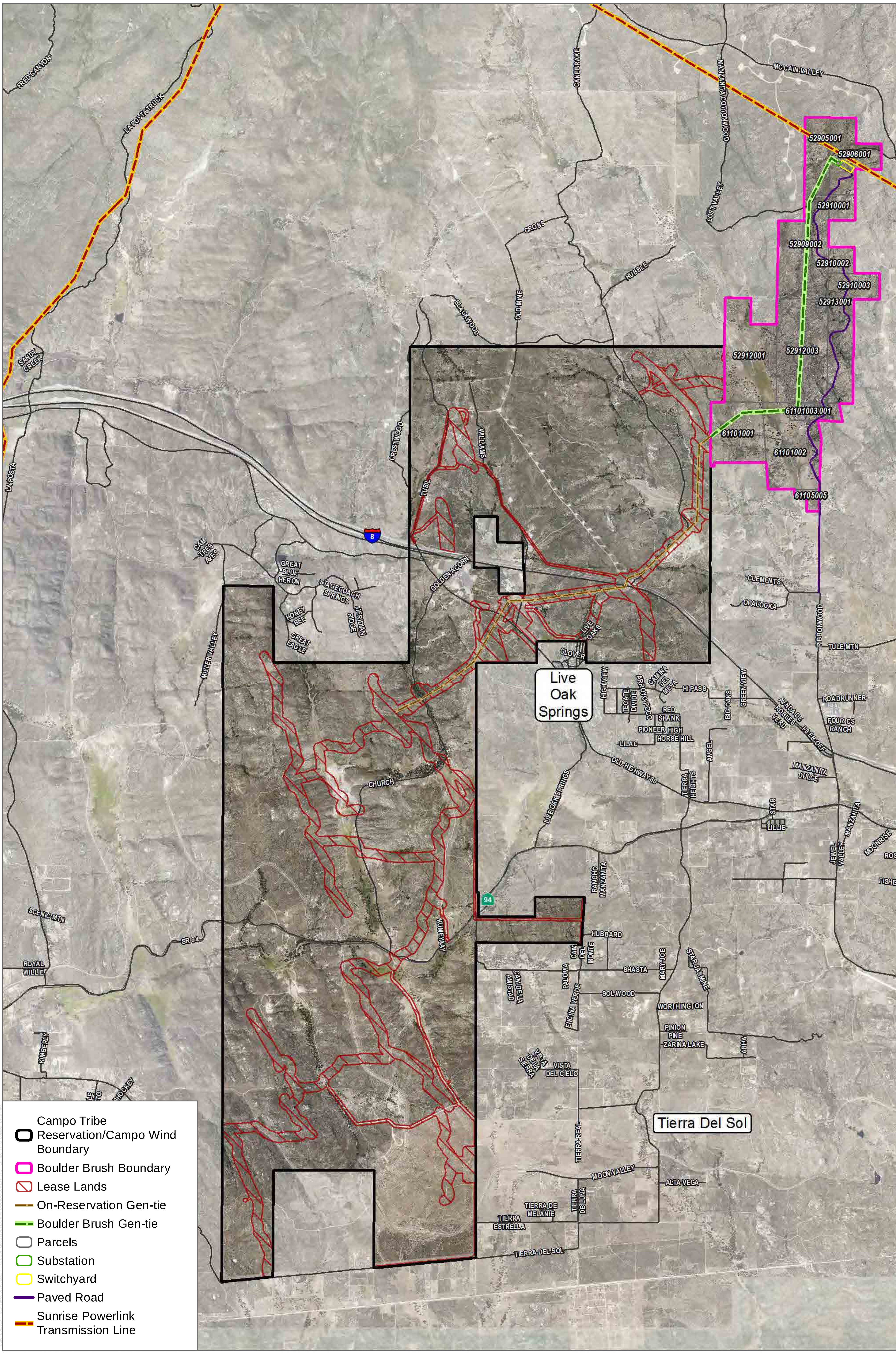
0 2,950 5,900 Feet

FIGURE 1-1

Project Location

Torrey Wind Project

APPENDIX F – CAMPO WIND MAP



SOURCE: SANGIS 2017

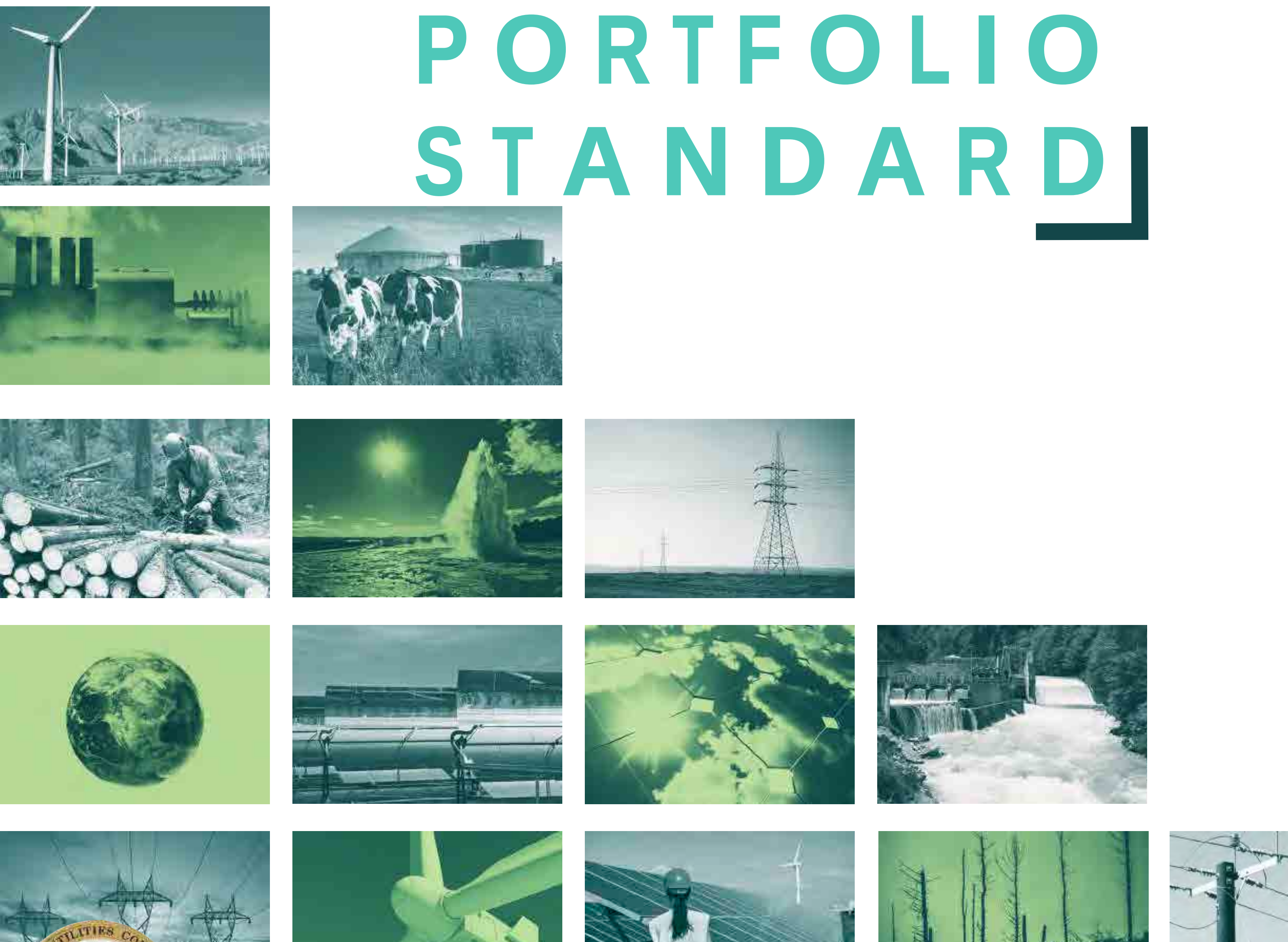
FIGURE 1
Project Location Map
Campo Wind and Boulder Brush Facilities

DUDEK

EXHIBIT
2

California Public Utilities Commission

RENEWABLES PORTFOLIO STANDARD



ANNUAL REPORT
NOVEMBER 2017

About this Report

The purpose of this annual report is to comply with Public Utilities Code Section 913.4. Each November, the CPUC is required to report to the Legislature on the progress of California's electrical corporations in complying with the Renewables Portfolio Standard (RPS) program.

Edited by

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California's
Renewables Portfolio Standard

ANNUAL REPORT

Submitted to the Legislature

November 2017

CONTENTS

TABLES & FIGURES

In compliance with Senate Bill (SB) 1222 (Hertzberg, 2016; as codified in Public Utilities Code Section 913.4[1]), the California Public Utilities Commission (CPUC or Commission) reports to the Legislature each year on the progress of the RPS program. This report describes the progress of the State's electrical retail sellers in complying with the Renewables Portfolio Standard (RPS) Program and shows that:

- California's electrical corporations met the 25% RPS requirement for 2016, and in many cases, substantially exceeded this requirement.[2]
- The large investor-owned utilities (IOU) have executed renewable electricity contracts necessary to exceed 2020's 33% RPS requirement.
- The IOUs' aggregated forecast project they will meet the 2030 RPS requirement of 50% by 2020.
- Community Choice Aggregators (CCA) and the small and multi-jurisdictional utilities (SMJU) report compliance with current RPS requirements, and forecast that they will meet or exceed 2020's 33% RPS requirement.
- The RPS program has helped achieve large reductions in cost for renewable electricity: between 2008 and 2016, the price of utility scale solar contracts reported to the CPUC have gone down 77%, and between 2007 and 2015 reported prices of wind contracts have gone down 47%.[3]

[1] See Appendix B for full text of Public Utilities Code (PU Code) Section 913.4.

[2] Based on filings submitted to the CPUC by retail sellers, they are exceeding RPS requirements with the exception of a few filings by ESPs.

[3] This does not reflect further wind contract price reductions in 2016 or 2017 because of limited new wind contracts reported to the CPUC during that time.

About the Annual RPS Report

Each November, the CPUC reports to the Legislature on the progress and compliance of California's electricity retailers in meeting RPS requirements. Specifically, this report complies with Public Utilities Code 913.4 sub-sections:

(a) Progress on RPS procurement activities;

(b) Details on RPS activities and implementation;

(c) Projected ability to meet RPS under cost limitations;

(d) Status of RPS plans, activities, procurement, and transmission;

(e) Barriers and policy recommendations to achieving RPS; and

(f) Efforts of electrical corporations related to workforce development, training, and diversity.

About the RPS Program

California's ambitious RPS program is jointly implemented and administered by the California Public Utilities Commission (CPUC) and the California Energy Commission (CEC). The RPS program requires the State's Investor-Owned Utilities (IOUs), Community Choice Aggregators (CCAs), Electric Service Providers (ESPs), and Publicly Owned Utilities (POUs) to procure 50 percent of their total electricity retail sales from eligible renewable energy resources by 2030.

The CPUC reviews and approves RPS Procurement Plans and Compliance Reports for the IOUs, CCAs, and ESPs. The CEC oversees RPS compliance for the POUs.[4]

RPS LEGISLATIVE HISTORY

California's RPS program was established in 2002 by Senate Bill (SB) 1078 (Sher) with the initial requirement that 20% of electricity retail sales be served by renewable resources. The program was accelerated in 2006 under SB 107 (Simitian), which required that the 20% mandate be met by 2010.

In April 2011, Governor Brown signed SB 2 (1X) (Simitian), which codified a higher RPS requirement of 33% to be achieved by December 31, 2020.

In 2015, the Governor signed into law SB 350 (De León), The Clean Energy and Pollution Reduction Act of 2015. SB 350 increased RPS requirements to 50% by December 31, 2030.

In addition, SB 350 includes interim RPS targets of 40% by December 31, 2024 and 45% by December 31, 2027, with three-year compliance periods continuing indefinitely thereafter. The 50% RPS requirement is a minimum.

Governor Brown also signed into law in 2015 SB 697 (Hertzberg), which adopted the Public Utilities Commission Accountability Act of 2015 and recasted some of the Commission's RPS reporting requirements.

[4] This report covers only the entities that the CPUC regulates.

The purpose of increasing the level of renewables in the State's energy mix is to provide a range of benefits to Californians, including:

- Reducing greenhouse gas emissions and air pollution;
- Stabilizing electricity rates;
- Diversifying the energy generation portfolio;
- Meeting resource adequacy requirements; and
- Contributing to the reliable operation of the electrical grid.

California's electricity retail sellers, defined as any entity engaged in the retail sale of electricity to end-use customers located within the State, are required to comply with the RPS program. Within the CPUC's jurisdiction, the large IOUs served approximately 75% of the State's retail electricity load in 2016, while the SMJUs, CCAs, and ESPs collectively served the remaining 25%. The POUs serve approximately 20-25% of California's electric load, but are not retail sellers.

An electricity retailer operating in California is generally classified into one of four categories:

- **IOU:** A private enterprise that engages in the generation and distribution of electricity for sale in a regulated market. Customer rates for utilities are set and regulated by the CPUC through a public process that includes stakeholder participation.
- **SMJU:** An electric utility that has a customer base of 30,000, or fewer or that serves customers across multiple states.
- **CCA:** A local government agency that purchases and develops power on behalf of residents, businesses, and municipal facilities within a local jurisdiction.
- **ESP:** A non-utility entity that offers electric service to customers within the service territory of an electric utility.

California's Electricity Retailers

Large Investor-Owned Utilities (IOU)

Pacific Gas and Electric Company
Southern California Edison Company
San Diego Gas & Electric Company

Small and Multi-Jurisdictional Utilities (SMJU)

Bear Valley Electric Service
Liberty Utilities
PacifiCorp

Community Choice Aggregators (CCA)

Apple Valley Choice Energy
CleanPowerSF
Lancaster Choice Energy
Marin Clean Energy
Peninsula Clean Energy
Pico Rivera Municipal Energy
Redwood Coast Energy Authority
Silicon Valley Clean Energy
Sonoma Clean Power Authority

Electric Service Providers (ESP)

Direct access providers of electricity

How the RPS Program Works

The RPS program encourages investment in the development of new utility-scale renewable energy facilities to meet the electrical demands of the State of California. RPS is a market based program where compliance is determined by the quantity of Renewable Energy Credits (REC) acquired (1 REC = 1 megawatt hour (MWh)).

The CPUC's implementation of the RPS program complements the RPS program administered by the CEC, as well as supports California's climate change policies. The CPUC's compliance process is completed after the CEC verifies RPS-eligible procurement from renewable energy facilities.

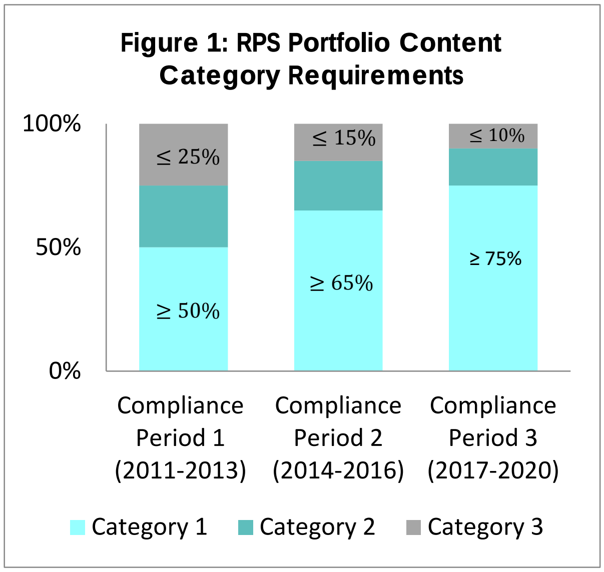
The CPUC establishes program policy within its RPS rulemaking proceeding and implements legislation through its Commission decisions to ensure that electricity retailers comply with CPUC rules and State law.[5]

The CPUC's responsibilities in the implementation of the RPS program include:

- Setting policy through a public stakeholder process;
- Reviewing and approving each retail seller's RPS procurement plan;
- Reviewing IOU contracts for RPS-eligible energy; and
- Determining and enforcing compliance with procurement targets.

Portfolio Content Category Rules

California's RPS program defines all renewable procurement acquired from contracts executed after June 1, 2010 into one of three portfolio content categories (PCCs):



- **Category 1:** Bundled renewable energy credits (RECs) from facilities with a first point of interconnection within a California Balancing Authority (CBA), or facilities that schedule electricity into a CBA on an hourly or sub-hourly basis.
- **Category 2:** Procurement which bundles RECs with incremental electricity, and/or substitute energy, from outside a CBA. Generally, Category 2 RECs are generated from out-of-state renewable facilities and require a Substitute Energy Agreement that details the simultaneous purchase of energy and RECs from an RPS-eligible facility.
- **Category 3:** Unbundled RECs that do not include the physical delivery of the energy attached to the REC. Generally, Category 3 RECs are associated with the sale and purchase of the RECs themselves, not the energy.

[5] The CPUC Rulemaking for the RPS program is currently R.15-02-020.

In addition to complying with RPS procurement requirements and PCC classifications, most retail sellers have specified requirements for the balance or mix of procurement from contracts that are executed after June 1, 2010. Specifically, these retail sellers must procure a minimum level of Category 1 RECs, which increases over the initial three multi-year compliance periods.[6] There is a maximum limit on the amount of Category 3 procurement that may be used in each compliance period, which decreases over the same timeframe.

The PCC requirements are instrumental in determining a retail seller's compliance with the RPS program. Figure 1 depicts the portfolio category limits and how they adjust across compliance periods until 2020, at which point they remain at those limits for each successive compliance period.

Eligible renewable generation facilities may be located anywhere within the Western Electricity Coordinating Council (WECC) region.[7] These facilities are permitted to sell RECs to California retail sellers of electricity to meet their RPS obligations, provided the facility meets all RPS eligibility criteria established by the CEC.

RPS Excess Procurement Rules

RECs that are not used to fulfill RPS obligations in one period may be "banked" and used in subsequent compliance periods. SB 2 (1X) (Simitian, 2011) established the ability for a retail seller to carry over procurement from one compliance period to another. The calculations for excess procurement rely on a combination of the PCC classification of the RECs and whether the RECs are associated with short-term or long-term contracts.

The Commission recently implemented SB 350, which changes the banking rules. Beginning in 2021-2024 compliance period, all excess PCC 1 RECs can be banked, regardless of whether they are associated with short- or long-term contracts; no PCC 2 or PCC 3 RECs can be banked.

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[6] See Public Utilities Code § 399.16(c) for additional information.

[7] The WECC region extends from the Canadian provinces of Alberta and British Columbia to the northern part of Baja California, Mexico, and encompasses the 14 western U.S. states in between.

RPS Compliance Requirements

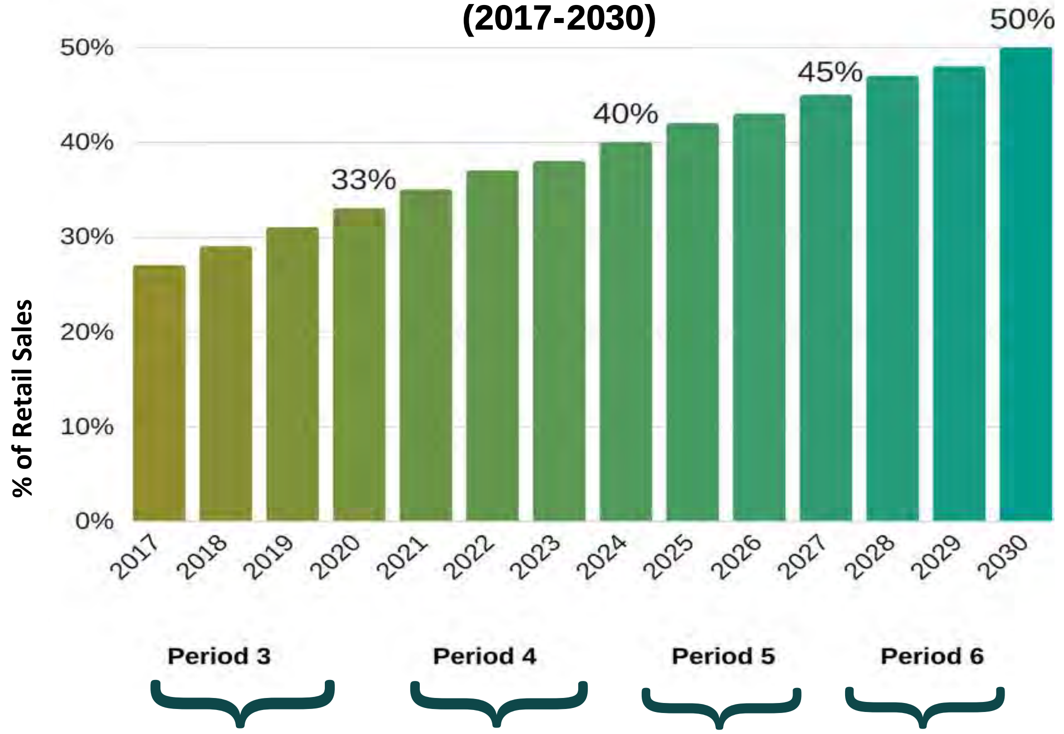
RPS compliance requirements are jointly administered, verified, and enforced by the CPUC and the CEC. Each August 1, retail sellers must submit annual Compliance Reports to the CPUC. The compliance verification process ensures that electricity retailers are on-track to meet a 50% RPS requirement by 2030, via interim compliance period targets.

How RPS Compliance Progress is Measured

The RPS program has six interim compliance periods leading up to 2030 for the purpose of monitoring electricity retail seller progress towards the 50% RPS mandate:

- **2013:** 20%
- **2016:** 25%
- **2020:** 33%
- **2024:** 40%
- **2027:** 45%
- **2030:** 50%

Figure 2: RPS Compliance Period Requirements (2017-2030)



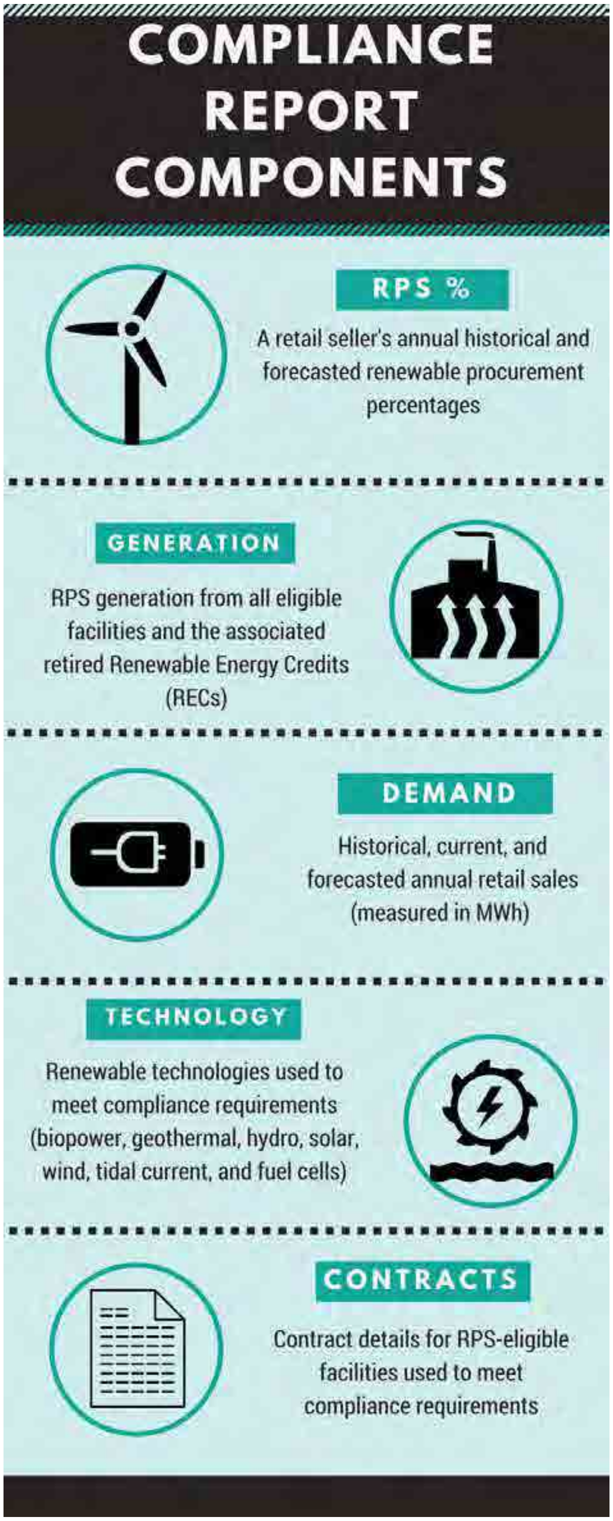
Each year, the CPUC evaluates the utilities' Procurement Plans to review their long-term RPS forecasts and planning mechanisms. The Plans provide information regarding current supplies, projects under development, and forecasted need for additional RPS procurement.

Progress towards the RPS mandate is measured in several ways, including through the analysis of detailed RPS Procurement Plans and Compliance Reports. These documents determine the compliance status of each retail seller in achieving the statewide mandate.

Retail sellers are required to submit annual Compliance Reports to the CPUC that contain historical and forecasted details about their annual renewable procurement. The CPUC evaluates these reports to ensure progress is being made towards the interim targets.

The CPUC works closely with the CEC to ensure that the utilities meet their RPS requirements. Compliance evaluations and official determinations by the CPUC can only take place after the CEC verifies a retail seller's annual REC claims.

The CEC receives reports from energy retailers generated by the Western Renewable Energy Generation Information System (WREGIS) describing the amount of renewable electricity generated by every eligible facility.[8] The CEC analyzes WREGIS reports to determine: eligibility of the facility, the quantity of RECs created from each RPS-eligible facility, and retail sellers' RPS procurement claim to ensure each REC claimed is eligible for compliance with the RPS and is only counted once.



[8] The Western Renewable Energy Generation Information System (WREGIS) is an independent renewable energy tracking system for the region covered by the Western Electricity Coordinating Council (WECC).

Once the CEC has verified the number of RPS eligible RECs, a retail seller can use those RECs to meet their compliance obligations, and those RECs are retired. The CPUC is responsible for reviewing how a retail seller's RPS procurement is classified into PCCs. However, the CPUC can only enforce compliance at the conclusion of the multi-year Compliance Periods.

This chapter uses historical data through December 31, 2016 from the Compliance Reports and the Procurement Plans from the large IOUs, SMJUs, CCAs, and ESPs to illustrate the state of the RPS program. The data presented in this chapter is used by the CPUC to evaluate aspects of RPS procurement, including:

- Procurement progress towards the 50% RPS mandate;
- Current renewable procurement status;
- Renewable portfolio and technology mix;
- Installed renewable capacity; and
- RPS contracting activities.

Large IOUs: Well-positioned to Meet RPS Requirements

All electricity retail sellers were required to serve 25% of their load with RPS-eligible resources by December 31, 2016, as an interim target between compliance periods. The large IOUs surpassed this requirement, as illustrated in Table 1.[9]

Table 1: Actual RPS Procurement Percentages Towards Meeting the 25% Requirement in 2016	
PG&E	32.9%
SCE	28.2%
SDG&E	43.2%

Data source: IOU Annual RPS Compliance Filings, August 2017

Table 1 shows that the large IOUs have individually met the 25% target. The IOUs may choose to apply eligible renewable electricity procured in 2016 that is in excess of the RPS requirement to meet their RPS requirements in future compliance periods, or they may sell RECs associated with the excess procurement to third parties.[10]

As further described in Chapter 3 under "Excess Procurement," a variety of market conditions have caused the IOUs to be procured beyond their minimum RPS requirements, including the need to hedge against initial program experience with project failure and/or increasing departing load to CCAs.

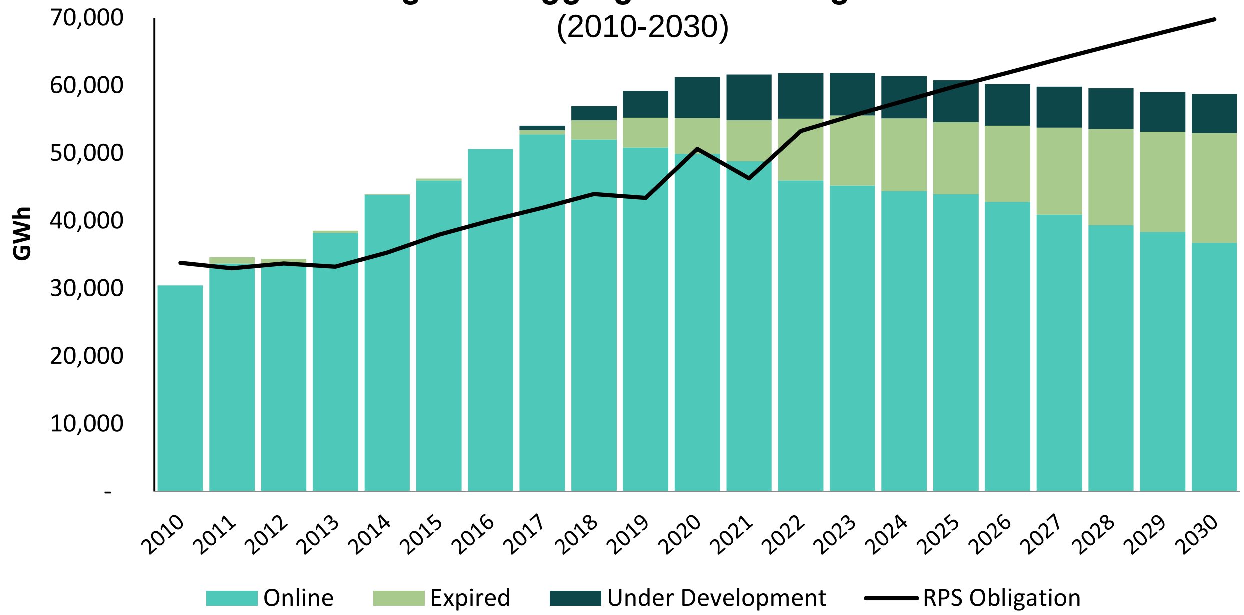
[9] Based on their annual RPS Procurement Plans, as well as Compliance Reports filed with the CPUC in August 2017, the three large IOUs are well-positioned to meet their procurement targets for the 50% RPS mandate by 2030 using excess procurement through the banking provisions described in Chapter 1.

[10] The three large IOUs forecast having excess procurement for the next five years and are positioned to exceed their RPS obligations (see Table 2).

Figure 3 uses the most current annual data to illustrate the actual and forecasted progress the large IOUs have made toward meeting the 50% RPS mandate on a risk-adjusted basis.[11] The graph shows a forecasted surplus of renewable generation through 2020 and a deficit beginning in 2022.[12] [13] As reported in their Procurement Plans and Compliance Reports, the IOUs forecast that they will meet the 33% RPS requirement by 2020 (see Table 2).[14]

The IOUs forecast that they can meet their RPS requirements by using banked RECs. Given the IOUs have significant excess eligible RPS procurement, they chose not to conduct annual RPS solicitations in 2016 or 2017, nor do they plan to undertake solicitations in 2018 (as described further in Chapter 3).[15]

Figure 3: Aggregated IOU Progress
(2010-2030)



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[11] The data used to create Figure 3 was taken from the IOUs' 2017 Annual RPS Procurement Plans. Generation forecasts from projects "under development" are risk adjusted to account for a certain degree of project failure. Failure rate assumptions are provided by the IOUs in their renewable net short calculation provided with their Draft Annual RPS Procurement Plan that were submitted in July 2017.

[12] Projects that are currently "Under Development" are expected to decrease beginning in 2023 out to 2030 because the project developers and IOUs focus their efforts on the nearer term.

[13] The "Expired" field represents the amount of generation associated with facilities that no longer have a PPA with one of the IOUs. Although this generation is not under contract, there is a possibility that one of the IOUs will re-contract with these facilities.

[14] The RPS obligation decreases from 2020 to 2021 due to the varying Compliance Period timeframe (from three years to four years in a Period).

[15] The IOUs' excess procurement is based on the current forecast of bundled electricity load and additional CCA departures will result in increased amounts of excess.

Table 2 below depicts the large IOUs' actual RPS procurement and forecasted procurement, and shows that the IOUs forecast that they will meet or exceed their 2020 RPS compliance period requirements, and meet the 2030 50% RPS requirement by 2020. The data is aggregated to provide a statewide view of progress and anticipated compliance.[16]

Table 2: Average Large IOUs' RPS Procurement Percentages for PG&E, SCE, and SDG&E in 2016

Actuals						Forecasted			
Compliance Period 1			**Compliance Period 2**			**Compliance Period 3**			
20% Requirement			*25% Requirement*			*33% Requirement*			
2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
20%	20%	23%	28%	30%	35%	38%	42%	47%	50%

Data source: IOU RPS Compliance Reports, August 2017[17]

SMJUs: Demonstrate Need to Procure within the Next Five Years

The SMJUs project that the will meet the current RPS targets for Compliance Period 2 (2014-2016), but have indicated they will need to procure additional resources to meet the post-2020 compliance targets. Table 3 data show an average of two SMJUs' procurement percentages (Liberty and BVES), and does not reflect the procurement of the individual utilities. Both Liberty Utilities and Bear Valley Electric Service (BVES) included their forecasted RPS procurement percentages in their 2017 RPS Procurement Plan and compliance filings.[18]

Table 3: Average SMJUs' RPS Procurement Percentages BVES and Liberty in 2016

Actuals						Forecasted			
Compliance Period 1			**Compliance Period 2**			**Compliance Period 3**			
20% Requirement			*25% Requirement*			*33% Requirement*			
2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
20%	21%	22%	29%	25%	27%	28%	29%	32%	33%

Data source: SMJU RPS Compliance Reports, August 2017

[16] Each retail seller must file its annual RPS Procurement Plan and Compliance Report. Renewable procurement data is not automatically confidential but may be claimed as such through a formal filing. In the formal confidentiality filing, the retail seller must justify why the information should be treated as confidential by the CPUC. Generally, historical data should be public and individual contracts may be confidential for 3 years from the date that energy deliveries begin. Additionally, retail sellers are allowed to redact forecast information three years forward. See the CPUC's Decision on Confidentiality (D.06-06-066) for more information: http://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/57772.PDF.

[17] Note: The forward-looking data (2017-2020) of each IOU is treated as confidential information per D.06-06-066.

[18] PacifiCorp data is not included in Table 3 due to confidentiality rules, as its confidential information could be derived due to public data available from Liberty and BVES.

CCAs: Demonstrate Need to Procure within the Next Five Years

RPS Compliance Reports submitted by Marin Clean Energy (MCE), Sonoma Clean Power (SCP), Lancaster Choice Energy (LCE), Peninsula Clean Energy (PCE) and CleanPowerSF indicate the CCAs have met the current RPS targets. However, their preliminary compliance reports indicate they will need to procure renewable resources to meet the 50% RPS target by 2030. Table 4 provides an average of these CCA's reported procurement percentages.

Table 4: Average CCA RPS Procurement Percentages for MCE, SCP, LCE, PCE, and CPSF in 2016

Actuals						Forecasted			
Compliance Period 1			Compliance Period 2			Compliance Period 3			
20% Requirement			*25% Requirement*			*33% Requirement*			
2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
28%	29%	30%	48%	39%	47%	46%	38%	38%	30%

Data source: CCA RPS Compliance Reports, August 2017

The information provided above is based on the various operational statuses of the CCAs. From 2011 to 2013, Marin Clean Energy was the only CCA in operation. In 2014, Sonoma Clean Power started serving load, and Lancaster choice started serving load in 2015. Accordingly, the CPUC has collected robust data on the CCAs with the longest operational history, given that the other six certified CCAs have only recently begun serving customers. All certified CCAs, have begun executing contracts for new renewable energy projects that will come online within the next five years.

ESPs: Procurement Assessment Unknown Due to Lack of Long-term Forecasting

ESPs are non-utility electricity service providers which currently serve approximately 13% of California's electricity load. Though California's ESPs are required to file both Compliance Reports and Procurement Plans, they do not provide long-term forecasts on their renewable procurement. The forecasted renewable procurement percentages are not a required element of the Compliance Reports and most ESPs do not forecast beyond the current reporting year. Therefore, the CPUC is unable to provide data on the long-term RPS outlook of the ESPs.

The Status of Current Renewable Portfolios

To provide a more detailed view of the status of RPS portfolios, this section describes a variety of perspectives for retail sellers with available information, including renewable resource mix, installed renewable capacity, and contracting activities. Among the retail sellers in California:

- The large IOUs have the most diverse renewable energy portfolio mix;
- The CCAs have a moderately diverse renewable energy portfolio mix; and
- SMJUs have the least diverse portfolio mixes.

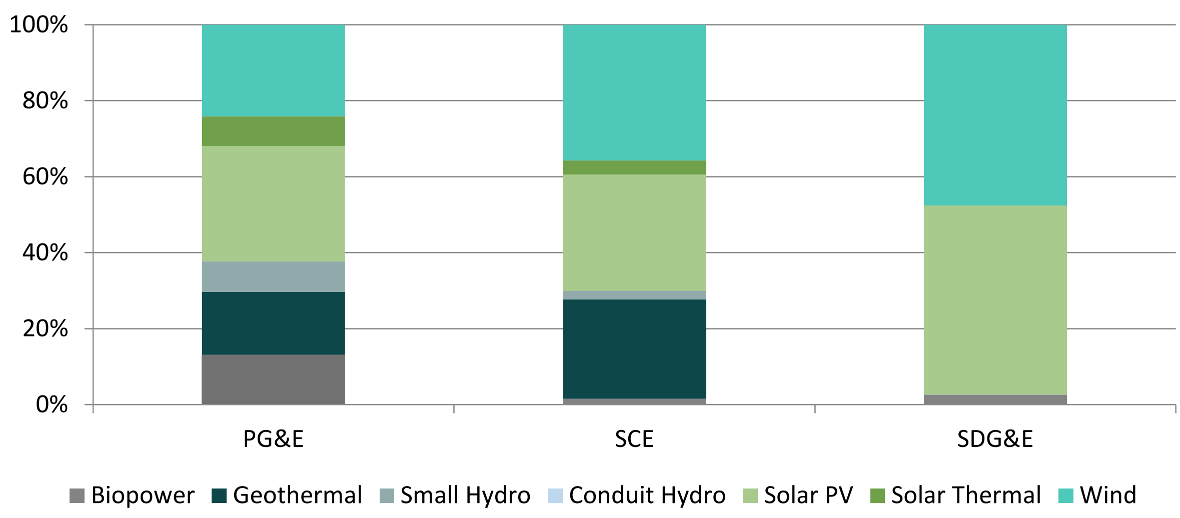
The large IOUs and CCAs have contracted with developers for new renewable facilities to add more capacity to reach the 50% RPS mandate. The SMJUs have been less active in contracting for renewables, but have secured the contracts needed to achieve the RPS requirements.

Renewable Technology Mix

Large IOUs

Since the inception of the RPS program in 2002, the large IOUs have continuously added new renewable technologies to their portfolios in order to satisfy their RPS procurement requirements. The large IOUs contract with a wide range of renewable technologies. Figure 4 shows that as of December 2016, the IOUs have procured diverse renewable energy resources such as wind, solar thermal, solar photovoltaic (PV), geothermal, biopower, and hydroelectric facilities to meet the requirements of the RPS program.[19]

Figure 4: IOU Renewable Portfolio Mixes in 2016



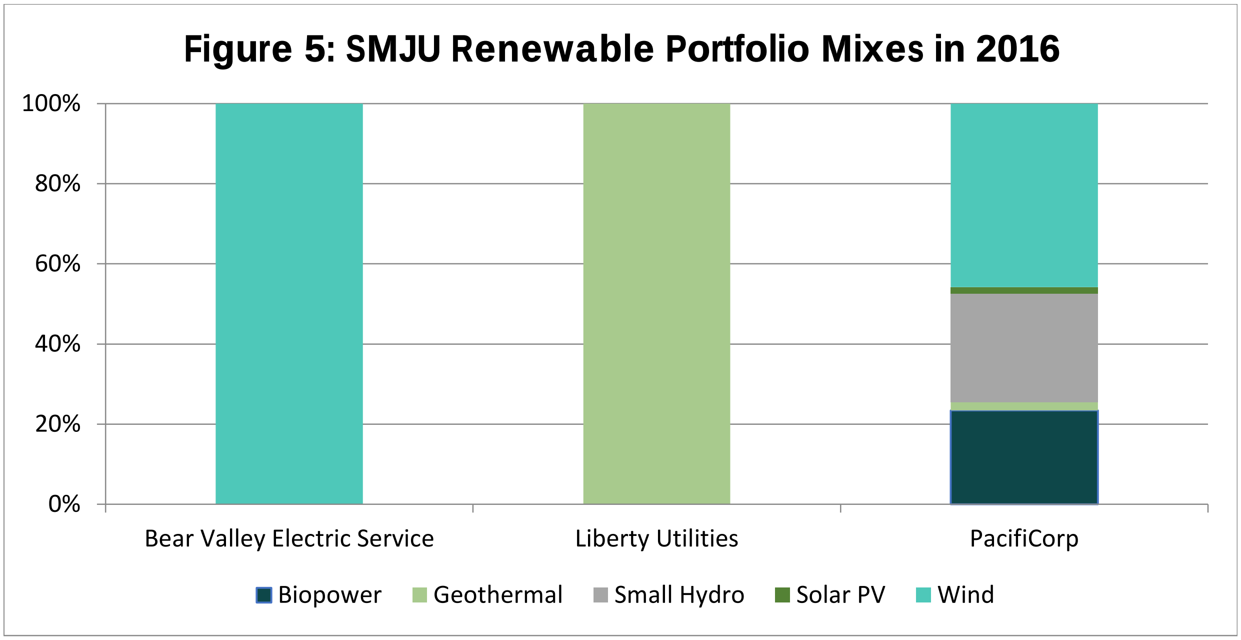
Data Source: IOU Annual Compliance Reports, submitted August 2017

[19] Approximately 1% of SCE's renewable portfolio is comprised of Conduit Hydroelectric technology. The technology category of "Biopower" consists of biomass, biogas, biodiesel, landfill gas, and municipal solid waste.

SMJUs

With the exception of PacifiCorp, the renewable portfolio mixes of California's SMJUs are not as diverse as those of the large IOUs or the CCAs. As Figure 5 shows, Bear Valley Electric Service and Liberty Utilities, respectively, procured one technology each - wind and geothermal - to meet their RPS requirements.

In 2016, PacifiCorp had five technologies in its renewable energy portfolio, with the majority comprised of wind (44%) and biopower (23%).



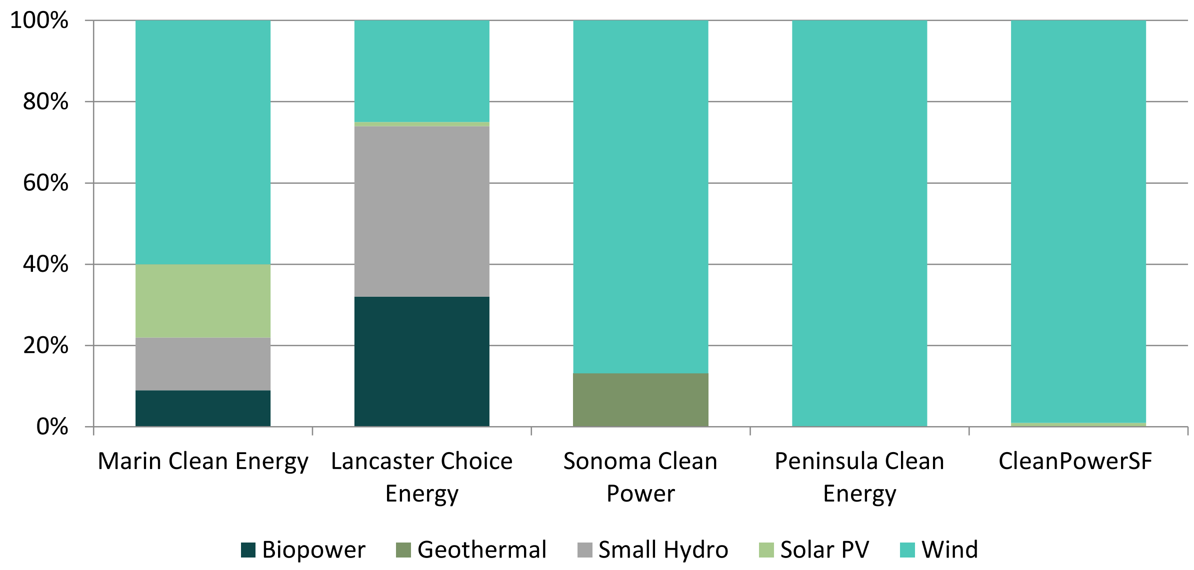
Data Source: SMJUs' Annual Compliance Reports, submitted August 2017

CCAs

Figure 6 illustrates the renewable energy portfolio mixes of the five CCAs that operated in California in 2016. Marin Clean Energy (MCE), Lancaster Choice Energy (LCE), and Sonoma Clean Power (SCP) have been in operation for six, three, and two years, respectively, and have more diverse resource mixes than Peninsula Clean Energy (PCE) and CleanPowerSF. Both PCE and CleanPowerSF began delivering energy in 2016.

In 2016, wind energy resources comprised the majority of MCE, SCP, PCE and CleanPowerSF's renewable portfolios at 60%, 86%, 100%, and 99%, respectively. The majority of LCE's portfolio (74%) consisted of small hydroelectric and biopower facilities.

Figure 6: CCA Renewable Portfolio Mixes in 2016



Data Source: CCA Annual Compliance Reports, submitted August 2017

Installed Renewable Capacity

Since 2003, the three large IOUs have installed 15,193 MW of renewable capacity under the RPS program. As of October 2017, 344 MW of new renewable capacity came online. An additional 453 MW of renewable capacity is forecasted to achieve commercial operation in the next two years. The approved RPS capacity described in Figure 7 below includes both in-state and out-of-state facilities, with the majority of the facilities being in-state and solar PV being California's largest in-state renewable resource.

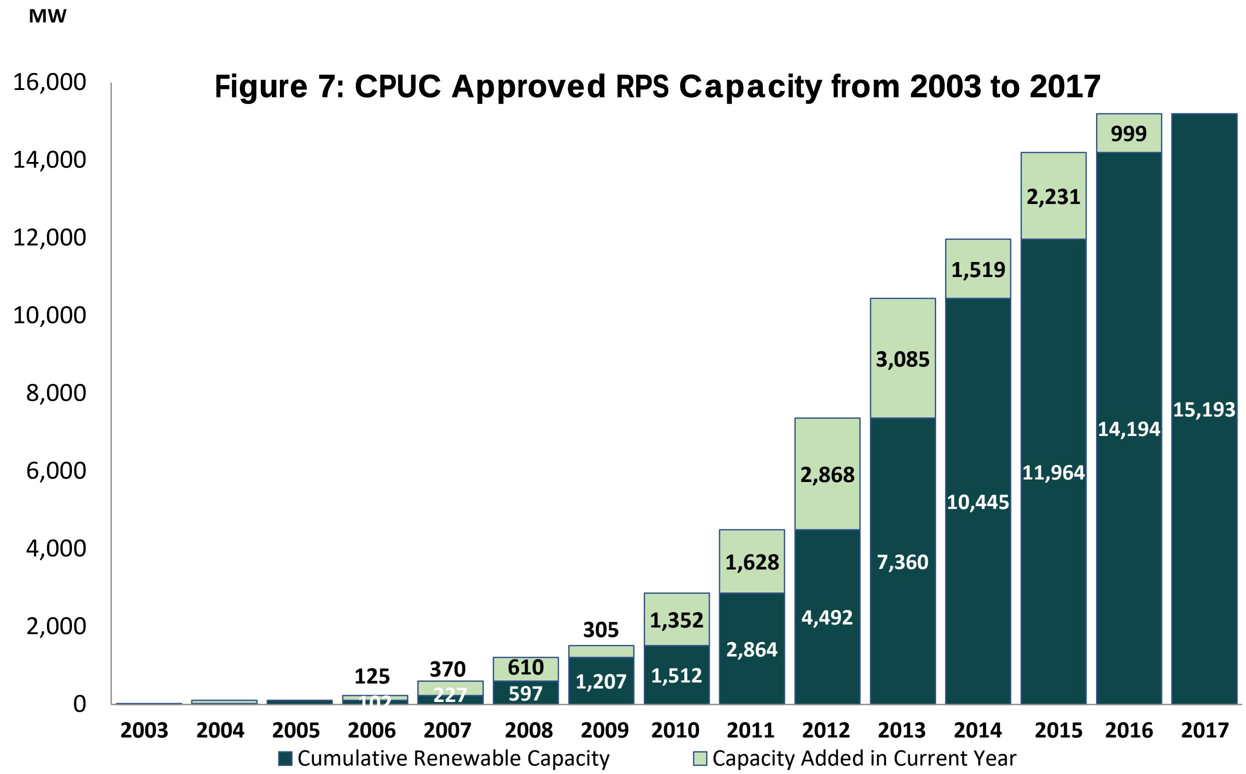


Figure 7: CPUC Approved RPS Capacity from 2003 to 2017

Data source: IOU Project Update Submissions to the CPUC's RPS Contract Database (October 2017)

2016 Renewable Contracting Activities

In 2016, the IOUs collectively executed five BioRAM contracts, three Request for Offer (RFO) contracts, fourteen ReMAT contracts, and four Qualifying Facilities (QF) contracts for a total of 209 MW of new RPS capacity. Table 5 below shows that PG&E executed twelve contracts, six of which were ReMAT contracts. PG&E signed six other contracts, half of which were from RFOs and half that were from QFs. Similarly, SCE executed twelve contracts where eight of them were under the ReMAT program, three were BioRAM, and one was a QF contract. SDG&E signed two contracts, both of which were to fulfill their BioRAM program requirement.[20]

Table 5: Number of Large IOU RPS Contracts Approved by the CPUC in 2016

	PG&E		SCE		SDG&E		Totals	
Procurement Program	Contracts	MW	Contracts	MW	Contracts	MW	**Contracts**	**MW**
BioRAM (Biomass)	0	0	3	67	2	48	**5**	**115**
ReMAT	6	6	8	15	0	0	**14**	**21**
RFO	3	65	0	0	0	0	**3**	**65**
QF CHP	3	7	0	0	0	0	**3**	**7**
QF Standard Contract	0	0	1	1	0	0	**1**	**1**
Totals	12	72	12	83	2	48	**26**	**209**

Data source: IOU Project Update Submissions to the CPUC's RPS Contract Database (October 2017)

2016 Power Purchase Agreement Diversity

While the table above illustrates that BioRAM had the most RPS-eligible MWs procured, the table below shows that ReMAT had the largest proportion of executed contracts based on number of contracts. Table 6 shows that the majority (54%) of the IOUs' executed contracts were from the ReMAT program. In addition, the data show that the smallest percentage (12%) of the RPS contracts originated through RFOs.

Table 6: Percentage of IOU RPS Contracts (2016)

RPS Program	# of Contracts
ReMAT	54%
BioRAM	19%
QF Contracts	15%
RFO/Solicitation	12%

[20] Table 5 illustrates data from the large IOUs, but there were also other RPS contracts signed by the SMJUs, CCAs, and ESPs. Per D.12-06-038, the CPUC collects monthly data from the large IOUs on: RPS projects, including contract details, project development status, technology type, location, capacity, financing status, construction start date, commercial online date, regulatory status, and interconnection details.

Chapter 3 uses data through October 2017 to provide an overview of 2017 RPS activities, describing implementation of the large IOUs' RPS procurement and status:

- Renewable procurement
- Implementation of RPS Legislation
- RPS Compliance and Enforcement

In addition, Chapter 3 describes the 2017 Draft RPS Procurement Plans for the large IOUs, SMJUs, and the CCAs that were submitted in July 2017. Once approved, these Plans will provide guidance for 2018 RPS activities, and beyond.

While the Commission assures that RPS Procurement Plans for the CCAs and ESPs meet required planning criteria, the CPUC has limited jurisdiction over their procurement activities.

2017 RPS Procurement Activities of the Large IOUs

As demonstrated in Chapter 2, the large IOUs are currently long on procurement and are anticipated to meet their 2030 RPS requirements by 2020. Accordingly, the IOUs chose not to hold annual RPS solicitations in 2017.

However, the IOUs were required to procure renewable energy through other RPS programs in order to meet RPS and various other State policy goals. These programs include:

- Renewable Auction Mechanism (RAM)
- Bioenergy Renewable Auction Mechanism (BioRAM)
- Renewable Market Adjusting Tariff (ReMAT)
- Bioenergy Market Adjusting Tariff (BioMAT)

Renewable Auction Mechanism (RAM)

The Renewable Auction Mechanism (RAM) is a simplified, market-based mechanism for renewable distributed generation projects. RAM allows the IOUs to competitively procure RPS-eligible generation via a streamlined procurement process, allowing bidders to set their own price, use a standard contract, and allow IOUs to submit projects to the CPUC through an expedited regulatory review process.

RAM is designed to facilitate quick and simple transactions for projects that meet minimum criteria. Since the inception of the RAM program, the IOUs have held seven auctions, and procured a total of 1,332.5 MW.

The Commission views the RAM program as a targeted and cost-effective means to reduce greenhouse gas emissions, consistent with its integrated resource planning strategies. The initial purpose of the RAM program was to create a simplified market-based procurement process for smaller (<20 MW) RPS generation projects. Subsequently, the size restriction was removed to provide greater flexibility for RAM projects. The IOUs may use their annual RPS Procurement Plan to propose any additional RAM solicitation.

2017 RAM Procurement

Each of the IOUs approached RAM in various ways in 2017:

- **SCE:** did not hold any RAM solicitations given that it met its RAM obligations in 2016.
- **SDG&E:** is expected to meet its RAM obligation through its recent RAM 7 solicitation.
- **PG&E:** executed three contracts and is expected to launch a RAM solicitation by the end of 2017.

RAM Status in 2017

Table 7 below shows that the IOUs are required to procure a balance of 245 MW for the RAM program. SCE has exceeded their RAM requirements, while PG&E and SDG&E are in the process of holding solicitations to meet their remaining requirements.[21]

Table 7: IOU RAM Procurement Status (2017)

RAM Mandated Capacity (MW)	PG&E	SCE	SDG&E	Total
Total RAM Procurement Targets	653	756	165	1,574
RAM Capacity Contracted	515	789	58	1,333
Capacity Remaining	**138**	**0.0**	**107.0**	**245**

Data Source: IOU Draft RPS Procurement Plans, July 2017

Bioenergy Renewable Auction Mechanism (BioRAM)

2017 BioRAM Procurement

The BioRAM program used the RAM process to implement the Governor's October 2015 Emergency Order on Tree Mortality, as well as addressed emergency strategies in SB 859. BioRAM requires the large IOUs to procure 146 MWs of bioenergy from forest fuel in High Hazard Zones (HHZ) from dead and dying trees, in order to aid in mitigating the threat of wildfires.

In early 2017, the Commission approved the final BioRAM contracts, fulfilling the State's emergency orders on Tree Morality that require the IOUs to procure their proportional share of bioenergy from High Hazard Zone (HHZ) forest fuel. In February and April 2017, respectively, the CPUC approved PG&E's executed biomass contracts with the Burney and Wheelabrator facilities, totaling 43 MWs and completing the required BioRAM procurement.[22]

[21] Although PG&E and SDG&E filed requests to eliminate their remaining RAM procurement obligations, the CPUC denied the requests.
[22] SCE and SDG&E executed their required BioRAM contracts in 2016.

2017 BioRAM Status

Table 8 outlines the IOUs' BioRAM contracts that comply with the State's emergency orders. The Governor's Emergency Order resulted in the CPUC's implementation of BioRAM 1 procurement. SB 859 resulted in the CPUC's implementation of BioRAM 2 procurement.

Table 8: Overview of IOU BioRAM Contracts
(All 5-year Terms)

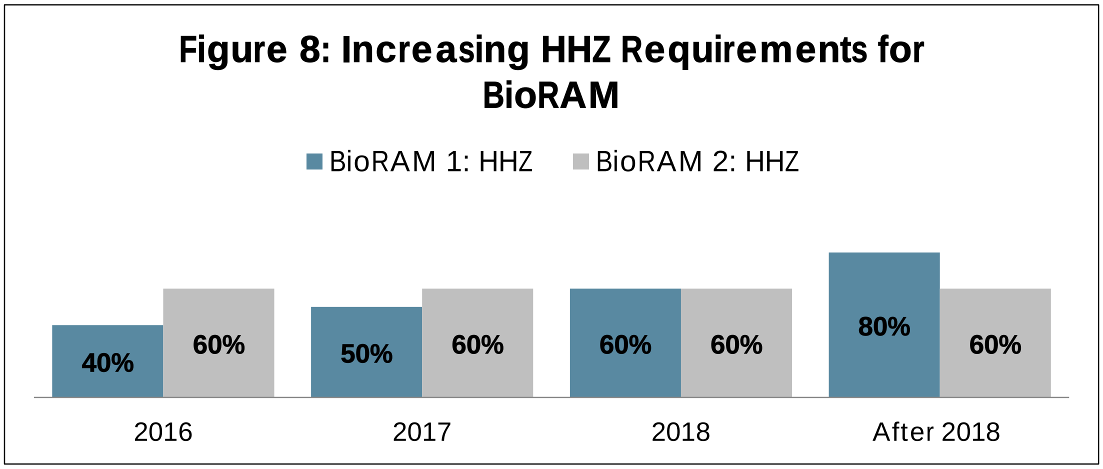
IOU	Facility	Location	BioRAM Procurement (MW)	BioRAM Phase
PG&E	Burney	Burney	29	BioRAM 1
PG&E	Wheelabrator Shasta	Anderson	34	BioRAM 2
SCE	Rio Bravo Fresno	Fresno	24	BioRAM 1
SCE	Rio Bravo Rocklin	Lincoln	24	BioRAM 1
SCE	Ultrapower Chinese Station	Jamestown	18	BioRAM 1
SDG&E	Honey Lake Power Company / Greenleaf	Lassen	24	BioRAM 1
TOTAL			**153**	

Data Source: CPUC analysis of approved contracts, 2017

High Hazard Zone (HHZ) Fuel Requirements for BioRAM:

As figure 8 illustrates, BioRAM contracts are required to achieve assigned HHZ forest fuel usage targets:

- **BioRAM 1 (Governor's Emergency Order):** Starts at 40% and increases to 80% beyond 2018.
- **BioRAM 2 (SB 859):** At least 60% HHZ, with 80% from sustainable forest.



Data Source: Commission Resolutions E-4770 and E-4805

Tracking High Hazard Zone Forest Fuel Requirements for BioRAM:

The IOUs collect quarterly data from the biomass facilities in order to track the amount of bioenergy that is being produced from HHZ forest fuel in the BioRAM contracts. The HHZ requirement is based on an annual calendar year measurement. Table 9 shows the amount of HHZ fuel used in 2017 as part of BioRAM contracts. This data reflects bioenergy from the two facilities currently operating that have collected data, Chinese Station and Honey Lake Power. The Burney facility commenced operation at the end of October 2017. The other three contracted BioRAM projects have not yet commenced delivery.

Table 9: High Hazard Zone (HHZ) Forest Fuel Usage in 2017 from BioRAM 1 Contracts
(Aggregated Statewide)

Total HHZ Used (BDT)	Average % of Total Biomass Fuel from HHZ Fuel
56,951	41.45%

Note: BDT = Bone Dry Tons, which is approximately 1:1 equivalent with MWh

Data Source: CPUC Aggregated Data from IOUs, available as of 10/2/17 - Aggregated due to confidentiality rules

The IOUs are currently in the process of devising their fuel verification processes for BioRAM programs. Verification programs will examine the self-reported data from biomass facilities, and ensure that they are meeting their assigned HHZ fuel requirements on an annual basis, at the end of each calendar year.

BioRAM Non-Bypassable Charge Proceeding

SB 859 directed that the costs from BioRAM procurement be allocated to all customers, including CCAs and ESPs, given that all customers benefit from preventing wildfires. In 2017, the CPUC began the process to establish the mechanism to allocate costs from these programs to customers.

Feed-in Tariff (FIT) Programs

A Feed-in Tariff (FIT) program is a policy mechanism designed to accelerate investment in small, distributed renewable energy technologies. The goal of Feed-in Tariff programs is to offer long-term contracts and price certainty that aid in financing renewable energy investments. The RPS program has two FIT programs:

- Renewable Market Adjusting Tariff (ReMAT)
- Bioenergy Market Adjusting Tariff (BioMAT)

Both programs have capacity procurement mandates established by the Legislature, which are generally allocated to each IOU based on their proportionate share of statewide load served.

Renewable Market Adjusting Tariff (ReMAT)

The ReMAT is a large IOU program that provides market-based adjusting prices for small RPS-eligible facilities (generating up to 3 MW) to sell renewable electricity to utilities under standard terms and conditions.

The ReMAT program was established by SB 32 (Negrete McLeod, 2009) and SB 2 (1x) (Simitian, 2011) and commenced in 2013 offering a fixed-price standard contract to export electricity to California's three large IOUs. The ReMAT program replaced California's original FIT program established by AB 1969 (Yee, 2006) in order to expand the program and increase eligible project size from a maximum of 1.5 MW to up to 3 MW. Recently, AB 1979 modified the program to increase the maximum project capacity to 4 MWs for conduit hydroelectric facilities, if they deliver no more than 3 MW.

IMPLEMENTATION OF AB 1979

In August 2017, the CPUC implemented AB 1979 (Bigelow, 2016) with decision D.17-08-021.

This decision creates ReMAT eligibility for a conduit hydroelectric generation facility of up to 4 MW in capacity, if the facility:

- **was operational as of January 1, 1990;**
- **complies with CPUC and other interconnection rules; and**
- **delivers no more than 3 MW to the grid at any time.**

As a result of AB 1979, conduit hydropower facilities that originally intended to only provide municipal water are now able to leverage their power generating capability.

2017 ReMAT Procurement

In 2017, PG&E procured six ReMAT contracts totaling 6.2 MWs. One of these was a new solar PV project, and the remaining five are existing small hydropower projects. SCE procured three new solar PV projects, totaling 9 MWs. SDG&E did not procure any new ReMAT projects.

ReMAT Program Status

SCE has recently reached the procurement level where, under the program rules, its ReMAT program could be suspended at the end of 2019. SDG&E has suspended its program and therefore SDG&E did not procure any new ReMAT projects. PG&E has the largest amount of capacity remaining at 122 MW.

The IOUs have collectively procured 255.7 MW out of their total 493.6 MW ReMAT requirement. As of the September 2017 program period, the IOUs have procured these proportions of their assigned ReMAT capacity mandate:

- PG&E: 44%
- SCE: 60%
- SDG&E: 47%

Table 10 below provides an overview of the progress that each IOU has made toward their ReMAT capacity mandate from the program's inception in 2013 to present. The ReMAT program has a total of 238 MW of capacity remaining.

Table 10: ReMAT Mandated Allocations Per Large IOU (MW)

	PG&E	SCE	SDG&E	Totals
Total ReMAT Procurement Requirement	219	226	49	**494**
ReMAT Capacity Contracted	97	136	23	**256**
Capacity Remaining	**122**	**90**	**26**	**238**

Data source: CPUC RPS Contract Database, September 2017

Bioenergy Market Adjusting Tariff (BioMAT)

The Bioenergy Market Adjusting Tariff (BioMAT) is a Feed-in-Tariff program created by SB 1122 (Rubio, 2012), which added an additional 250 MW of RPS-eligible procurement for small-scale bioenergy projects up to 3 MW. Modeled after the ReMAT program using a fixed-price standard contract, BioMAT allocates procurement to the distinct bioenergy areas of Biogas, Agriculture, and Forest.

The goal of the BioMAT program is to promote a competitive market with a simple procurement mechanism for bioenergy developer entrants.

2017 BioMAT Procurement

Biogas Category: The Biogas category yielded contracts at the program starting price of $127.72/MWh. Since that time, four biogas contracts have been executed for a total of 7.4 MW, with each IOU having at least one biogas contract. Three biogas contracts were signed in 2017, totaling to 5.85 MW. These contracts were executed at the program price of $127.72/MWh and are expected to come online in mid-2019.

IMPLEMENTATION OF AB 1923

On August 28, 2017, the CPUC issued a decision (D.17-08-021) implementing a portion of AB 1923 (Wood, 2016), which expanded the eligibility of market participants by allowing a biomass facility of up to 5 MW in nameplate capacity to participate in BioMAT if it:

- **complies with CPUC and other interconnection rules; and**
- **delivers no more than 3 MW to the grid at any time.**

In October 2017, the CPUC issued a Ruling to implement the remaining portion of AB 1923. This phase will update BioMAT rules so that BioMAT projects can connect to the existing transmission system in order to increase developer opportunities, increase system efficiencies, and reduce interconnection costs.

Agriculture Category:

This category consists of the Dairy and Other Agriculture sub-queues. From August 1 – September 30, 2017, dairy digester developers accepted a price of $187.72/MWh, totaling 3 MWs. This program period queue did not meet the price adjustment trigger. Accordingly, the price will remain at $187.72/MWh during the October 1 – November 31, 2017 program period.

Forest Category:

For the October 1, 2017 program period, forest biomass developers accepted a price of $199.72/MWh, totaling 5 MWs. Given the number of developers in the queue, the price in this category will remain at $199.72/MWh for a second period. When the bid price remains at this level for two consecutive periods (November 1, 2017), it will trigger a CPUC Energy Division investigation pursuant to program rules adopted in D.14-12-081.

BioMAT Program Status

The BioMAT program launched in February 2016 and has resulted in few contracts, as developers appear challenged by various high costs to entry. Given there are few interested parties in the program queues, the market price has only adjusted upward in the Agriculture and Forest categories, and remained stagnant in the Biogas category.

Table 11: Assigned BioMAT Targets and MWs Achieved

BioMAT Category	BioMAT MW Allocation	MW Contracted
Biogas	110	7.4
Dairy/Agriculture	90	3.0*
Forest	50	5.0*
Total	**250**	**15.4**

Data source: CPUC RPS Contract Database, 2017

**Contracts are not yet executed*

RPS Program Compliance and Enforcement

In 2017, the CPUC implemented and administered RPS Compliance Rules for California's retail sellers of electricity subject to CPUC jurisdiction, which include the large IOUs, SMJUs, CCAs, and ESPs. In August 2017, these entities were required to submit annual Compliance Reports describing their progress towards the State's 50% RPS mandate. The CPUC has begun reviewing retail sellers' 2016 compliance reports.[23]

RPS Program Enforcement Process

The CPUC is responsible for establishing RPS enforcement procedures for retail sellers of electricity and imposing penalties for non-compliance with the RPS program.

In 2017, the CPUC began to revise the existing RPS enforcement framework to comply with SB 350. The Commission expects to issue a decision in 2018 implementing SB 350 mandated changes to the RPS enforcement process. The upcoming decision will be the third decision in a series of SB 350 implementation decisions. It will include the process by which retailers may seek a waiver of some, or all, of their RPS obligations, as well as a "schedule of penalties," as directed by SB 350.

Once notice is given to retail sellers who are deemed non-compliant with their RPS procurement obligations for a compliance period, current statute allows them to request a waiver for the penalty if they can demonstrate any of the following conditions:

- Inadequate transmission capacity;
- Delays caused by permitting or interconnection issues;
- Unanticipated curtailment of eligible renewable resources; or
- Unanticipated increase in retail sales due to transportation electrification.

CHANGES TO THE RPS PROGRAM MANDATED BY SB 350

WAIVER CONDITIONS

SB 350 added conditions that could justify a waiver of a retail seller's RPS requirements, which include:

- Unanticipated curtailment of eligible RPS resources, if the waiver would not cause an increase in GHG emissions; or

- Unanticipated increase in retail sales due to transportation electrification (Pub. Util. Code § 399.15).

In future compliance periods, parties may assert these additional justifications for a waiver request, which will be ruled upon within the RPS proceeding.

LONG-TERM CONTRACTING REQUIREMENTS

Beginning in 2021, SB 350 requires retail sellers to demonstrate that 65% of their procurement comes from long-term contracts. A long-term contract is defined as a contract lasting 10 or more years.

EXCESS PROCUREMENT

The CPUC determined that, beginning in the 2021-2024 Compliance Period, only Category 1 RECs can be banked. Category 1 RECs primarily include renewable generation that has a first point of interconnection in California and can be banked whether procured with short or long-term contracts.

[23] See Chapter 2 for an overview of progress for RPS goals.

2017 Draft RPS Procurement Plans

California's Renewable Portfolio Standard (RPS) program, requires that electricity retail sellers file annual RPS Plans to assist the CPUC, stakeholders, and California in monitoring renewable procurement to ensure that the State is on-track to meet its renewable energy goals. The RPS Plans provide the CPUC with an overview of the status of RPS procurement and generally describe both the need for additional renewable resources and the actions proposed to achieve those resources.

IMPLEMENTATION OF RPS PROCUREMENT REVISIONS MANDATED BY SB 350

In June 2017, the Commission implemented revised RPS compliance requirements established in SB 350 (D.17-06-026), requiring new standards commencing in the 2021-2024 Compliance Period:

- Retail sellers must demonstrate that 65% of their procurement comes from long-term contracts; and

- Portfolio Content Category (PCC) 1 RECs can be banked, in order to be used or sold in the future. PCC 1 RECs include renewable generation that has a first point of interconnection in California and can be the result of either short or long-term contracts.

These updates to RPS procurement criteria promote the development of new renewable resources that will be used to both increase eligible renewable facilities in the State and reduce greenhouse gas emissions.

Accordingly, each year, the CPUC approves RPS Procurement Plans for the large IOUs and SMJUs. While the CPUC also requires CCAs and ESPs to submit RPS Plans, the CPUC has limited oversight of such procurement activities as solicitations, offer evaluations, and contract approvals. The CPUC's role is to review the Plans of the CCAs and ESPs to ensure that they comply with the CPUC's RPS Plan requirements.

This section provides an overview of key issues presented in the 2017 RPS Draft Procurement Plans by the large IOUs, SMJUs, CCAs, and ESPs.

CPUC RPS Plan Guidelines

The CPUC issues guidance each year, prior to the retail sellers submitting their annual RPS Procurement Plans. In May 2017, the CPUC issued a Ruling with a detailed list of criteria that the utilities must address in their 2017 RPS Plans. These Plans must address the 14 point criteria listed on the table below.

In its decision D.16-12-044, the Commission established key criteria for guiding the development of RPS Procurement Plans.

RPS Procurement Plan Guidance	
Criteria	**Description**
1. Assessment of RPS Portfolio Supplies and Demand	The supply assessment details the retail seller's RPS portfolio and technology mix and the percentage of power served with renewable resources. The demand assessment focuses on retail sales and annual procurement need.
2. Project Development Status Update	Update of development of RPS-eligible resources currently under contract. These resources may be either in development, under construction, or online.
3. Potential Compliance Delays	Rationale for potential delays in achieving compliance with the RPS program. These reasons could include various obstacles for project developers such as securing project financing or interconnecting projects to the electricity grid.
4. Risk Assessment	Evaluation of risks associated with retail sales, generation, project failure, curtailment events, and project delays.
5. Quantitative Information	Quantitative information, such as retail sales forecasts, renewable net short calculations, annual procurement percentages and forecasts, failure percentages, expired contracts, and RECs generated from online and terminated projects.
6. "Minimum Margin" of Procurement	Analysis of information on minimum margin of procurement, defined as the minimum amount of renewables needed to address anticipated project failure or delay.
7. Bid Solicitation Proposals, Including Least-Cost Best-Fit Methodologies	Detail bid selection protocol for procuring additional RPS resources, which includes Least-Cost Best-Fit methodologies used to evaluate new projects.
8. Workforce Development	Details required from project developers to assess how much employment growth would happen during the construction and operation of a new project.
9. Disadvantaged Communities (DACs)	Detail questions for project developers about how the project will impact disadvantaged communities, including the location of the project in proximity to DACs and how the proposed facility will provide benefits to adjacent DACs.
10. Consideration of Price Adjustment Mechanisms	Include perspective on price-adjustment mechanisms in contracts and evaluate what impacts they will have on ratepayers.
11. Curtailment Frequency, Costs, and Forecasting	Detail curtailment activities (e.g., economic curtailment) and how curtailment has affected RPS planning and compliance.
12. Expiring Contracts	Detailed information on expiring RPS contracts.
13. Cost Quantification	Annual summary of actual and forecasted RPS procurement costs and generation by technology type.
14. Safety Considerations	Information on RPS contract provisions related to safety of a facility's operations, construction, and decommissioning, including general operation safety procedures, annual capacity and reliability testing, best industry practices, performance testing, and reporting requirements for all safety related incidents that occur onsite.

Large IOU RPS Plans

On or before July 21, 2017, the IOUs submitted their Draft 2017 RPS Plans to the CPUC. The following sections describe key issues addressed by the IOUs in their RPS Plans. See Chapter 6 for more information on challenges the utilities face in implementing their RPS Plans.

IOU Procurement Assessment

The large IOUs all show long RPS positions and are forecasted to have significant REC bank balances going forward, and as a result are expected to exceed their 2030 RPS targets. A long RPS position means a retail seller procures more energy from RPS-eligible resources than is required under the RPS procurement rules. Accordingly, none of the IOUs propose to hold general RPS solicitations in 2018.

Because of PG&E's long position in meeting RPS goals, in 2017 it held a REC sales solicitation and contracted to sell over 2 million MWh of energy and RECs to 3 Phases Renewables Inc., Direct Energy Business Marketing, LLC, EDF Trading North America, LLC, Exelon Generation Company, LLC, and Peninsula Clean Energy Authority. In 2018, all three IOUs propose additional REC sales in response to their long RPS positions.

Curtailment

The IOUs' RPS Plans describe curtailment as a possible risk to meeting their RPS obligations because the resources might not generate as much RPS-eligible energy as originally forecasted. Curtailment occurs when there is an oversupply of generation or congestion on the grid. The IOUs are preparing for this risk by forecasting expected renewable curtailment in the future, holding long RPS positions, and (since 2011) including economic curtailment terms in executed or amended contracts.

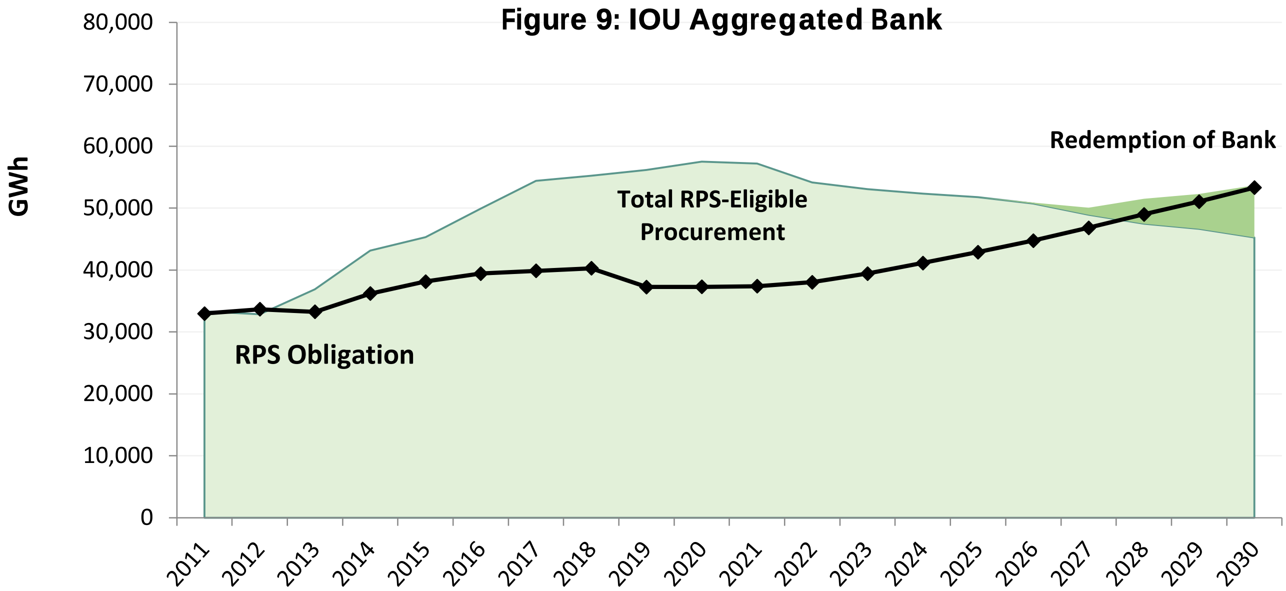
The addition of economic curtailment terms to RPS contracts allows the IOUs to respond to CAISO price signals. The benefits of economic curtailment include both avoided costs and cost savings. Day-ahead curtailments avoid costs of paying negative market prices, which require schedulers or generators to pay to generate. Real-time curtailments capture market opportunity costs (i.e., IOUs get paid to curtail).

Excess Procurement

Initially, the IOUs procured more renewables than necessary in order to hedge against potential RPS shortfalls due to high project failure rates. In addition, excess procurement resulted from market conditions such as the 2008 recession, successful energy efficiency strategies, and renewable energy deployment that benefitted from federal tax incentives. More recently, load migration from IOUs to CCAs has served to further increase the IOUs' long RPS positions.

As described in Chapter 1, retail sellers may bank excess RPS to meet future requirements. The IOUs are forecasted to accumulate significant banks going forward, and therefore, the IOUs have forecasted no need for incremental procurement of RPS-eligible resources until after 2030.

Figure 9 below shows the IOUs' potential aggregate bank accumulation and use of their bank. Bank balance forecasts by individual IOUs are confidential. Accordingly, this data has been aggregated in order to present a statewide view showing that the IOUs are on-track to meet their RPS obligations. In addition, Figure 9 shows the IOUs exhibiting a need for incremental RPS-eligible resources beginning in 2027, and how that need could be met through application of the bank through 2030.



Data source: CPUC's Integrated Resource Planning Modeling Results, E3 Modeling, 2017

Least-Cost Best-Fit Methodology

In order to ensure that the IOUs procure cost-effective resources that most closely match the need of each IOU's portfolio,[24] the Commission adopted criteria for the ranking and selection of Least-Cost Best-Fit (LCBF) renewable resources on a total cost basis.

Accordingly, each IOU in its RPS Plan must propose a LCBF methodology that meets the requirements articulated by the Commission and describes how renewable energy offers will be valued and evaluated, using both quantitative and qualitative criteria.

- **Quantitative Valuations:** May include criteria such as energy cost, congestion cost, locational preference, and transmission costs.
- **Qualitative Valuations:** May include criteria of resource diversity and benefits to disadvantaged communities.

The Commission then approves the LCBF methodologies through the RPS Plans, and the IOUs apply their methodologies to bids within the RPS solicitations. The Commission has given the IOUs substantial flexibility to develop their own individual LCBF methodologies, provided that a transparent rationale is offered to the CPUC and stakeholders.

The draft 2017 RPS Plans contained minimal revisions to the IOUs' LCBF methodologies because the IOUs do not propose to hold annual RPS solicitations in 2018. PG&E and SDG&E submitted revised time-of-delivery factors and SCE proposed to use an Effective Load Carrying Capacity ("ELCC") methodology to calculate Resource Adequacy benefits.

In the past several years, both the Commission and parties to the RPS proceeding have noted a need to revisit the LCBF methodologies. Chapter 4 provides more details on plans for LCBF reform.

Disadvantaged Communities

SB 2 (1X) (Simitian, 2011) requires the IOUs to take environmental justice considerations into account by giving preference to RPS bids that provide environmental or economic benefits to disadvantaged communities (DACs).

In their RPS Procurement Plans, the IOUs propose to collect information from bidders concerning a proposed project's expected benefits for DACs. The information collected from the project bidder is focused on the economic and environmental effects of a new project or facility on DACs. This qualitative information will then be taken into consideration in the LCBF evaluation of RPS bids.

[24] As required by Public Utilities Code 399.13(a).

SMJU RPS Plans

As described in Chapter 1, SMJUs are utilities with fewer than 30,000 customers. The SMJUs include PacifiCorp, Liberty Utilities, and Bear Valley Electric Service (BVES). SMJUs are subject to Pub. Util. Code §§ 399.17 and 399.18, and must meet a smaller subset of the RPS Plan requirements (e.g., they are not required to submit information on expiring contracts).

Further, the RPS procurement requirements allow these retail sellers to meet their procurement obligations without regard to the RPS portfolio content category limitations (PCC). Therefore, new procurement for these SMJUs has consisted of unbundled PCC 3 RECs.

Bear Valley Electric Service

BVES submitted its Draft RPS Plan on July 20, 2017. Currently, a 2013 REC-only contract with Avangrid Renewables, LLC fully satisfies BVES's RPS requirements. BVES stated in its RPS Plan that it is seeking to procure cost-effective bundled RECs to ensure ongoing, long-term RPS compliance. BVES is currently engaged in a Request for Proposals (RFP) for approximately 3 MW of RPS-eligible generation.

Liberty Utilities

Liberty submitted its Draft 2017 RPS Plan on July 21, 2017. Liberty currently serves its load through a combination of utility-owned resources and has a power purchase agreement for PCC 3 RECs with Sierra Pacific Power Company/NV Energy. In 2017, Liberty's 50 MW Luning Solar Project went online. Liberty has also requested CPUC approval to acquire the Turquoise Solar Project to displace additional RPS-eligible energy NV Energy would have provided.

PacifiCorp

PacifiCorp is a multi-jurisdictional utility for RPS purposes. PacifiCorp is permitted to use an Integrated Resource Plan (IRP) prepared for regulatory agencies in other states to satisfy its annual California RPS Procurement Plan requirement so long as the IRP complies with the requirements specified in Pub. Util. Code § 399.17(d). PacifiCorp prepares its IRP on a biennial schedule, filing its plan with the Commission in odd numbered years. It files a supplement to this plan in even numbered years. PacifiCorp filed its 2017 IRP with the Commission on April 4, 2017, and its "on-year" supplement to its 2017 IRP on May 4, 2017. Consequently, PacifiCorp did not file a comprehensive supplement this year.

Community Choice Aggregator (CCA) RPS Plans

CCAs must submit annual RPS Plans to the CPUC and meet the same RPS compliance requirements as investor-owned utilities. On or before July 21, 2017, the CPUC received Draft RPS Plans from all CCAs currently registered with the CPUC. As indicated in their RPS Plans, four of the nine CCAs (Apple Valley, Pico Rivera, Redwood Coast, and Silicon Valley) have begun to serve electricity load in late 2017.

CCA Procurement

The 2017 CCA RPS Procurement Plans forecast that all of the operational CCAs are projected to meet or exceed RPS procurement obligations over the long-term planning horizon (ten or more years). Table 12 below shows that the forecasted 2017 RPS positions of all CCAs in operation vary between a position of 26% and 67%. When the new long-term contracting requirement goes into effect in 2021, it is anticipated that drastic fluctuations in RPS positions will be reduced from year to year, as facilities come online and stay contracted for longer periods of time.

Table 12: Annual RPS Position of CCAs (%)

Online Date	CCA	Actuals	Forecasted	
		2016	2017	2018
2010	Marin Clean Energy	55%	67%	54%
2014	Sonoma Clean Power	36%	43%	46%
2015	Lancaster Choice Energy	39%	26%	26%
2016	Peninsula Clean Energy	59%	51%	29%
2016	CleanPowerSF	45%	44%	32%
2017	Apple Valley Choice	No Data	32%	30%
2017	Pico Rivera	No Data	50%	25%
2017	Redwood Coast	No Data	33%	16%
2017	Silicon Valley	No Data	50%	42%

Data Source: RPS Procurement Plans and Compliance Reports (2017)

CCA Renewable Development

In 2016-2017, Marin Clean Energy (MCE), Lancaster Choice Energy (LCE), and Sonoma Clean Power (SCP) executed contracts which allowed 10 new in-state renewable projects to be financed, built, and brought online. The technologies of these new renewable projects include solar, wind, and biogas. All new projects have long-term contracts ranging from 12 to 25 years in length and will be located in California.

As of September 2017, these three CCAs have a large portion of their renewable generation located in California, with an average of 71% of facilities being located in-state. The generation located in California primarily includes wind, solar, biomass, and geothermal, as well as small and large hydroelectric facilities. MCE has the highest amount of in-state RPS generation with roughly 87% of its total coming from California facilities. SCP and LCE procure approximately 70% and 55%, respectively, of their RPS generation from in-state facilities.

The CCAs of MCE, LCE, SCP, and Peninsula Clean Energy have a total of nine new facilities under contract, which are set to become operational in 2018-2021. As Table 13 shows, the nine new facilities will be comprised of wind and solar projects, totaling 768 MW of new capacity.

Table 13: New Renewables Projects with CCA Contracts
Online Date: 2018-2021

Technology Type	# of Projects	# of MW
Solar (Power Purchase Agreement)	6	555
Wind (Power Purchase Agreement)	3	213
TOTAL	**9**	**768**

Data source: CCA RPS Procurement Plans, 2017

Apple Valley Choice, Pico Rivera, and Redwood Coast Energy have only entered into contracts with facilities that are already in commercial operation. Silicon Valley Clean Energy has entered into one utility-scale contract for a solar facility set to come online in early 2018.

RPS Plan Implementation Schedule

The Commission anticipates issuing a decision on the Draft 2017 RPS Procurement Plans by the end of 2017. The decision will either approve the utilities' proposed RPS Plans or order them to make modifications. Once the CPUC approves the RPS Procurement Plans, the IOUs can commence implementation. The Commission will initiate the next cycle of RPS Plans in the first half of 2018.

Summary of Accomplishments

November 2016	▪ BioRAM Contracts Executed / Approved ▪ PG&E contracted a 1.6 MW municipal bioenergy project under the BioMAT program
December 2016	▪ CPUC approves 2016 RPS Procurement Plans ▪ CPUC adopts D.16-12-040 implementing SB 350's new RPS requirements and compliance periods
January 2017	▪ PG&E contracted 1.4 MW of existing small hydro under the ReMAT Program
February 2017	▪ CPUC approves PG&E BioRAM contract for Burney ▪ IOUs begin offering monthly BioMAT contracts for forest biomass projects
March 2017	▪ PG&E contracted a 0.6 MW existing small hydro project under the ReMAT Program
April 2017	▪ CPUC approves PG&E BioRAM contract for Wheelabrator Shasta
May 2017	▪ CPUC issued RPS Plan Assigned Commissioner/Administrative Law Judge Ruling providing guidance for 2017 RPS Procurement Plans and proposal for RAM procurement ▪ PG&E contracted a 3 MW solar PV project under the ReMAT Program
June 2017	▪ CPUC approves SCE RPS contract for 125 MW Maverick Solar project (Resolution E-4851) ▪ CPUC holds Pre-Hearing Conference on Tree Mortality Non-bypassable Charge ▪ PG&E contracted a 0.85 MW Municipal BioMAT project ▪ PG&E contracted a 0.3 MW existing small hydro project under the ReMAT Program
July 2017	▪ CPUC adopts D.17-06-026 implementing SB 350 ▪ IOUs, CCAs, and ESPs submitted their RPS Procurement Plans to the CPUC ▪ SCE contracted a 2 MW Municipal BioMAT project ▪ PG&E contracted a 1 MW existing small hydro project under the ReMAT Program
August 2017	▪ IOUs, CCAs, and ESPs submitted their RPS Compliance Reports to Energy Division ▪ CPUC issued D.17-08-021 implementing AB 1979 with revisions to ReMAT ▪ CPUC issued D.17-08-021 implementing AB 1923 expanding eligibility for BioMAT participants ▪ SDG&E contracted a 3 MW project for Municipal BioMAT
September 2017	▪ Biomass facility took price for PG&E Dairy BioMAT contract for a total of 3 MW
October 2017	▪ CPUC issued a Staff Proposal via Ruling to implement AB 1923's provision to interconnect to existing transmission ▪ Biomass facility took price for PG&E Forest BioMAT contract for a total of 5 MW
November 2017	▪ CPUC anticipates issuing a proposed decision on 2017 RPS Procurement Plans
December 2017	▪ SDG&E Expected to Announce Results of RAM ▪ PG&E expected to launch RAM solicitation ▪ CPUC anticipates a final decision on 2017 RPS Procurement Plans

Public Utilities Code 913.4 directs the CPUC to provide information on RPS planning related to cost limitation, implementation, and transmission development. The CPUC utilizes analytical and policy tools to plan for the most cost-effective renewable energy and then implements evaluation processes to measure RPS success. Building off of 2017 RPS efforts, in the coming year, the CPUC will continue to refine and improve policy tools and quantitative methodologies that promote the State's clean energy goals.

Program Planning & Coordination

The CPUC coordinates with its sister State agencies on an ongoing basis to promote and implement consistent statewide RPS policies that benefit all Californians. The CPUC works with the California Energy Commission, California Air Resources Board, California Independent System Operator, and CAL FIRE on such issues and projects as:

- Integrated Resource Planning
- Statewide RPS Compliance and Enforcement
- The Tree Mortality Task Force and its Bioenergy Working Group
- California Renewable Marine Energy Working Group
- Transmission Planning

Statewide RPS Coordination

State agency coordination is at the core of the RPS program, and the CPUC works to align the parallel planning processes of other agencies to improve the program and achieve the State's greenhouse gas emissions reduction goals.

Compliance and Enforcement

The CPUC will continue to coordinate closely with the CEC to ensure a consistent policy approach for RPS compliance and enforcement. CPUC determinations on RPS compliance will rely on the verification report issued by the CEC. The CPUC will utilize the CEC's compliance verification report to inform its future RPS-related compliance decisions.

Tree Mortality and Bioenergy Issues

The CPUC will continue to participate in regular, ongoing forums that address the State's emergency status due to more than a hundred million dead and dying trees in California since 2010. The CPUC is an active participant in the Governor's Tree Mortality Task Force.[25] In addition, RPS staff participates in monthly meetings of the Bioenergy Working Group. The CPUC also engages in other related forums on this topic, such as the Little Hoover Commission.

The issue of tree mortality intersects with the RPS programs of BioMAT and BioRAM. To ensure that these programs address the State's policy goals, CPUC staff will continue to work with other stakeholders to address such issues as program costs, interconnection barriers, and program evaluation.

Marine Renewable Energy

The CPUC is a member of the California Marine Renewable Energy Working Group, which is led by the Ocean Protection Council. The Council seeks to promote regulatory consistency and to improve scientific data that can find common ground for emerging technologies and planning for siting marine renewables. The CPUC's role is to offer insight into the RPS procurement process and the Commission's procedures. The CPUC anticipates working with the Council in the coming year, as the State considers marine renewable energy as a resource.

[25] See http://www.fire.ca.gov/treetaskforce/ for more information.

Ongoing CPUC Planning Efforts for RPS

CPUC staff coordinate internally to ensure that program policy and planning efforts are consistent and cost-effective in providing benefits to ratepayers.

Integrated Resource Planning (IRP)

SB 350 (De León, 2015) requires the CPUC to adopt an IRP process that aims to move away from siloed planning and procurement toward a framework that optimizes potential resource solutions across all applicable retail sellers in order to achieve GHG emissions reductions at the least cost.

On September 19, 2017, CPUC staff released a Proposed Reference System Plan. This Plan identifies a diverse and balanced portfolio of resources capable of ensuring a reliable electricity supply that provides optimal integration of cost-effective renewable energy. By statute, the portfolio must rely upon zero carbon-emitting resources to the maximum extent reasonable and be designed to achieve statewide greenhouse gas emissions limits. The CPUC anticipates issuing a proposed decision by the end of 2017 that will adopt both an IRP process and a Reference System Plan.

Parameters of the Reference System Plan

Staff has proposed that retail sellers should file an IRP by mid-2018 that fits within the parameters set by the Proposed Reference System Plan and ensures that the retail seller will:

- Contribute towards GHG emissions reduction targets for the electricity sector;
- Procure at least 50 percent eligible renewable energy resources by December 31, 2030;
- Enable each IOU to fulfill its obligation to serve its customers at just and reasonable rates;
- Minimize impacts on ratepayers' bills;
- Ensure system and local reliability;
- Strengthen the diversity, sustainability, and resilience of the bulk transmission and distribution systems, and local communities;
- Enhance distributed systems and demand-side energy management; and
- Minimize localized air pollutants and other GHG emissions, with early priority for disadvantaged communities.

CPUC staff propose to analyze and aggregate the retail sellers' IRPs so that the Commission can issue a Preferred System Plan by the end of 2018.

The Reference and Preferred System Plans could inform the RPS procurement targets. Details of how the IRP process will interact with the RPS proceeding are currently being discussed within both proceedings.

Reforms to RPS Least-Cost Best-Fit Methodology

A key part of integrated resource planning is an accurate comparison of resource costs through a Least-Cost Best-Fit (LCBF) methodology. Currently, the utilities implement their own CPUC-approved LCBF methodologies to evaluate bids. This process informs how IOUs select RPS resources that will provide the most value to ratepayers.

Key Issues for LCBF Reform

In order to increase transparency and improve the usefulness of LCBF, the Commission has indicated that several specific issues related to the utilities' LCBF methodologies would be reformed. The specific issues related to the utilities' LCBF methodologies will be addressed in the LCBF reform activity, including:

- Time-of-delivery factors;
- Portfolio optimization;
- Greenhouse gas emissions;
- Disadvantaged communities; and
- Consistency with the RESOLVE modeling tool.[26]

Consequently, the CPUC has developed a set of proposed objectives and a draft work plan for LCBF reform activity that will continue into 2018.

LCBF Reform Objectives

The objectives of LCBF reform recommended by CPUC staff propose to:

1. Ensure compliance with statutory requirements, particularly SB 2 (1X) (Simitian, 2011) and SB 350 (De León, 2015);
2. Improve market efficiency by increasing transparency and consistency of LCBF;
3. Evaluate methodologies used for bid evaluation across utilities and CPUC proceedings; and
4. Lay a foundation for interaction between RPS program and integrated resource planning (IRP).

The CPUC is currently engaging with stakeholders through workshops and formal comments. A CPUC decision on LCBF reform is expected in 2018 in the RPS docket.

[26] RESOLVE is an optimal investment and operational model designed to inform long-term planning questions with regards to renewables integration in systems with high penetration levels of renewable energy. The model is formulated as a linear optimization problem that can solve for the optimal investments in renewable resources, energy storage technologies, new gas plants, and gas plant retrofits subject to an annual constraint on delivered renewable energy that reflects the constraints of the RPS policy, greenhouse gas emissions and maintaining resource adequacy and reliability. For more information see: http://www.cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/UtilitiesIndustries/Energy/EnergyPrograms/ElectPowerProcurementGeneration/LTPP/2017/RESOLVE_CPUC_IRP_Inputs_Assumptions_2017-05-15.pdf

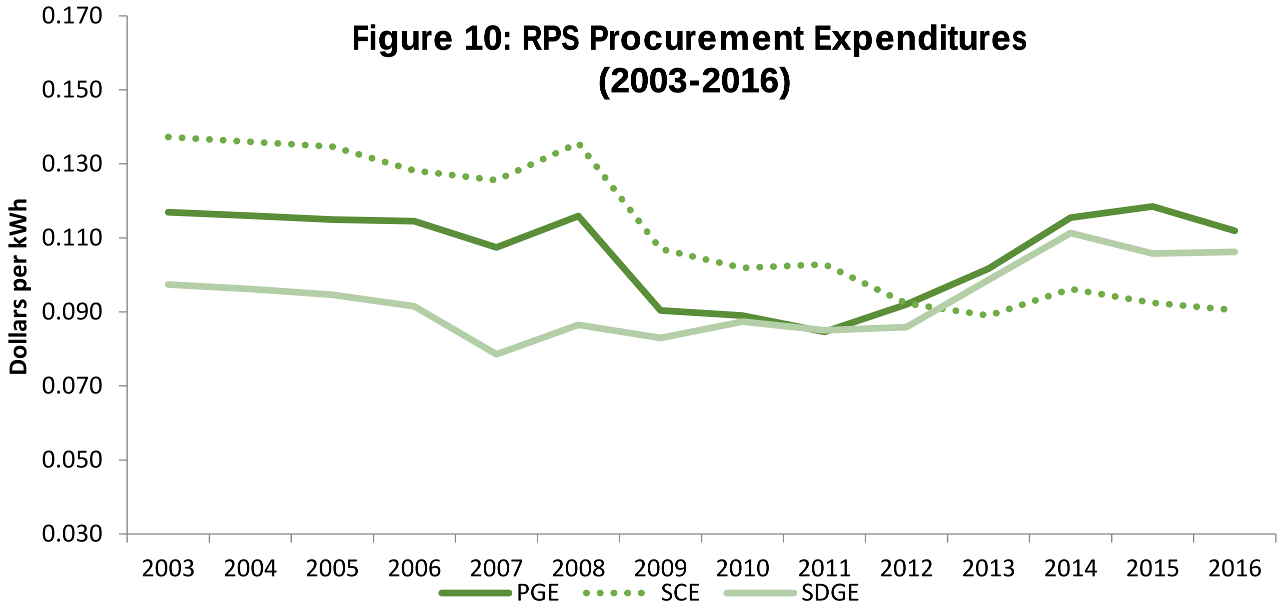
Cost Limitation Projections

To understand the impact that RPS costs will have on ratepayers, the CPUC sets cost-effectiveness policies and collects various price data to understand cost trends. The IOUs use competitive procurement mechanisms and a LCBF evaluation methodology, described above, to ensure procurement of renewable resources that provide the most value in their RPS Procurement Plans. Although the CPUC has not previously established cost limitations for RPS procurement, it is using the IRP as a way to identify the most cost-effective resources to inform future procurement activities.

RPS Procurement Expenditures

Figure 10 illustrates the annual weighted average RPS procurement expenditures for bundled renewable energy in real dollars (prices adjusted for inflation) per kilowatt hour ($/kWh) for each of the large IOUs. The key factor driving the cost differences between the three utilities is the resource mix of RPS resources within an IOU's portfolio and the year the RPS contracts were executed. The RPS contracts that were executed from 2003 to 2008 were more expensive than contracts signed in later years. As the RPS program has expanded, procurement expenditures have expanded in parallel.

In 2018, ratepayers should experience minimal additional rate impacts given that the IOUs do not plan to hold procurement solicitations, and may realize savings from the IOUs' proposed REC sales.



Data Source: IOU RPS Weighted Average RPS Procurement Expenditures, submitted 2016

2017 Renewable Contract Prices

The CPUC tracks the cost of renewables to understand the impact on ratepayers. California's investment in renewables has increased over time and, therefore, the price of solar PV and wind contracts have been decreasing significantly. This section focuses on solar and wind trends given that they are the primary resources used to meet RPS requirements in the State.[27]

As demonstrated in Chapter 2, California's RPS requirements have contributed to increased investment in renewable resources. Relative to other renewable technologies, the utility-scale solar and wind market has expanded rapidly and the prices have decreased significantly in the last decade. The consistent decrease in the average prices of solar PV projects are reflected in the sharp decrease in IOU contract prices observed from 2008 to 2016. Similarly, the decrease in the cost of developing wind projects can be observed through the decline in the average prices of wind contracts from 2007 to 2015.

Solar PV: IOU Contract Prices Decreased 77% from 2010 to 2016

Table 14 shows the percent change in the prices of solar contracts from 2008, 2010, and 2016. The prices of solar PV declined significantly from 2008 to 2016. The prices of utility-scale solar contracts have decreased roughly 77 percent from 2010 to 2016, from an average of $127.55/MWh to an average of $29.17/MWh.

Table 14: Average Contract Prices for Utility-Scale Solar PV Projects (> 20 MW)

Year	Average Price ($/MWh)	% Change
2008	135.90	
2010	127.55	-6%
2016	29.17	-77%

Data Source: RPS Contract Database Submissions, October 2017

[27] See http://www.caiso.com/informed/Pages/CleanGrid/default.aspx for more information on California's renewables breakdown.

Wind: IOU Contract Prices Decreased 47% from 2010 to 2015

Table 15 shows the percent change in the prices of wind contracts from 2007, 2010, and 2015. The data show that the average prices of utility-scale wind contracts have decreased approximately 47 percent in the last decade from an average of $96.72/MWh in 2010 to $50.99/MWh in 2015.[28]

Table 15: Average Contract Prices for Utility-Scale Wind Projects (> 20 MW)

Year	Average Price ($/MWh)	% Change
2007	97.11	
2010	96.72	-0.4%
2015	50.99	-47%

Data Source: RPS Contract Database Submissions, October 2017

Transmission Development Supporting RPS Implementation

The CPUC works with other State agencies and organizations in the planning of transmission, necessary to support the delivery of renewable energy to California homes and businesses. Transmission planning can take several years from the initial Transmission Planning Process with the Energy Commission and the CAISO to the CPUC's role in required environmental review.

The CPUC is responsible for ensuring that transmission-related projects comply with the California Environmental Quality Act (CEQA). CPUC staff perform detailed CEQA analysis to identify and mitigate environmental impacts from large-scale utility projects and to identify alternatives to the projects.

Suncrest Dynamic Reactive Power Support Project

The CPUC is in the process of evaluating NextEra Energy Transmission West's (NEET) application to construct an upgrade to Suncrest Substation. The proposed project is purported to support increased renewable generation in Southern California. CAISO selected NEET West through a competitive solicitation after finding that the *Suncrest Dynamic Reactive Power Support Project* met stringent bid requirements to address forecasted increases in renewable generating capacity in the Imperial Valley, due to the retirement of the San Onofre Nuclear Generating Station (SONGS).

As part of its 2013-2014 transmission planning process, CAISO determined that the proposed project was needed to address voltage stability issues on the grid. Voltage stability refers to the ability of power systems to maintain a steady voltage, which is necessary to ensure that the system provides continuous, reliable power to all users.

[28] This does not reflect any further reductions in wind contract prices in 2016 or 2017 because the IOUs did not execute wind contracts in those years.

The CPUC's Draft Environmental Impact Report was circulated in November 2016. Formal Proceeding testimony for the project was held in July 2017, with project hearings held in August. A draft of the Final Environmental Impact Report is due before the end of 2017, with a final CPUC Suncrest decision on the proposed project expected in 2018.

California's climate policies and robust RPS program are impacting the demand for an educated and qualified "clean tech" workforce. This chapter describes RPS workforce development activities of the large IOUs and SMJUs, consistent with Public Utilities Code 913.4(f). This statute requires the CPUC to report on the efforts of California's electrical corporations related to workforce development, training, and diversity.

Overview of RPS Workforce

Chapter 5 provides details on efforts of the large IOUs and SMJUs related to:

- Current RPS workforce;
- Diversity of current staff;
- Strategies used to recruit a diverse staff and develop RPS and other clean energy staff of the future; and
- Training IOUs provide for their current workforce.

The CPUC gathered information on the above topics directly from each of the IOUs.

This chapter first describes the workforce development of the large IOUs and is followed by information on the SMJUs.

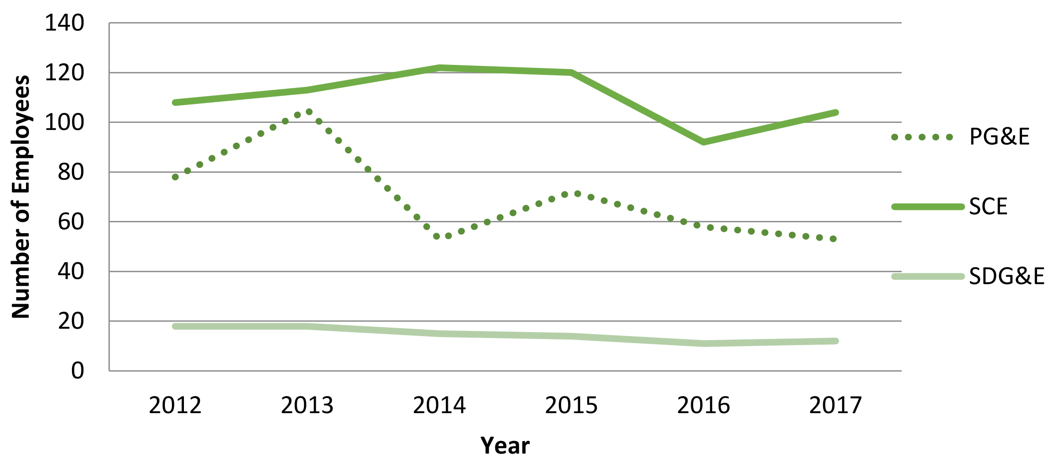
Large IOU Workforce Development

The large IOUs report having a significant focus on offering equal employment opportunities with respect to the recruitment, hiring, and professional development practices associated with the implementation of the RPS program.

Current IOU RPS Workforce

Figure 11 below provides an overview of the number of full-time PG&E, SCE, and SDG&E employees who have worked on RPS-related issues from 2012-2017. This graph illustrates how the IOUs' RPS staffs have changed over the past five years.[29]

Figure 11: Full-time RPS Employees at Large IOUs
2012-2017



Data source: PG&E, SCE, and SDG&E

IOU Current RPS Workforce Diversity

The large IOUs have reported having company-wide diversity goals to build a workforce that reflects the diversity of the State of California. Common diversity efforts across the IOUs include providing equal employment opportunity in all aspects of their employment practices and hiring more women, minority, and disabled veterans for the purposes of implementing the RPS program.[30]

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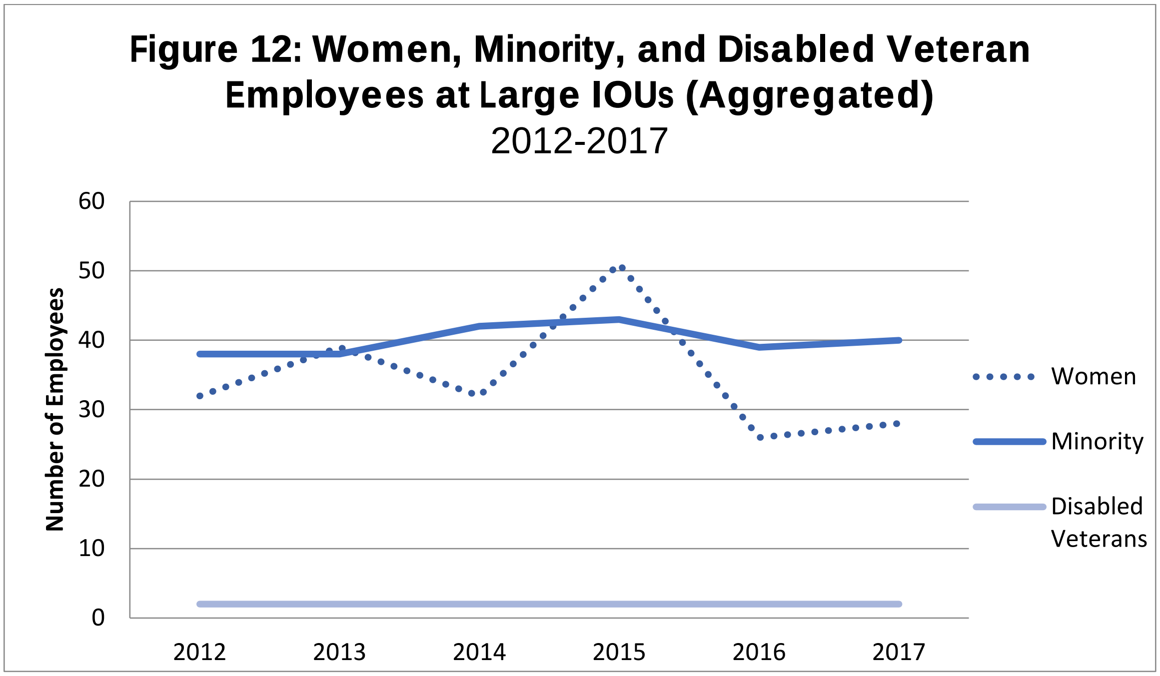
[29] This time series data is current as of August 2017 and includes employment data from January 2012 through July 2017.

[30] PG&E, SCE, and SDG&E do not track if their employees identify as Lesbian, Gay, Bisexual, and Transgender (LGBT). While the three large IOUs do not collect data on LGBT employees, they do have supplier diversity requirements as set out in General Order 156 and are required to submit an annual Supplier Diversity Report.



In 2017, all three large IOUs reported working with organizations focused on professional development for women, minority, and disabled veterans. They were also compliant with General Order 156[31] requirements on supplier diversity. Figure 12 illustrates aggregated data on the number of Women, Minorities, and Disabled Veterans who are full time employees at the three large IOUs who work on the RPS program.

Pacific Gas and Electric Company (PG&E):

Table 16 shows the number of PG&E's RPS employees that are women, minority, and disabled veterans compared with total RPS staff. In 2016, 74% of PG&E's RPS staff was comprised of women, minorities, or disabled veterans.

Table 16: Number of Women, Minority, and Disabled Veteran RPS Employees from 2012-2017 (PG&E)

PG&E	RPS Employees (Full Time)					
	2012	2013	2014	2015	2016	2017
Women	32	39	20	36	13	14
Minority	38	37	35	32	28	29
Disabled Veterans	2	2	2	2	2	2
Total RPS Staff	78	105	53	72	58	53

[31] General Order 156 refers to the rules governing the development of programs to increase participation of women, minority, disabled veterans and LGBT business enterprises in procurement contracts from IOUs as required by Public Utilities Code Sections 8281-8286.

Southern California Edison (SCE):

SCE reported that 73% of the company's RPS employees are either women or minorities. Table 17 below shows the number of SCE's RPS employees that are women, minority, or disabled veterans. In 2016, 75% of SCE's total RPS staff was comprised of women, minorities, or disabled veterans.

Table 17: Number of Women, Minority, and Disabled Veteran RPS Employees from 2012-2017 (SCE)

SCE	RPS Employees (Full Time)					
	2012	2013	2014	2015	2016	2017
WMDV[32]	71	73	81	84	69	76
Women	No Data				29	31
Minority	No Data				40	45
Total RPS Staff	108	113	122	120	92	104

San Diego Gas & Electric Company (SDG&E):

Table 18 illustrates the number of SDG&E's RPS employees that are women, minority, or disabled veterans.

Table 18: Number of Women, Minority, and Disabled Veteran RPS Employees from 2012-2017 (SDG&E)

SDG&E	RPS Employees (Full Time)					
	2012	2013	2014	2015	2016	2017
Women	No Data	No Data	12	15	13	14
Minority	No Data	No Data	7	11	11	11
Disabled Veterans	No Data					
Total RPS Staff [33]	18	18	15	14	11	12

[32] Women Minority and Disabled Veterans (WMDV) were tracked as one data point by SCE until 2016. Disabled veterans are not being tracked as separate data points.
[33] The value displayed for the total number of RPS staff is based on the percentage of time employees actually spend working on RPS issues (a range of 0 to 100%), while the WMDV information is calculated based on whether or not the employee is a woman, minority, or disabled veteran.

SDG&E reported having one RPS contract in 2017 with a minority owned business enterprise. SDG&E uses a qualitative component when evaluating contracts to determine which projects are the best fits for SDG&E's portfolio. This qualitative component includes the Diverse Business Enterprise (DBE) status of a project and SDG&E has reported strongly encouraging DBEs, including women-owned, minority-owned, disabled veteran owned or LGBT owned business enterprises to participate in its renewable power related Request for Offer solicitations.

Recruiting Strategies

Recruiting efforts at each of the IOUs tend to utilize both broad outreach, as well as strategies targeted to a diverse community. In addition, the utilities also offer programs that can act as training and recruitment of future employees, including long-term efforts within California's school systems.

PG&E

General Outreach:

As part of its broader recruiting efforts, PG&E frequently utilizes online job boards and reaches out to prospective candidates through websites such as LinkedIn, Getting Hired, and Direct Employers.

Diverse Employee Recruitment:

PG&E works with groups such as the Society of Women Engineers, National Society of Black engineers, Society of Hispanic Professional Engineers, and specific university programs to encourage a diverse candidate pool. Open positions at PG&E are frequently posted on electronic job boards targeted to diverse recruitment, such as GIJobs.com, Out and Equal Workplace Advocates, and Hero 2 Hired. However, PG&E has not reported a formal company policy outlining the strategies for increasing the amount of women, minority, disabled veterans, and LGBT employees working on the RPS program.

University Outreach:

PG&E has a "University Programs" team primarily focused on recruitment activities on California college campuses such as UC San Diego, UC Davis, UC Merced, Cal Poly San Luis Obispo, Sacramento State, and Chico State. The University Programs team targets recent college graduates who have studied engineering, finance, business, information technology, and environmental science.

Special Programs:

PG&E administers a separate recruitment and training program called PowerPathway that consists of a partnership with community colleges throughout PG&E's service territory. The PowerPathway program has two separate arms – the Affinity Program and PG&E's Signature Program.

- **Affinity Program:** PG&E provides input on certificate and degree curriculums, introduces college staff to PG&E subject matter experts, and arranges for PG&E sponsored guest speakers to give in-class presentations.
- **Signature Program:** Entails assisting community college professors through providing input on curriculum and technical training coursework, as well as providing up to three years of career coaching for program graduates.

From 2012 through June 2017, the PowerPathway Signature Program has mentored 575 program graduates. Of those graduates, 46% of the graduates were placed into full time positions at PG&E and 34% of graduates went on to pursue industry-related careers. PG&E is developing a new PowerPathway Skilled Trades internship program that aims to recruit, train, and produce new qualified professionals for the future utility workforce.

K-12 Outreach & Education:

In addition to working with university and community colleges, PG&E has a K-12 program to expose a younger generation to careers in sustainability.

SCE

General Outreach:

As a part of their targeted recruitment efforts for clean energy professionals, SCE recruits through online job sites such as LinkedIn, Direct Employers, and Glassdoor. With regards to college recruitment, SCE has reported robust recruitment efforts and outreach strategies targeted at students pursuing undergraduate degrees in engineering, accounting, finance, information technology and cyber security.

SCE leverages social media, including hosting a YouTube channel where they post videos for the public on a variety of topics including the electricity grid of the 21st century, updates on renewable energy project developments, and grid reliability.

University Outreach:

SCE actively recruits and employs interns from four California State Universities, five University of California schools, and the University of Southern California. SCE has also created a rotational development program for MBA students and partners with the East Los Angeles Skills Center to help prepare interested students for energy careers. In 2016, SCE employed 59 interns from California Polytechnic University Pomona, where 15 of those interns went on to become full time employees after graduation.

SDG&E

General Outreach:

SDG&E's recruitment and workforce development efforts center on targeting students primarily from universities in California and Nevada who are studying accounting, finance, engineering, and information technology. SDG&E reports that it uses LinkedIn to advertise job vacancies and participation on group pages to recruit qualified candidates for open positions.

Diverse Employee Recruitment:

SDG&E places a large emphasis on college recruiting and recruitment from diverse professional development organizations including the Society of Women Engineers, National Society of Black Engineers, and the Society of Mexican-American Engineers. As a part of its workforce development and recruitment efforts, SDG&E partners with universities that have a high minority student population such as Howard University, San Diego State University, California Polytechnic University Pomona, and the University of Nevada/Las Vegas. On the recruitment marketing and social media front, SDG&E leverages social media websites focused on professionals in energy with diverse backgrounds such as Women Working in Utilities, American Association of Blacks in Energy, and Hispanics in Energy.

University Outreach:

In 2017, SDG&E began a new paid internship program with UC San Diego and Southwestern College designed to prepare students for clean energy careers with career pathways such as Solar Design and Energy Storage.

K-12 Outreach & Education:

SDG&E offers a workforce education and training program for K-12 students interested in green energy, science, technology, engineering and mathematics (STEM) careers. From September 2016 through August 2017, approximately 10,000 K-12 students have completed the program.

SMJU Workforce Development

Given the smaller size of their RPS staffs, the three SMJUs (Bear Valley Electric Service, Liberty Utilities, PacifiCorp) have significantly fewer resources dedicated to RPS workforce development. For example, on average, the SMJUs employ between one to three full-time RPS employees.

Bear Valley Electric Service (BVES)

BVES has not engaged in college recruitment efforts or offered scholarships to students within their service territory. Bear Valley Electric Service does not conduct internal training courses but RPS employees are encouraged to attend training and workshops elsewhere in the State.

Liberty Utilities

Out of the three SMJUs, Liberty Utilities is the only utility to engage in recruitment efforts with local high schools and universities. During the summer of 2017, Liberty attended a career fair at the University of Nevada, Reno and recruited two student engineers for positions after graduation. Liberty also posts job opportunities on career fair web portals at local universities. Liberty Utilities offers scholarships to graduating high school students within the service territory and offers one community college scholarship. With regards to RPS-focused training, Liberty Utilities conducted one training course on the RPS program and greenhouse gas emission reduction strategies for five employees from 2016-2017.

Liberty stated that it is an equal opportunity employer and is committed to ensuring an equal and diverse workforce to implement the RPS program. In 2017, Liberty reported hiring two additional employees to implement the RPS program, both of which are minority recruits.

PacifiCorp

PacifiCorp has not engaged in college recruitment efforts or offered scholarships to students within their service territory. PacifiCorp employs one person to work on RPS related issues throughout all states served by PacifiCorp and does not conduct internal training for that employee.

Given that PacifiCorp employs one employee who oversees the RPS program in all states served by PacifiCorp, no specific diversity statistics were provided.

Public Utilities Code 913.4 requires the CPUC to identify barriers to achieving the RPS, and to propose recommendations to address those barriers. Chapter 6 examines at a high level RPS program challenges and describes actions the CPUC is taking to address these issues, as well as offers recommendations for future actions. The challenges addressed in this chapter include the areas of RPS procurement, ratepayer impacts, and the individual RPS programs of ReMAT and BioMAT.

Challenge 1: Uncertainty in IOU Load Forecasts

Issue: It is difficult to forecast future IOU load, given increasing departing load to CCAs. Current CPUC estimates suggest that over 1 million IOU ratepayers will be served by CCAs for their generation needs by the end of 2017. Forecasting scenarios suggest that some IOUs could lose 60 to 90 percent of their current demand in the next 8 to 10 years. This number is expected to grow quickly. As additional CCAs are formed, the CPUC will oversee a significantly smaller percentage of renewable procurement in the State, as the CPUC has limited jurisdiction over the procurement activities of CCA or ESP providers. If the IOUs lose such large portions of their customer demand, the result will be that the CPUC will not have the authority to monitor most renewable energy procurement activities in as much detail, as it has traditionally done for RPS. This may cause challenges in the IRP process due to the CPUC's lack of market visibility with regards to CCA and ESP procurement activities.

Recommendation: The CPUC should continue to closely monitor procurement activities of all the retail sellers to the extent possible. The CPUC forecast models for the IRP process will be used to develop optimum portfolios to meet California's GHG goals. This process is continuing and will ultimately lead to procurement authorizations for the IOUs and IRP plans for IOUs, CCAs, and ESPs. The IRP proceeding and the RPS planning process should work together to achieve California's GHG and renewable goals.

Challenge 2: Increased Amounts of Renewables have Resulted in Increased Incidents of Curtailment

Issue: Curtailment of renewable generation has increased in recent years as more solar has been added to the grid. The initial finding of the CPUC's IRP modeling is that curtailment is a cost-effective strategy for integrating more renewable capacity, rather than investing in other integration options such as transmission upgrades or energy storage. While curtailment does not appear to be a barrier to achieving current RPS requirements, there is a need to fully understand the causes of curtailment and ways to reduce its frequency.

In most other parts of the country, wholesale markets continue to report negligible levels of curtailment. The addition of significant wind capacity in Texas and the Midwest has caused increased congestion and curtailment in those regions. To address the issue, the Electric Reliability Council of Texas (ERCOT) has expanded its transmission grid and adopted market rules to facilitate economic curtailment, and the Midcontinent Independent System Operator (MISO) has promoted economic curtailment.

Recommendation: The State should rely upon the CPUC's IRP process to balance the increased procurement of renewables with the risk of curtailment. Initial modeling results in the IRP proceeding indicate that buying additional solar and economically curtailing renewable resources in the limited hours of the year when they are not needed is a cost-effective strategy to integrating more renewables into the grid and displacing natural gas generation. Further, recent data suggests that curtailment is not a significant risk. While the CAISO has seen the number of pricing intervals with negative prices increase over the last several years, the clearing prices are becoming less negative. In other words, the frequency of negative pricing events has increased, but the magnitude of each curtailment event has lessened. This indicates that the CAISO has generally been able to balance supply and demand using economic signals.

Challenge 3: Stranded Costs Resulting from Increased Departing Load Could Fall to IOU Customers

Issue: As described above, there is significant departing load from the increasing formation of CCAs. As a result, there is a significantly smaller ratebase of customers over which to allocate energy costs. Policies established now, but implemented after the load has departed could result in stranded costs and rate shock for remaining bundled IOU customers. Parties are challenging the current mechanisms in place to prevent IOU ratepayers from paying for stranded assets. This is illustrated in current proceedings such as BioRAM to address Tree Mortality, and in the more global proceeding for the Power Charge Indifference Adjustment (PCIA).

Recommendation: The CPUC has open proceedings to develop workable solutions to these challenges. Any new procurement strategies should consider the impact of policies on ratepayers in the context of weighing all costs and benefits to ratepayers. In addition, the IRP process proposes to take a system wide view at the combined planning and procurement of IOUs, CCAs, and ESP providers, which should provide a roadmap to not only reach GHG goals, but also to achieve cost-effective procurement recommendations.

Challenge 4: The ReMAT Program Has Experienced Significant Project Terminations and Uneven Market Interest

Issue: As explained in the report, the IOUs do not need to execute any additional ReMAT contracts to achieve the RPS. It is worth noting that the ReMAT program has resulted in large percentages of terminated capacity since the program commenced in 2013. The proportion of capacity terminated by the IOUs has been:

- PG&E = 48%
- SCE = 30%
- SDG&E = 56%

These termination percentages are higher than the termination levels seen for large-scale (>20 MW) projects. It is not clear why there are such varying results and whether such terminations are related to developer experience, project viability, interconnection, permitting challenges, and/or lack of financing for small projects.

Additionally, there has been uneven interest among the three product categories:

- As-Available Peaking;
- As-Available Non-Peaking; and
- Baseload.

For the As-Available Peaking category, 12.1 MWs are currently under contract, whereas there is only 1 MW for the Baseload category. As a result of the uneven interest, the allocated As-Available Peaking MWs may be fully contracted while significant capacity remains in the other categories.

A challenge of the ReMAT Baseload category, or reason for lack of market interest, may be the overlap with the BioMAT program. Some of the projects that could be eligible for the ReMAT Baseload category could also be eligible for BioMAT, which currently has a higher offered price.

While the program initially saw regular adjustments in price and execution of contracts, activity has slowed down. For example, PG&E's offered price for As-Available Peaking category has not changed over the last 24 months. SDG&E has suspended its ReMAT program. SCE has recently reached the procurement level in As Available Peaking where, it could soon suspend its entire ReMAT program by the end of 2019.

Recommendation: The Commission plans to review these program challenges, as well as recent market observations, within the scope of the RPS proceeding in order to obtain stakeholder input. In reviewing the issues and stakeholder input, the CPUC should consider possible program modifications that could address these concerns.

Challenge 5: The BioMAT Program Appears to Have Limited Market Interest

Issue: As previously noted, the IOUs do not need to execute any additional BioMAT contracts to achieve the RPS. The original objective of the BioMAT program was to create a simple procurement mechanism for new bioenergy developer entrants of up to 3 MWs. BioMAT is comprised of three categories of bioenergy (Biogas, Dairy/Other Agriculture, and Forest Biomass) for which SB 1122 (2012, Rubio) allocated a total of 250 MWs. In the three categories, there has been little activity:

- **Biogas:** There was market activity at the initial price of $127/MWh, but the category price has since remained stagnant, with a total of 7.4 MWs of executed contracts.
- **Dairy and Other Agriculture:** There was no initial market activity, but the price of $187.72/MWh was taken in the period from August 1, 2017 program period, for a total of 3 MWs.
- **Forest:** There was no initial market activity, but the price of $199.72/MWh was taken in the period from October 1, 2017 period for a total of 5 MWs.

Only 15.4 MW have been subscribed out of the total 250 MW allocated since the program's initial offering in February 2016. While each category has its respective barriers, key challenges appear to be related to the high costs associated with equipment and interconnection.

Recommendation: In its 2014 decision implementing the BioMAT program, the Commission established ratepayer protections to investigate the BioMAT program if the program price were to reach $197/MWh for more than two program periods. The Forest category reached this threshold on November 1, 2017. The Director of Energy Division now also has the discretion to suspend the awarding of BioMAT contracts. Accordingly, the CPUC should seek stakeholder input to identify potential ways to simplify and improve the program, address barriers to increased participation, and evaluate potential program cost limitations.

APPENDIX A

Glossary of Acronyms and Terms

BioMAT: The Bioenergy Market Adjusting Tariff is a feed-in tariff program for bioenergy renewable generators less than 3 MW in size.

BioRAM: The Bioenergy Renewable Auction Mechanism (BioRAM) program implements the Governor's October 2015 Emergency Order on Tree Mortality, as well as SB 859, and mandates utilities to procure bioenergy from forest fuel from High Hazard Zones (HHZ) to mitigate the threat of wildfires.

CBA – California Balancing Authority: A balancing authority is charged with maintaining the safe and reliable transportation of electricity on the power grid and ensures transparent access to the transmission network and market transactions.

CCA - Community Choice Aggregator: CCAs are local government agencies that purchase and may develop power on behalf of residents, businesses, and municipal facilities within a local or sub-regional area. As of November 1, 2017, there are 9 operational CCAs in California.

Electrical Corporation: An electrical corporation includes every corporation or person owning, controlling, operating, or managing any electric plant for compensation within California, except where electricity is generated on or distributed by the producer through private property solely for its own use (not for transmission to others).

ESP - Electric Service Provider: An ESP is an entity that offers electrical service to customers within the service territory of an electrical corporation and includes the unregulated affiliates and subsidiaries of an electrical corporation.

GTSR - Green Tariff Shared Renewables: The GTSR Program is intended to expand access to all eligible renewable energy resources to ratepayers who are unable to access the benefits of onsite generation and create a mechanism where customers can meet their electricity needs with renewables. The GTSR program is designed to allow PG&E, SCE, and SDG&E customers to receive 50% - 100% of their electricity demand from solar generation.

IRP - Integrated Resource Plan: A planning mechanism to consider all of the CPUC's electric procurement policies and programs to ensure California has a safe, reliable, and cost-effective electricity supply. It will implement an integrated resource planning process that will ensure that retail sellers meet targets that allow the electricity sector to contribute to California's economy-wide greenhouse gas emissions reductions goals.

IOU - Investor-Owned Utility: IOUs are privately owned electricity and natural gas providers and are regulated by the California Public Utilities Commission (CPUC). Pacific Gas and Electric, San Diego Gas and Electric, and Southern California Edison comprise approximately three quarters of the retail electricity supply in California.[34]

LCBF - Least-Cost Best-Fit: A process that provides criteria for the rank ordering and selection of least-cost and best-fit eligible renewable energy resources to comply with California's Renewables Portfolio Standard program obligations on a total cost and best fit basis.[35]

LSE - Load Serving Entity: All entities that serve electricity to customers including IOUs, CCAs, and ESPs.

PPA – Power Purchase Agreement: The contractual agreement under which the financial and technical aspects of renewable energy generation projects are agreed upon between power sellers and retail sellers.

RAM - Renewable Auction Mechanism: The RAM program is a procurement program the IOUs may use to procure RPS generation and to satisfy authorized procurement needs or legislative mandates. RAM streamlines the procurement process for developers, utilities, and regulators by 1) allowing project bidders to set their own price, 2) providing a simple standard contract for each utility, and 3) allowing all contracts to be submitted to the CPUC through an expedited regulatory review process.

REC - Renewable Energy Credit: RECs play an important role in driving the deployment of renewable energy in California and achieving the goals of Renewables Portfolio Standard (RPS). A REC confers to its holder a claim on the renewable attributes of one unit of energy (MWh) generated from a renewable resource. A REC consists of the renewable and environmental attributes associated with the production of electricity from a renewable source. RECs are "created" by a renewable generator simultaneous to the production of electricity and can subsequently be sold separately from the underlying energy.

ReMAT – Renewable Market Adjusting Tariff: ReMAT is a feed-in tariff program for small renewable generators up to 3 MW in size.

RPS - Renewables Portfolio Standard: Established in 2002 under Senate Bill 1078, accelerated in 2006 under Senate Bill 107, expanded in 2011 under Senate Bill 2, and enhanced further in 2015 with Senate Bill 350 California's RPS is one of the most ambitious renewable energy standards in the country. The RPS program requires investor-owned utilities (IOUs), electric service providers, and community choice aggregators to increase procurement from eligible energy resources to 50% of total procurement by 2030.

Retail Sellers: All entities that sell electricity to customers, including IOUs, CCAs and ESPs. A Publicly Owned Utility does not meet the definition of a retail seller and is regulated by the CEC.

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[34] For information on the differences between Publicly-Owned Utilities and Investor-Owned Utilities, please visit the California Energy Commission's website: http://www.energy.ca.gov/pou_reporting/background/difference_pou_iou.html

[35] For more information on the LCBF methodology see Public Utilities Code 399.13(A).

APPENDIX B

Public Utilities Code Section 913.4

In order to evaluate the progress of the state's electrical corporations in complying with the California Renewables Portfolio Standard Program (Article 16 (commencing with Section 399.11) of Chapter 2.3), the commission shall report to the Legislature no later than November 1 of each year on all of the following:

(a) The progress and status of procurement activities by each retail seller pursuant to the California Renewables Portfolio Standard Program.

(b) For each electrical corporation, an implementation schedule to achieve the renewables portfolio standard procurement requirements, including all substantive actions that have been taken or will be taken to achieve the program procurement requirements.

(c) The projected ability of each electrical corporation to meet the renewables portfolio standard procurement requirements under the cost limitations in subdivisions (c) and (d) of Section 399.15 and any recommendations for revisions of those cost limitations.

(d) Any renewable energy procurement plan approved by the commission pursuant to Section 399.13, schedule, and status report for all substantive procurement, transmission development, and other activities that the commission has approved to be undertaken by an electrical corporation to achieve the procurement requirements of the renewables portfolio standard.

(e) Any barriers to, and policy recommendations for, achieving the renewables portfolio standard pursuant to the California Renewables Portfolio Standard Program.

(f) The efforts each electrical corporation is taking to recruit and train employees to ensure an adequately trained and available workforce, including the number of new employees hired by the electrical corporation for purposes of implementing the requirements of Article 16 (commencing with Section 399.11) of Chapter 2.3, the goals adopted by the electrical corporation for increasing women, minority, and disabled veterans trained or hired for purposes of implementing the requirements of Article 16 (commencing with Section 399.11) of Chapter 2.3, and, to the extent information is available, the number of new employees hired and the number of women, minority, and disabled veterans trained or hired by persons or corporations owning or operating eligible renewable energy resources under contract with an electrical corporation. This subdivision does not provide the commission with authority to engage in, regulate, or expand its authority to include, workforce recruitment or training.

EXHIBIT 2

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Wind turbine noise and its mitigation techniques: A review

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Abstract

This paper discusses various noise generation mechanisms in wind turbines and potential noise reduction techniques. Special emphasis has been laid on reviewing aerodynamic noise sources and recent advances in mitigation of aerodynamic noise. Several studies on the effect of wind turbine noise on human health have linked wind turbine noise with annoyance and sleep disturbance. Thus, there is a need to reduce these noise emissions which can be achieved by targeting the specific noise sources. Techniques for mitigation of trailing edge noise, tip noise and leading-edge inflow noise have been discussed along with recent developments.

Keywords: Wind turbine noise; Trailing edge noise; Tip noise; Noise reduction; Aeroacoustics; Serrations.

1. Introduction

Withthe increasing global energy demand, wind turbines offer an effective way to harness the energy contained in the wind. To satiate an ever-increasing energy demand around the world, more wind farms are being established and it is becoming difficult to keep these wind farms very far from human population. As these turbines are placed in the vicinity of human habitats, several issues like noise, structural vibration and visual impact have been reported by the

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local communities. Among these, wind turbine noise is one of the major hindrances in the development of wind power industry [1]. Due to noise complaints by residents where these wind turbines are installed, several researchers have conducted studies to find the link between wind turbine noise and its potential implications on the mental and physical health of nearby residents.

An expert panel on wind turbine noise and human health [2] found sufficient evidence to establish a causal relationship between wind turbine noise and annoyance. The panel also found limited evidence for a causal relationship between wind turbine noise and sleep disturbance. Studies by Pedersen and Waye [3] on perception and annoyance due to wind turbine noise found that the proportion of people annoyed by wind turbine noise was larger than those annoyed by community noise sources at same A-weighted Sound Pressure Level (SPL) and the proportion increased rapidly with increasing SPL (see Fig. 1). The issue of annoyance is found to be more dominant in rural landscape than urban surroundings, capable of inducing sleep disturbance and a hindrance to psycho-physiological restoration [4].

These studies reveal that wind turbine noise causes annoyance and even sleep disturbance in some cases. Thus, there is a need to further address the issue of wind turbines noise due to its above discussed adverse effects on nearby communities. The aim of this paper is to review wind turbine noise mechanisms which are dominant in modern wind turbines and discuss some promising noise reduction techniques.

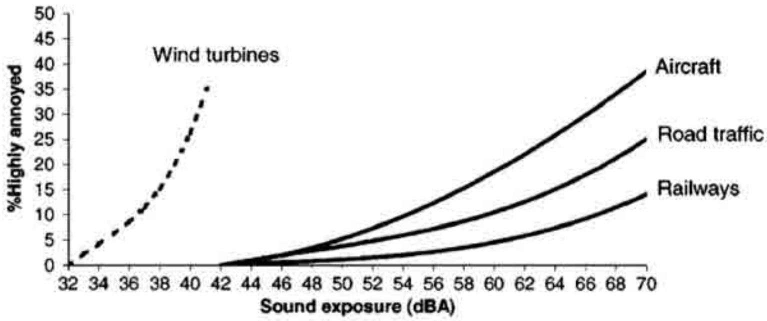

Fig. 1. A comparison between dose-response relationship of perception of wind turbine noise and transportation noise [3]

2. Global wind energy scenario

Wind turbines have become an integral part of the global energy landscape. It is noteworthy that the share of wind energy is 4.4% in total world electricity generation [5]. Wind energy has been on a steady rise for the past few years, as shown in global installed wind capacity presented in Fig. 2. In 2017 alone, global wind power generating capacity grew by 11% reaching over 539 GW [6].

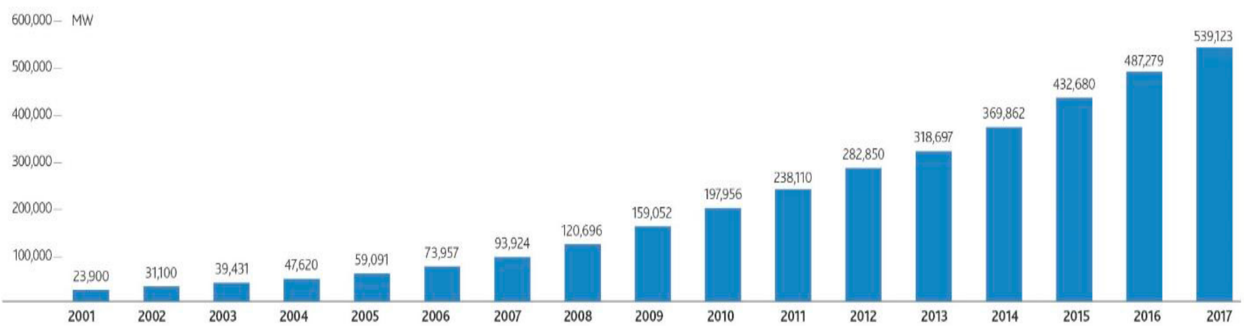

Fig. 2. Global cumulative installed wind capacity (2001-2017) [6]

According to the Global Wind Report (2018) by Global Wind Energy Council (GWEC), China, US, Germany and India are leading the global wind energy production followed by Spain, UK, France, Canada, Brazil and Italy which together account for 85% share of global wind energy capacity. These figures reflect an increasing reliance on wind energy around the world and the need to develop more efficient wind turbines with minimized noise for larger acceptance by communities.

3. Wind turbine noise

Noise generated from wind turbines are mainly of two types- mechanical and aerodynamic. Mechanical noise is generated from various machinery components in the wind turbine and is tonal in character. Aerodynamic noise is generated due to flow of air above the blades which interacts in different ways with the blade surface, leading to different aerodynamic noise sources. These mechanisms are discussed in detail in the following sub-section.

3.1. Mechanical Noise Sources

Mechanical noise in wind turbine is generated by various moving components present in the nacelle like gearbox, generator, cooling fans and other auxiliary devices. Mechanical noise is predominantly tonal in character, meaning that the noise generated from mechanical sources peaks around certain frequencies and is harsher to human ears than broadband noise. Mechanical noise can however be reduced to a large extent by properly shielding the nacelle, using sound absorbing materials and vibration suppression [7]. This reduction has resulted in aerodynamic noise becoming a dominant noise source in wind turbines which is the center of focus in this paper.

3.2. Aerodynamic Noise Sources

Aerodynamic noise is flow induced noise caused by interaction of flow structures with the blade wall. Aerodynamic noise from wind turbines can be classified as *inflow turbulence noise* and *airfoil self-noise*. Relative contribution of individual sources to total noise are shown in Fig. 3. These noise sources and their mechanisms are discussed in the following sub-sections.

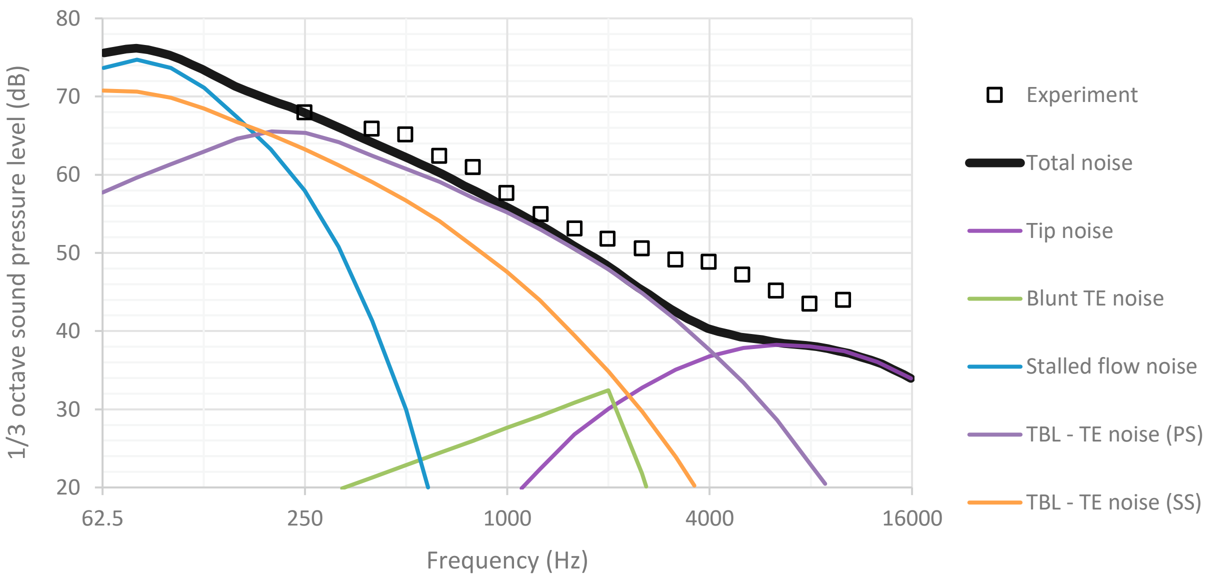

Fig. 3. Contribution of individual sources to noise from a wind turbine blade (reference tip) [7]

3.2.1 Inflow turbulence noise mechanism

Inflow turbulence (IT) noise is caused due to interaction of blade surface, especially the leading edge, with the oncoming atmospheric turbulence. This interaction of turbulent eddies with blade produces broadband noise which lies in the low frequency spectrum (up to 1000Hz) and is highly dependent on atmospheric turbulence intensity and turbulence length scale [7] (Fig. 4.a). Contribution of IT noise to total wind turbine noise has still not been completely investigated, especially due to its dependence on atmospheric stability and structure of turbulence. Recent experimental investigation by Buck et al. [8] carried out by measuring turbulence induced blade vibrations and comparison of directivity patterns show potential for characterization of IT noise for full scale wind turbines. Such experimental characterization can be instrumental in investigating the complete mechanism of this noise source.

3.2.2 Airfoil self-noise mechanisms

Turbulent boundary layer - trailing edge noise (TBL – TE)

Turbulent boundary layer - trailing edge noise, also known as trailing edge noise, is a dominating noise source in wind turbines which is of broadband nature with peak frequency lying between 500-1500Hz.TBL-TE noise occurs due to interaction of turbulent boundary layer with the sharp trailing edge of the airfoil (Fig. 4.c). At low Mach numbers, turbulent eddies are inefficient noise sources in free space or along an infinite plate, but on interaction with a sharp edge these turbulent eddies act as efficient noise sources and are strongly radiated into the atmosphere [7]. According to acoustic field measurements of Oerlemans *et al.* [9] contribution of trailing edge noise is most significant near tip region where flow velocity is high. The source strength shifts towards tip at higher frequencies.

Tip noise

Tip vortex is formed due to a cross flow generated by the pressure difference between pressure side and suction side. This tip vortex on interaction with the tip side and trailing edge leads to generation of tip noise, following the same noise mechanism as that of trailing edge noise [7] (Fig. 4.b). Itis of broadband character, typically lying in the high frequency region and is the dominant source in this range. Since human ears are most perceptible in the frequency range of 1-4 kH, tip noise becomes a prominent contributor to annoyance caused due to turbine noise.

Blunt trailing edge noise

A blunt trailing edge causes Von Karman type vortices resulting in tonal noise emission and can be seen as a sharp peak in a typical wind turbine noise spectrum (Fig. 4.d). This noise source is dependent on the shape of trailing edge, Reynolds number and the ratio δ^*/ t^* (where δ^* is the boundary layer displacement thickness and t^* is the trailing edge thickness) [7]. Normally blunt trailing edge noise can be eliminated through a sharp trailing edge.

Separated / stalled flow noise

Beyond a particular angle of attack, the blade gets stalled leading to large scale flow separation. The stalled flow is significantly unsteady and causes broadband noise emission (Fig. 4.e). Mild separation causes sound radiation from trailing edge, whereas deep stall causes noise radiation from the whole chord. It can be mitigated by avoiding stall conditions at the blade.

Laminar boundary layer noise

If the Reynolds number is less than about 10^6, the flow on both sides of the air foil may remain laminar up to the trailing edge (Fig. 4.f). In this case, boundary layer instabilities are likely to occur which can couple with trailing edge noise and resonate in a feedback loop. Such a condition will result in high levels of tonal noise from the turbine blade known as laminar boundary layer vortex shedding noise. It is found significant for small wind turbines where $Re < 10^6$. However, it can be avoided by tripping the boundary layer relatively far upstream of the trailing edge [7].

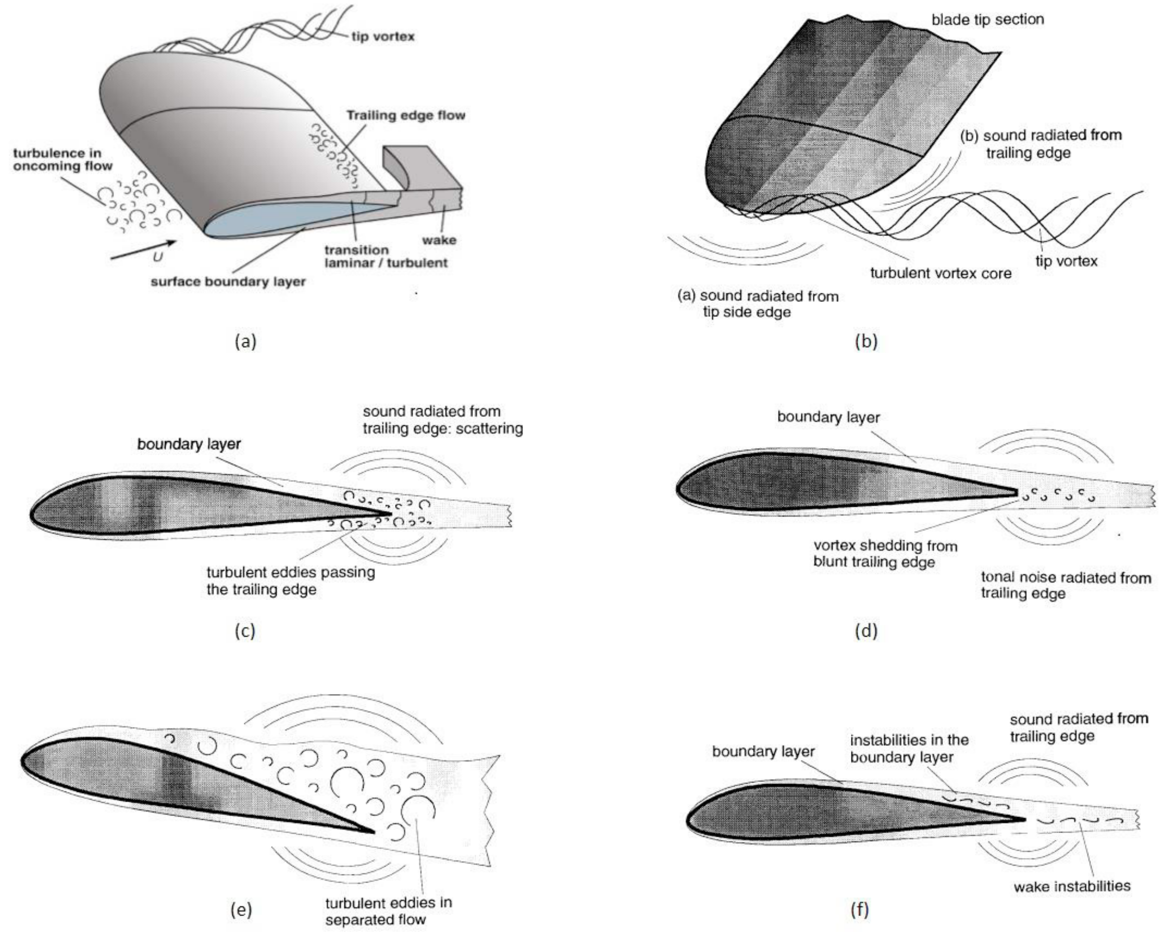

Fig. 4. (a). Flow over the outer section of a wind turbine blade; (b - f) Airfoil self-noise mechanisms [7]

4. Noise reduction techniques

Various experimental and numerical techniques have been developed for noise mitigation by taking advantage of our understanding of the noise mechanisms which provide an insight into the aero-acoustic characteristics of wind turbines. Some promising aerodynamic noise mitigation techniques targeting dominant noise sources have been discussed in this section.

4.1. Reduction of inflow turbulence noise

Dependence of inflow turbulence noise on atmospheric turbulence doesn’t allow for much flexibility to mitigate noise from this source. However, changes in leading edge shape are found to significantly affect noise generation [10]. Based on this characteristic, many different leading-edge profiles have been proposed to mitigate IT noise. Bio-mimetic exploration for noise reduction by leading edge modification has been a topic of interest for many researchers. Experimental study of Hansen *et al.* [11] based on the concept of tubercles found in Humpback whale flipper used sinusoidal leading edge for reduction of tonal noise components. Tubercles with large amplitude and small wavelength were found to be effective in reducing tonal noise with a marginal penalty for lift. The mechanism is postulated to be affected by steam-wise vortices generated from troughs of tubercles which enhance momentum exchange in the boundary layer thereby altering its stability characteristics and frequency of velocity fluctuations in the shear layer near the trailing edge. Also, as the location of separation varies due to sinusoidal leading edge the separation line gets disturbed leading to changes in shear layer stability and frequency of velocity fluctuations.

Experimental and numerical studies by Chaitanya *et al.* [12] and computational studies of bio-inspired leading-edge serrations based on adaptations of Barn owl by Agrawal and Sharma [13] have further explored sinusoidal leading edge for its effectiveness in reducing broadband noise. Recent experimental investigations by Chaitanya *et al.* [14] on different leading-edge profiles highlighted leading edge slits as being superior to single wavelength leading edge profile for low frequency noise reduction. The new profiles have two dominant noise and highly coherent compact noise sources per serration wavelength which undergo destructive interference to mitigate noise from the leading edge. As much as 15dB noise reduction was achieved with leading edge slits as opposed to just 7dB for conventional single wavelength serrations. The effect of these new profiles on aerodynamic performance of airfoil remains to be explored.

Fig. 5. (a) Design of sinusoidal leading edge [13]; (b) Experimental setup of leading edge serrated airfoil [12]; (c) Leading edge slits [14]

4.2. Reduction of trailing edge noise

Since TBL-TE is the dominant noise source for most wind turbines, a number of mitigation techniques have been developed for its control. A survey of TE noise reduction techniques by Barone [15] provides an overview of several methods devised to mitigate TE noise. Trailing edge noise is directly proportional to $\cos^3\gamma$ (see Fig. 6) as per the analytical derivation using semi-infinite flat plate approximation [16]. This dependence on $\cos^3\gamma$ shows that noise is scattered most effectively when the path of turbulent eddies is perpendicular to the trailing edge. Trailing edge serrations provide a way to reduce the angle between eddy path and edge below 90°, thus decreasing the scattering of sound. Experimental observations on full scale wind turbine of 94m diameter with serrations have reported reductions of 3.2 dB [17]. However, since these serrations cannot always be aligned to the flow direction due to variable incoming flow velocity, they lead to increased sound level at higher frequencies [10].

To overcome this problem of flow alignment with serrations, the concept of trailing edge brushes was introduced. Experimental investigations by Herr [18] and Finez *et al*. [19] prove the advantage of trailing edge brushes over serrations in reducing airfoil noise. Porous trailing edge works similar to trailing edge brushes for reducing sudden change in acoustic impedance encountered at the abrupt edge by near blade flow. Studies by Geyer *et al.* [20] and Kinzie *et al.* [21] show potential in this technology for noise reduction, however, conclusive full scale experimental studies are required.

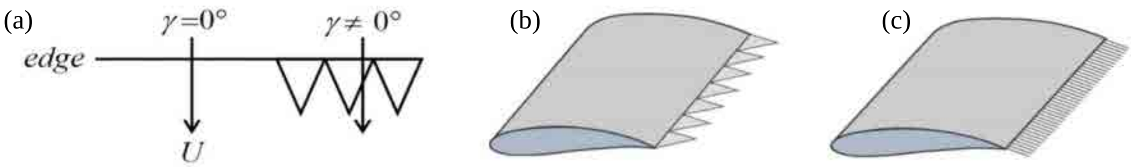

Fig. 6. (a, b) Trailing edge serrations; (c) Trailing edge brushes [10]

4.3. Reduction of tip noise

Tip noise is a dominant source of noise from wind turbines at high frequencies. Madsen and Fuglsang [22] initially identified tip vortex strength and extension of separation region with tip noise and suggested non-separating tip vortex tip as a probable solution. Fleig *et al.* [23] carried out numerical analysis of ogee type tip shape using acoustic analogy and gained 5dB noise reduction for frequencies above 4kH. Later experimental work by Kinzie *et al.* [21] over blunt, slender and ogee type tip explored the effectiveness of these tip shapes in mitigating tip noise. The selected tip shapes were designed to minimize the vortex wetted length and the interaction the vortex and side edge. Both slender and ogee tips proved to be effective in providing a reduction of 5-6 dB in Overall SPL.

Recent numerical investigations by Maizi *et al.* [24] for reducing tip noise by using reference tip and shark tip provided 7% noise reduction with shark tip but with a penalty in power of 3%. However, this computational aero-acoustic (CAA)analysis using Detached Eddy Simulation (DES) for resolving flow field and Ffowcs-Williams-Hawkings equation for acoustic calculation demands very high computational power. Deshmukh *et al.* [25] implemented an extended annular domain methodology which included the tip region in an annular domain to perform a parametric study of blended winglets for improved aerodynamic and aero-acoustic performance. This methodology provides a way to significantly reduce the computational cost (up to 75%) and resulted in about 25% noise reduction at mid-high frequencies along with enhanced torque output. Such low cost CAA methodologies can open the domain to extensive tip shape design optimization for noise reduction and power enhancement.

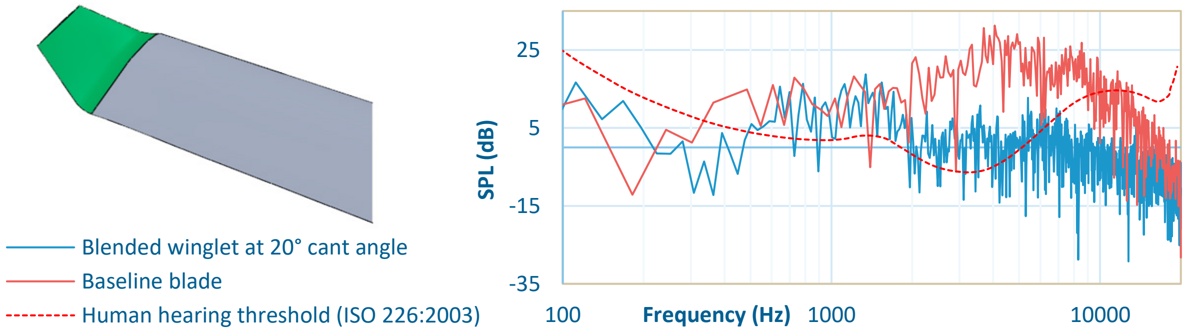

Fig. 7. Tip noise reduction through blended winglet: frequency spectrum of baseline blade vs blade with winglet [25]

5. Discussion

A review of various aerodynamic noise source mechanisms and techniques for noise reduction in wind turbine provided an insight into the fundamental nature of wind turbine aero-acoustics. Trailing edge noise and inflow turbulence noise are dominant in the low frequency region. Tip noise dominates the high frequency part of noise spectrum. Tip shape controls the strength and separation length of tip vortex which affects tip noise. Most of the noise with trailing edge as the source is generated from outbound portions of the blade where the flow velocity is higher. Blunt trailing edge noise, stall separation noise and laminar boundary layer noise are less significant as they can be easily regulated. Several techniques for noise mitigation have been discussed. Methods like serrated trailing edges for trailing edge noise reduction are already being used in some turbines but more effective methods for noise control are needed. Trailing edge brushes and porous trailing edges are potential technologies which can help gain extra trailing edge noise reduction. Lot of work has been done in identifying and mitigating inflow turbulence noise. Bio-mimicry has yielded leading edge serrations and slits for reduction of noise from this source. Leading edge slits have been shown to outperform serrations and provide very significant noise reduction. Tip noise reduction can be achieved by optimizing tip shape for reduced vortex strength and less interaction of vortex with tip edges. Computational aero-acoustics can help in faster optimization of blade shape to reduce noise by introducing less computationally expensive numerical techniques. Most of these technologies require further experimental validation and full-scale field tests.

6. Conclusions

The present paper reviewed several wind turbine noise mechanisms and mitigation methods along with the impact of noise from wind turbines on human life. Wind turbine noise is found to be more annoying than other community noise sources. Thus, effective methods for reducing wind turbine noise are required for minimizing human discomfort and prospective disorders. The effect of modifications on blade for noise reduction should not affect its aerodynamic performance or a tradeoff should be reached. Computational methods can ease design of low-noise blades by reducing time and effort. Full scale field implementation of new methods is required to examine their effectiveness in actual running conditions and interaction of noise from multiple wind turbines in farms.

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EXHIBIT
3

Two methods for estimating limits to large-scale wind power generation

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Wind turbines remove kinetic energy from the atmospheric flow, which reduces wind speeds and limits generation rates of large wind farms. These interactions can be approximated using a vertical kinetic energy (VKE) flux method, which predicts that the maximum power generation potential is 26% of the instantaneous downward transport of kinetic energy using the preturbine climatology. We compare the energy flux method to the Weather Research and Forecasting (WRF) regional atmospheric model equipped with a wind turbine parameterization over a 10^5 km^2 region in the central United States. The WRF simulations yield a maximum generation of 1.1 $W_e \cdot m^{-2}$, whereas the VKE method predicts the time series while underestimating the maximum generation rate by about 50%. Because VKE derives the generation limit from the preturbine climatology, potential changes in the vertical kinetic energy flux from the free atmosphere are not considered. Such changes are important at night when WRF estimates are about twice the VKE value because wind turbines interact with the decoupled nocturnal low-level jet in this region. Daytime estimates agree better to 20% because the wind turbines induce comparatively small changes to the downward kinetic energy flux. This combination of downward transport limits and wind speed reductions explains why large-scale wind power generation in windy regions is limited to about 1 $W_e \cdot m^{-2}$, with VKE capturing this combination in a comparatively simple way.

generation limits | turbine–atmosphere interactions | wind resource | kinetic energy flux | extraction limits

Wind power has progressed from being a minor source of electricity to a technology that accounted for 3.3% of electricity generation in the United States and 2.9% globally in 2011 (1, 2). Combined with an increase in quantity, the average US wind turbine also changed from 2001 to 2012; hub height increased by 40%, rotor-swept area increased by 180%, and rated capacity increased by 100% (2). Likely a combination of both the above-noted technological innovations and improved siting, the per-turbine capacity factor, the ratio of the electricity generation rate (MW_e) to the rated capacity (MW_i), increased globally from 17% in 2001 to 29% in 2012 (1, 2), making a recently deployed wind farm likely to generate about 70% more electricity from the same installed capacity.

Combining climate datasets with these observed trends of greater-rated capacities and capacity factors, several academic and government research studies estimate large-scale wind power electricity generation rates of up to 7 $W_e \cdot m^{-2}$ (3–7). However, a growing body of research suggests that as larger wind farms cover more of the Earth's surface, the limits of atmospheric kinetic energy generation, downward transport, and extraction by wind turbines limits large-scale electricity generation rates in windy regions to about 1.0 $W_e \cdot m^{-2}$ (8–14). Ideally, these inherent atmospheric limitations to generating electricity with wind power could be considered without scenario- and technology-specific complex modeling approaches, be easily applied to "preturbine" climatologies, and yield spatially and temporally variable generation rates comparable to the energetically consistent atmospheric modeling methods.

Here, we describe such a simple method that focuses on the vertical downward transport of kinetic energy from higher regions of the atmosphere to the surface. In the absence of wind farms, the downward flux of kinetic energy is dissipated by turbulence near the surface, which shapes near-surface wind speeds. When wind farms use some of this kinetic energy, the vertical balance between the downward kinetic energy flux and turbulent dissipation is altered and results in lower hub-height wind speeds. The more kinetic energy wind farms use, the greater the shift in the balance and the reduction of wind speeds should be. This trade-off between greater utilization and lower wind speeds results in a maximum in wind power generation from the vertical flux of kinetic energy (10). This maximum yields a potential for wind power generation of a region that is independent of the technological specifications of the turbines. Because this method is based on the vertical downward transport of kinetic energy, we refer to it as the vertical kinetic energy (VKE) method. Note that this reasoning assumes that the downward flux of kinetic energy remains unchanged, which was shown to be a reasonable assumption compared with climate model simulations at the continental scale (11), but which may not hold at the regional scale.

Here we evaluate the applicability of this method by using high-resolution simulations with the Weather Research and Forecasting (WRF) regional atmospheric model with a wind turbine parameterization. We use the region of central Kansas during the typical climatological period of June–September 2001, noting that this

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Significance

Wind turbines generate electricity by removing kinetic energy from the atmosphere. We show that the limited replenishment of kinetic energy from aloft limits wind power generation rates at scales sufficiently large that horizontal fluxes of kinetic energy can be ignored. We evaluate these factors with regional atmospheric model simulations and find that generation limits can be estimated from the "preturbine" climatology by comparatively simple means, working best when the atmosphere between the surface and hub height is naturally well-mixed during the day. Our results show that the reduction of wind speeds and limited downward fluxes determine the limits in large-scale wind power generation to less than 1 $W \cdot m^{-2}$.

Author contributions: L.M.M., N.A.B., and A.K. designed research; L.M.M., N.A.B., D.B.M., F.G., A.J.M., R.V., D.W.K., and A.K. performed research; L.M.M., N.A.B., D.B.M., and A.K. analyzed data; and L.M.M., N.A.B., D.B.M., A.J.M., R.V., D.W.K., and A.K. wrote the paper.

The authors declare no conflict of interest.

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period is before large-scale wind power deployment within this region. We then use the WRF simulation of this time period without wind farm effects to obtain the downward transport of kinetic energy into the region. This flux is used by the VKE method to predict the limit for wind power generation of the region. This limit as well as its temporal variations are then compared with a set of sensitivity simulations of the WRF model using different installed capacities of 0.3–100 $MW_i{\cdot}km^{-2}$ to derive the maximum wind power generation rate (the WRF method). These regional results will then be used within a broader interpretation on the role of horizontal and vertical kinetic energy fluxes to wind farms of differing installed capacities and spatial scales. We close with a brief conclusion on the implications of these two approaches for estimating large-scale wind power generation.

Methods

To evaluate the limits to wind power generation, we use a reference climatology of Central Kansas for the time period of May 15 to September 30, 2001 using the WRF-ARW v3.3.1 regional weather forecasting model (15, 16), forced with North American Regional Reanalysis data (17). This particular time period is climatologically representative for this region: a near-neutral El Niño southern oscillation phase, a climatologically standard position and strength of the Great Plains low-level jet, and an average summer soil moisture content (18). The simulation uses a single domain with a horizontal grid spacing of 12 km and 31 vertical levels, and the first 15 d of the simulation are excluded from the analysis to avoid spin-up effects. This WRF simulation represents our control simulation, which is used as input to the VKE method and as a reference for various WRF simulations with different densities of installed wind turbines to obtain the limit for wind power generation using the WRF method.

WRF Method. To estimate wind power generation using WRF, we use a version of the model that includes a parameterization of wind turbines that is slightly modified from a previously used approach (12, 19). This parameterization has been shown to be more realistic than previous roughness-based approaches (19). We perform a set of eight sensitivity simulations with different installed capacities of wind turbines that are placed within a contiguous wind farm region of 112,320 km^2 in central Kansas. Installed capacities (in units of $MW_i{\cdot}km^{-2}$) are simulated as an increased integrated quantity of wind turbines deployed to 780 grid cells of 144 km^2 each, which collectively represents the wind farm region. We use values of 0.3125, 0.625, 1.25, 2.5, 5.0, 10, 25, and 100 $MW_i{\cdot}km^{-2}$ for the installed capacities in the simulations and refer to the simulations by these capacities. The wind turbine characteristics are specified using the technical specifications of the Vestas V112 3.0 MW_i in terms of its power, thrust, and standing coefficients (see *SI Appendix* for the detailed model configuration). Note that this model setup does not have sufficient horizontal or vertical resolution to simulate interturbine interactions or wakes within the 12- × 12-km resolution grid cell, but rather uses the turbine specifications and installed capacity to derive one aggregate wind turbine for each grid cell and, where appropriate, the corresponding vertical levels. Additional simulations were performed to evaluate the sensitivity to the horizontal (to 3 km) and vertical spacing (to 24 levels in the lowest 1 km, 6 within the vertical rotor swept height) over a representative time period of June 15–21 and were found to yield comparable results (*SI Appendix*, Fig. 5).

VKE Flux Method. The VKE method expands upon one of the approaches of refs. 10 and 11, where a thought experiment illustrated how considering only wind speeds and turbine specifications can yield generation rates that are physically unrealizable. The method is based on an analytical description of the momentum balance of the wind farm, a central concept used in similar studies on large-scale wind power limits (20–22) or for other forms of renewable energy such as tidal power (23, 24) (detailed methodology is given in *SI Appendix*). It assumes that when wind farms extend tens of kilometers downwind, horizontal kinetic energy has either been extracted from the mean flow by the first few rows of turbines or has been lost to turbulent dissipation, so that the generation rate of wind turbines further downwind is then limited by the downward flux of kinetic energy. For this reason, it is assumed that the horizontal kinetic energy flux can be neglected for large-scale wind farms, allowing us to estimate the maximum extraction rate of kinetic energy by the turbines from the vertical downward flux of kinetic energy from the atmosphere above the wind farm. The model yields an analytic expression for the maximum extraction rate, $P_{max} = (2\sqrt{3}/9) \cdot \rho u_*^2 \cdot v_0$, where ρ is the air density, u_* is the friction velocity at the surface, and v_0 is the wind speed of the control simulation at the 84-m hub height. Note that in addition to the wind speed (v_0), this method uses the surface friction velocity (u_*) as an additional meteorological variable to yield the rate P_{max}. This additional information is not used in common methods that evaluate limits to wind power generation using only wind speeds and a prescribed installed capacity (3–7). We then convert this maximum rate into a limit for electricity generation by using the Betz limit and estimates of wake turbulence (25), resulting in a reduction to about 66%, or two-thirds, of P_{max}. Thus, we define the maximum electricity generation rate by a large wind farm as $P_e = (4\sqrt{3}/27) \cdot \rho u_*^2 \cdot v_0$. This results in the maximum electricity generation rate, P_e, to be equivalent to $(4\sqrt{3}/27) = 26\%$ of the turbulent dissipation occurring before wind farm deployment. Note that P_e is not specific to an installed capacity or wind turbine manufacturer specifications, thereby resulting in the maximum wind power generation rate possible from the pre-turbine climatological vertical kinetic energy flux through hub height.

Results and Discussion

As shown in Fig. 1, the WRF simulations show that a greater installed capacity within the wind farm region increases the total electricity generation rate. This increase is almost linear at the lower installed capacities (0.3 $MW_i{\cdot}km^{-2} \approx 0.13\ W_e{\cdot}m^{-2}$, 0.6 $MW_i{\cdot}km^{-2} \approx 0.24\ W_e{\cdot}m^{-2}$; subscripts i and e refer to the installed capacity and electricity generation, respectively). With further increases in the installed capacity, the marginal return of electricity generation predominantly occurs during higher wind speed periods. Such greater generation rates during windy periods can be seen in the differences between the simulations with 5.0 and 10 $MW_i{\cdot}km^{-2}$ during the high wind speeds of June, whereas the difference is smaller during the lower wind speeds of August and September. Because the greater generation rates occur during periods that are less frequent, the increase in generation is no longer linear. This is reflected by comparing the generated electricity of the 5.0 $MW_i{\cdot}km^{-2}$ to the 0.3 $MW_i{\cdot}km^{-2}$ simulation, which generates seven times more electricity with 16 times as many wind turbines. Stated differently, each wind turbine at 5.0 $MW_i{\cdot}km^{-2}$ generates electricity at half the rate as wind turbines with the same technical specifications but installed at 0.3 $MW_i{\cdot}km^{-2}$.

This difference in the relationship between generation rate and installed capacity is reflected in a change in the capacity factor. First, we use the hub-height wind speeds of the control simulation and the turbine power curve for the Vestas V112 turbine (*SI Appendix*, Fig. 6) to calculate the generation rate of a single isolated wind turbine deployed to each location and time. This yields a capacity factor of 47%, which represents the upper bound value for the case of no interactions between the wind turbines and the atmospheric flow. This estimate compares well to the capacity factors of 22–36% (1, 7) derived from installed capacity and operational generation data from Kansas during 2006–2012, even though this estimate includes turbines of various technical specifications taken over a much longer timescale than this study. Using the 2012 installed capacity of 2,713 MW_i (7) and the area of 213,000 km^2 for Kansas yields a state-scale installed capacity of

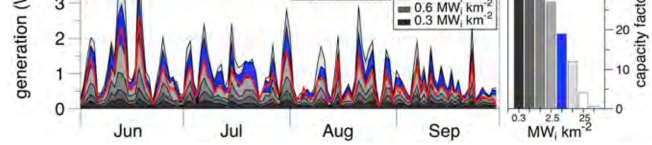

Fig. 1. (*Left*) Simulated daily mean electricity generation rates over the Kansas wind farm region (black square on map) for different installed capacities of up to 10 $MW_i{\cdot}km^{-2}$. The higher installed capacities of 25 and 100 $MW_i{\cdot}km^{-2}$ are not shown, because they often yield less than the 10 $MW_i{\cdot}km^{-2}$ simulation. For comparison, the VKE estimate is shown in red. (*Right*) The mean per-turbine capacity factor derived for the different simulations.

0.013 $MW_i \cdot km^{-2}$, which falls below the lowest installed capacity that we used. Our simulation with the lowest installed capacity of 0.3 $MW_i \cdot km^{-2}$ corresponds to a slightly reduced capacity factor of 42%, and 39% with 0.6 $MW_i \cdot km^{-2}$ (*SI Appendix*, Table 2). These capacity factors compare well with the previously used values for this region of 37% (6) and 40–47% used by the National Renewable Energy Laboratory (7). However, the estimates of refs. 6 and 7 used an installed capacity of 5.0 $MW_i \cdot km^{-2}$, which in our simulations yield a much lower capacity factor of 19%, which should thus result in much lower estimates for wind power generation.

The reduction in capacity factor with greater installed capacity results from an enhanced interaction of wind turbines with the atmospheric flow. Because a greater installed capacity of wind turbines removes more kinetic energy from the atmosphere and converts it into electric energy, this causes a decrease in the hub-height wind speed downwind (26), which decreases the mean per-turbine electricity generation rate of the wind farm. This reduction in wind speeds within the wind farm and its effects on the per-turbine electricity generation rate is shown in Fig. 2 in relation to the power curve of the turbine and the wind speed histogram (Fig. 2*A*) as well as the mean wind speed and mean per-turbine generation rate (Fig. 2*B*). The point spread around the 3.0 MW_i turbine power curve in Fig. 2*A*, with some values below the 3.0 $m \cdot s^{-1}$ cut-in wind speed, is due to the use of mean hourly hub-height wind speed and electricity generation rate for the entire wind farm region. Additionally, the variability in hub-height wind speed decreases with greater installed capacity (Fig. 2*B*), which also decreases the variability of per-turbine electricity generation. This reduction in wind speeds has also been observed in previous modeling studies (9–12, 27, 28).

Fig. 2*C* shows the increasing importance of considering the reduction in wind speed for the mean generation rate of the wind farm with greater installed capacity. The dashed line in Fig. 2*C* is derived by applying the turbine power curve to the control hub-height wind speeds for a mean per-turbine capacity factor of 47% (slope = 0.47). The WRF simulations with installed capacities of less than about 1 $MW_i \cdot km^{-2}$ yield similar estimates because the capacity factors remain high (see also *SI Appendix*, Table 2). At greater installed capacities, the WRF simulations resulted in proportionally lower estimates. For example, at an installed capacity of 2.5 $MW_i \cdot km^{-2}$ the "no interactions" estimate would yield a generation rate per unit area of the wind farm of 1.18 $W_e \cdot m^{-2}$, but this was simulated to be 0.68 $W_e \cdot m^{-2}$. This discrepancy continues with greater installed capacities, so at 5.0 $MW_i \cdot km^{-2}$ the estimate without interactions overestimates the average electricity generation rate by more than a factor of two (2.4 $W_e \cdot m^{-2}$ for no interactions, 0.95 $W_e \cdot m^{-2}$ with interactions). The maximum electricity generation rate of 1.1 $W_e \cdot m^{-2}$ is obtained with an installed capacity of 10 $MW_i \cdot km^{-2}$, at which the associated hub-height wind speed decreased by 42% and the capacity factor is reduced to 12%. Our WRF simulations suggest that previous estimates of mean wind energy generation potentials for Kansas of 1.9 $W_e \cdot m^{-2}$ (6), 2.0–2.4 $W_e \cdot m^{-2}$ (7), and 2.5 $W_e \cdot m^{-2}$ (4) are likely to be too high because the effects of reduced wind speeds were not considered. To place this reduction into the context of present-day wind power deployment, note that such installed capacities are several orders of magnitude larger than presently operational Kansas wind farms. Our simulations thus suggest that an equidistant deployment of 50 times more installed wind power in Kansas than is presently operational ($\approx$ 0.013–0.6 $MW_i \cdot km^{-2}$) would maintain the presently high per-turbine capacity factors and thus increase the generation rate 50-fold.

The VKE method captures the magnitude of wind power generation as well as its temporal variations. In our Kansas scenario, we estimate a maximum 4-mo mean generation rate from WRF at 10 $MW_i \cdot km^{-2}$ as 1.1 $W_e \cdot m^{-2}$ and VKE as 0.64 $W_e \cdot m^{-2}$. Based on the linear correlation, the daily mean estimates of the two methods are highly correlated: $r^2 = 0.98$, with a slope of $m = 1.76$, an rmse of 0.60, and a mean absolute error (MAE) of 0.47. The WRF estimate from the 5.0 $MW_i \cdot km^{-2}$ simulation, an installed capacity often used for wind power planning and policy analysis (6), also compares very well, with daily mean estimates being highly correlated with VKE with $r^2 = 0.98$, $m = 1.47$, rmse = 0.39, and MAE = 0.32. The mean generation rate of this WRF simulation was 0.95 $W_e \cdot m^{-2}$, nearly the same rate as the 10 $MW_i \cdot km^{-2}$ simulation, but from half the number of turbines. When hourly estimates of WRF and VKE are compared (Fig. 3), we note that correlations are very high during day and night, but the slope is much better captured by VKE during the day, whereas at night VKE underestimates the magnitude of electricity generation by almost 45% in this simulation.

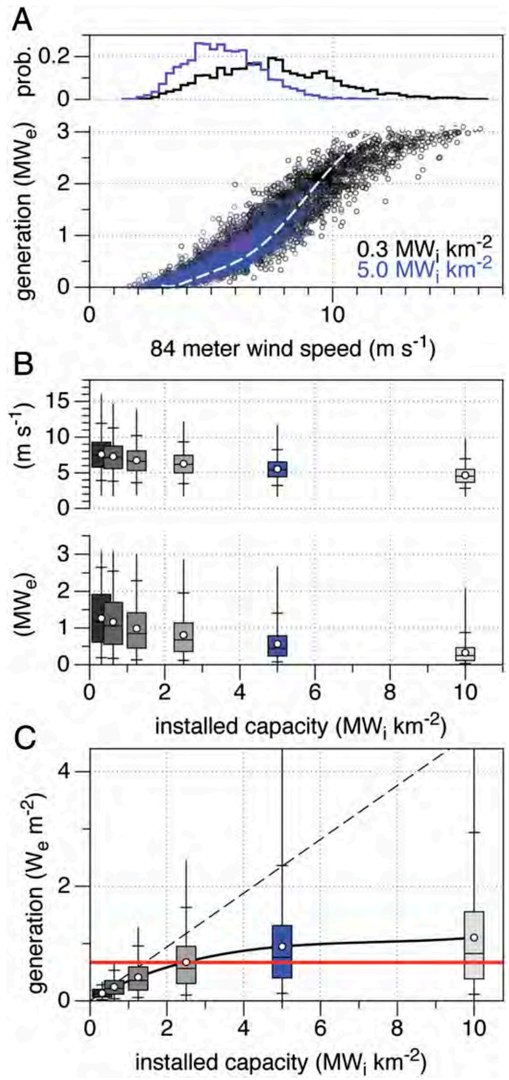

Fig. 2. (*A*) The per-turbine electricity generation rate for two select WRF simulations as a function of hub-height wind speed at 84 m as well as its histogram (*Top*). The dashed line shows the Vestas V112 3.0 MW_i power curve of a single turbine. (*B*) Mean per-turbine generation rate and the 84 m mean hub-height wind speed of the wind farm region as a function of installed capacity. (*C*) Mean per-turbine electricity generation rate as a function of installed capacity when the capacity factor of a single turbine is extrapolated to high installed capacities (dashed line, "no interactions") and the relationship derived from the WRF simulations (solid line, "interactions"). The red line shows the VKE estimate. All box-whisker plots show the 5, 25, 50, 75, and 95% values, with the extent showing the minimum–maximum and the circles showing the mean.

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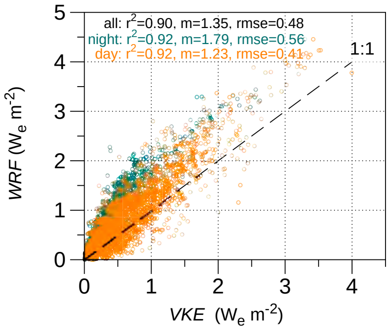

Fig. 3. Comparison of hourly mean electricity generation rates for the wind farm region estimated by VKE and WRF with an installed capacity of 5 $MW_i{\cdot}km^{-2}$.

We attribute this underestimation of wind power generation by VKE at night to its use of the preturbine downward kinetic energy flux of the control. The atmospheric flow in this region typically decouples from the stable surface conditions at night in the summer, which leads to the formation of the low-level jet (LLJ) near the surface (29). The typical nighttime structure of the LLJ (Fig. 4*B*) with a mean stable boundary layer height of 40 m (12–124 m, 5th–95th percentile, respectively) from June–September 2001 in the WRF control mean is consistent with height observations of about 50–350 m in southeastern Kansas during October 1999 (30). Observed LLJ maxima at about 100 m after sunset with an increase in height to about 225 m over the course of the night were also observed for this region on October 25, 1999 (30). The rotors of the wind turbines extend from 28 to 140 m in height and thus reside above, within, or at the upper boundary of the stable boundary layer. The wind turbines in the WRF simulations can thus sometimes directly use the kinetic energy from above the constant stress layer and the LLJ at night. This increased utilization of kinetic energy of the LLJ and the flow of the free atmosphere results in an increased downward kinetic energy and thus a greater maximum generation rate in WRF compared with the VKE method, which does not account for this effect. Based on the nighttime hourly mean values for the wind farm region, a hub-height speed of 9.5 $m{\cdot}s^{-1}$ and a surface momentum flux of 0.15 $kg{\cdot}m^{-1}{\cdot}s^{-2}$ yields a downward kinetic energy flux of 1.39 $W{\cdot}m^{-2}$ with an associated maximum generation rate of 0.36 $W_e{\cdot}m^{-2}$ by VKE. Daytime atmospheric conditions are different. The daytime mean convective boundary layer height in the WRF control simulation is 1,268 m. Of this total height, the constant stress layer, the vertical depth over which the downward kinetic energy flux is considered negligible, typically constitutes the lowest 10% of the convective boundary layer (31, 32). Therefore, during the daytime, the upper extent of the turbine rotors is likely to be within the constant stress layer. Based on mean daytime values, a hub-height speed of 6.9 $m{\cdot}s^{-1}$ and a surface momentum flux of 0.37 $kg{\cdot}m^{-1}{\cdot}s^{-2}$ yields a downward kinetic energy flux of 2.55 $W{\cdot}m^{-2}$ with an associated maximum generation rate of 0.65 $W_e{\cdot}m^{-2}$ by VKE. Note how the daytime VKE estimate is about double the nighttime estimate, even though the wind speed during the daytime is lower. These differences between the nighttime and daytime downward kinetic energy fluxes also help explain the similarities and discrepancies between the daytime and nighttime VKE and WRF estimates (Fig. 3).

One last point to note is that the maximum mean electricity generation rate of 1.1 $W_e{\cdot}m^{-2}$ achieved in WRF has notable effects on the atmosphere and would likely induce considerable differences in climate. Although several recent studies evaluated how wind power generation caused climatic differences in measurements (33, 34) and modeling (10, 12, 13, 27, 35–37), the reduction of wind speeds is relevant here, because this reduction sets the large-scale limit to wind power generation. The mean hub-height wind speed in the 10 $MW_i{\cdot}km^{-2}$ decreased by 42% compared with the control (Fig. 2*B*). This decrease is consistent with VKE, which provides an analytic expression for the decrease in wind speed at maximum generation of $(1-\sqrt{3}/3)\cdot v_0 = 42\%$. As described above, it is this decrease in wind speed with greater kinetic energy extraction by more wind turbines that limits the wind power generation at large scales. That VKE reproduces the decrease in v_0 very well is likely the reason why it captures the magnitude and temporal dynamics of limits to large-scale wind power generation of the WRF simulation.

Interpretation

Our estimates from both methods are compared with several other recent studies in Fig. 5. There is a clear discrepancy between estimates based on climatological wind speeds (black symbols) from estimates derived with atmospheric models (colored symbols), which are generally lower. We attribute these discrepancies to the inclusion of turbine–atmosphere interactions in the case of the atmospheric models that result in the reduction of wind speeds in the wind farm. However, one study included in Fig. 5 was derived from existing operational wind farms and observed generation rates, which calls for a more detailed explanation of the discrepancy between those and our estimates. Numerous footprints of operational wind farms in the United Kingdom were digitized (38) and compared with their documented generation rate, thereby inherently including turbine–atmosphere interactions. With the majority of the wind farms used in ref. 38 covering relatively small areas of about 2.4 km^2 (0.1–13 km^2) of "footprint area" in hilltop or offshore locations, the wind farms have a mean generation rate of about

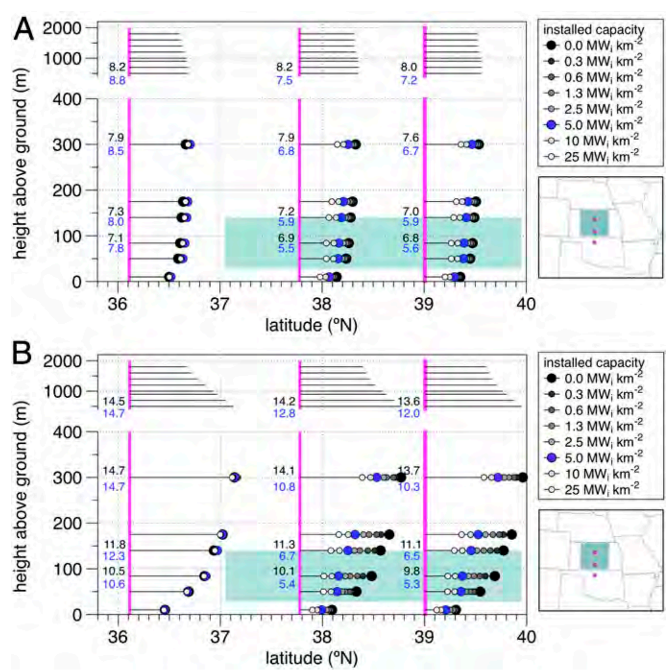

Fig. 4. Mean (*A*) daytime and (*B*) nighttime wind speeds for three selected locations across the wind farm region (*Inset*) for the control and seven WRF simulations with different installed capacities with one location generally upwind and two locations within the wind farm region. The teal boxes show the spatial and vertical extent of the wind farm. The pink bars and dots show the spatial locations where the mean wind speeds were taken. Wind speeds at the hub height of 84 m and top-of-rotor height of 140, 300, and 500 m for the three locations are noted as text for the control (black numbers) and 5.0 $MW_i{\cdot}km^{-2}$ (blue numbers). Note the break in both *y* axes.

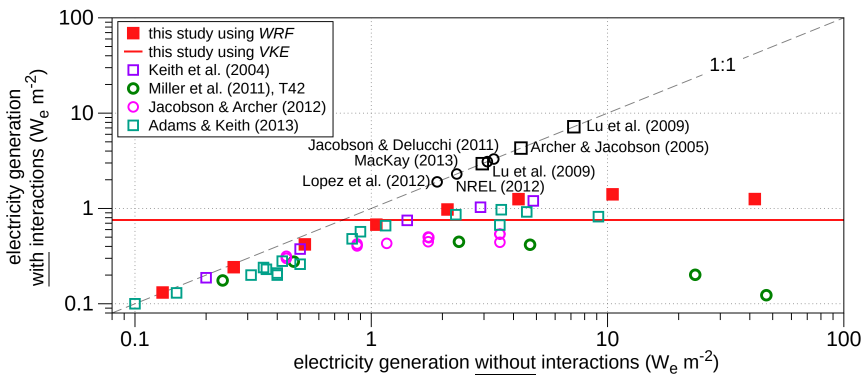

Fig. 5. Regional (squares) and continental-to global scale (circles) large-scale electricity generation estimates in relation to the effect of turbine–atmosphere interactions. The estimates represented by black squares and circles used preturbine wind speeds without including turbine–atmosphere interactions and are placed on the 1:1 line for reference. The colored points refer to estimates based on atmospheric models. These estimates simulate wind speeds and include turbine–atmosphere interactions (*y* axis). The value on the x axis was derived from using the turbine power curve, installed capacity, and the wind speeds of the control simulation. The horizontal line at 0.64 $W_e{\cdot}m^2$ with interactions is the VKE estimate for Kansas (based on figure 4 from ref. 12 with additional studies and the VKE estimate added).

2.9 $W_e{\cdot}m^{-2}$ (0.8–6.6 $W_e{\cdot}m^{-2}$) from a mean installed capacity of about 11 $MW_i{\cdot}km^{-2}$ (3.5–24 $MW_i{\cdot}km^{-2}$). These generation rates are substantially higher than our 1.1 $W{\cdot}m^{-2}$ limit of large-scale wind power generation in Kansas, although the size of the wind farms is also notably smaller.

This difference in wind power generation rates can be understood by relating the kinetic energy used by the wind turbines to their sources. For this, we distinguish between the import of kinetic energy by horizontal and vertical fluxes into the wind farm region. These two contributions change as the spatial scale of the wind farm increases. This change can be illustrated by using the mean values of the wind farm region from the WRF control simulation over the 4-mo period. The mean horizontal flux of kinetic energy is given by $KE_{in,h} = (1/2)\rho v_0^3 \cdot x \cdot h$, where $\rho = 1.1$ $kg{\cdot}m^{-3}$ is the air density at hub height, $v_0 = 8.0$ $m{\cdot}s^{-1}$ is the hub-height wind speed at 84 m, $x = 360{,}000$ m is the east–west extent of the wind farm that is perpendicular to the mean wind direction, and $h = 112$ m is the height of the wind farm, assumed here to be equivalent to the rotor diameter of the 3.0 MW_i turbine. This yields a mean horizontal kinetic energy flux of $KE_{in,h} = 11$ GW (or 282 $W{\cdot}m^{-2}$ per unit cross-sectional area) into the upwind vertical cross-section of the wind farm region. The mean vertical kinetic energy flux is given by $KE_{in,v} = \rho u_*^2 \cdot v_0 \cdot x \cdot y$, where the mean (spatial and temporal) friction velocity at the surface $u_* = 0.45$ $m{\cdot}s^{-1}$ and $y = 312{,}000$ m is the north–south extent of the wind farm that describes the downwind length of the wind farm. This yields a mean vertical kinetic energy flux downward into the entire wind farm region of $KE_{in,v} = 200$ GW or 1.8 $W{\cdot}m^{-2}$ per unit surface area of the wind farm region, so that in the Kansas setup, $KE_{in,v}$ provides about 20 times as much kinetic energy as the horizontal influx. Note that this vertical flux of kinetic energy, derived from the WRF control simulation, served as the input to the VKE estimate. When the wind farm increases in downwind length with a greater value of *y*, the contribution by the vertical kinetic energy flux into the wind farm region increases linearly whereas the horizontal contribution remains relatively unchanged. WRF simulations with an installed capacity of 1 $MW_i{\cdot}km^{-2}$ or greater (>110 GW_i) represent wind farms in which the installed capacity is of the order of the mean kinetic energy flux into the wind farm region (about 211 GW), which is when the reductions of wind speed start to play a role in shaping the generation rate.

In the context of the Kansas wind farm region, we can use these considerations to estimate the downwind depth at which the horizontal kinetic energy flux is fully consumed by electricity generation and turbulence. Assuming a conservative 33% loss to turbulence during the extraction process (25), the 11-GW mean horizontal kinetic energy flux would result in a maximum electricity generation rate of 7.4 GW_e. This generation rate is equivalent to about 5,800 wind turbines of 3.0 MW_i capacity with a 42% capacity factor, which is close to our WRF simulation at the lowest installed capacity of 0.3 $MW_i{\cdot}km^{-2}$. When considering the much greater installed capacity of 5.0 $MW_i{\cdot}km^{-2}$, the 11 GW of horizontal kinetic energy flux would be fully consumed within a downwind depth of about 10 km (see also ref. 22). Therefore, as the downwind extent of the wind farm grows, electricity generation rates of successive downwind turbines are derived progressively less from the horizontal flux and more from the vertical flux. This results in an edge effect of higher generation rates at the upwind border of the wind farm compared with lower generation rates in the interior of the wind farm region (see also *SI Appendix*, Fig. 9). This edge effect does not exist for the VKE estimate (*SI Appendix*, Fig. 9), because it neglects the horizontal kinetic energy flux as an energy source. This can in part explain the lower estimates of the VKE method. However, when considering wind farms of greater sizes, the influence of this edge effect on the mean generation rate becomes progressively less important to consider.

Generation rates above those estimated by VKE could be achieved if the incoming horizontal kinetic energy flux is available to the wind farm because it was not extracted by upwind turbines, or relate to an increase in the vertical kinetic energy flux by the wind turbines, as shown to particularly occur in the WRF simulations at night. The spatial extent over which this enhanced vertical kinetic energy flux can be maintained, how much it alters the LLJ, and possibly how this results in a regional redistribution in this flux remain as open questions.

An overall increase in the downward kinetic energy flux at larger deployment scales seems unlikely to occur, because climate model simulations performed at continental and global scales do not predict such an increase for present-day radiative forcing conditions (10, 13). Although these studies did not include a full analysis of the energetics, their predictions broadly agree with the predictions of the VKE method in terms of a maximum of 25–27% of the natural dissipation rate that could be used for electricity generation (10) and a slowdown of hub-height wind velocities by 51% globally, 50% over land, and 51% over the ocean (13). Despite its lack of considering changes in the downward kinetic energy flux, it would nevertheless seem that the VKE method is suitable to provide first-order estimates of the magnitude of wind power generation by large wind farms, but this would require further confirmation.

This agreement does not resolve the apparent discrepancy between our estimates and the observation-based estimates from small UK wind farms (38); note that these wind farms have downwind depths much less than 10 km, making their electricity generation rates almost exclusively dependent on the horizontal kinetic energy flux. Formulated differently, edge effects determine the generation rate of these small wind farms. To illustrate compatibility with WRF-simulated results, we apply the footprint area definition of ref. 38 for isolated 3.0 MW_i wind turbines (i.e., a circle with diameter five times the turbine diameter, or 0.25 km^2 per turbine) to our simulation of 0.3 $MW_i{\cdot}km^{-2}$. This results in each 3.0 MW_i turbine being spaced 3.1 km apart and yields a comparable

5.1 $W_e \cdot m^{-2}$ for the turbines. For progressively larger installed capacities, this estimate decreases to 4.7 $W_e \cdot m^{-2}$ for an installed capacity of 0.6 $MW_i \cdot km^{-2}$, to 4.0 $W_e \cdot m^{-2}$ for 1.3 $MW_i \cdot km^{-2}$, to 3.3 $W_e \cdot m^{-2}$ for 2.5 $MW_i \cdot km^{-2}$, to 2.3 $W_e \cdot m^{-2}$ for 5.0 $MW_i \cdot km^{-2}$, and to 1.3 $W_e \cdot m^{-2}$ for 10 $MW_i \cdot km^{-2}$.

In summary, these considerations illustrate the strong dependence of small-scale wind farms on a horizontal kinetic energy flux that is not influenced by other wind farms upwind. Our results suggest that expanding wind farms to large scales will limit generation rates by the vertical kinetic energy flux, thereby constraining mean large-scale generation rates to about 1 $W_e \cdot m^{-2}$ even in windy regions. Large-scale estimates that exceed 1 $W_e \cdot m^{-2}$ thus seem to be inconsistent with the physical limits of kinetic energy generation and transport within the Earth's atmosphere.

Conclusion

We evaluated large-scale limits to wind power generation in a hypothetical scenario of a large wind farm in Kansas using two distinct methods. We first used the WRF regional atmospheric model in which the wind farm interacts with the atmospheric flow to derive the maximum wind power generation rate of about 1.1 $W_e \cdot m^{-2}$. This maximum rate results from a trade-off by which a greater installed capacity resulted in a greater reduction of wind speeds within the wind farm. This reduction in wind speeds reflects the strong interaction of the wind farm with the atmospheric flow, with speeds reduced by 42% at the maximum generation rate. We then showed that these estimates can also be derived by the VKE method, which used the downward influx of kinetic energy of the control climatology and its partitioning into turbulent dissipation and wind-energy generation as a basis. The VKE method predicts that the maximum generation rate equals 26% of the instantaneous downward transport of kinetic energy through hub height. This method only required the information of wind speeds and friction velocity of the control climate to provide an estimate of a maximum wind power generation rate. With an estimate of 0.64 $W_e \cdot m^{-2}$, the VKE method underestimates the maximum wind power generation rate, particularly during night, but it nevertheless captures the temporal dynamics as well as the reduction in wind speeds very well.

Both methods used here yield estimates for the limits to large-scale wind power generation that are energetically consistent. Although many current wind farms are still comparatively small and can therefore sustain greater generation rates, an energetically consistent approach becomes relevant when the installed capacity of the wind farm approaches the kinetic energy flux into the wind farm region. Although the VKE method assumes this influx to be fixed, it nevertheless demonstrates that an energetically consistent estimate can be done in a comparatively simple way, thus providing a useful means to derive a first-order estimate of large-scale wind power generation from preturbine climatologies. We conclude that large-scale wind power generation is thus limited to a maximum of about 1 $W_e \cdot m^{-2}$ because of this inevitable reduction of wind speeds and the comparatively low vertical kinetic energy fluxes in the atmosphere.

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EXHIBIT 3

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Understanding stress effects of wind turbine noise – The integrated approach

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ABSTRACT

To better understand causes and effects of wind turbine (WT) noise, this study combined the methodology of stress psychology with noise measurement to an integrated approach. In this longitudinal study, residents of a wind farm in Lower Saxony were interviewed on two occasions (2012, 2014) and given the opportunity to use audio equipment to record annoying noise. On average, both the wind farm and road traffic were somewhat annoying. More residents complained about physical and psychological symptoms due to traffic noise (16%) than to WT noise (10%, two years later 7%). Noise annoyance was minimally correlated with distance to the closest WT and sound pressure level, but moderately correlated with fair planning. The acoustic analysis identified amplitude-modulated noise as a major cause of the complaints. The planning and construction process has proven to be central – it is recommended to make this process as positive as possible. It is promising to develop the research approach in order to study the psychological and acoustic causes of WT noise annoyance even more closely. To further analysis of amplitude modulation we recommend longitudinal measurements in several wind farms to increase the data base — in the sense of "Homo sapiens monitoring".

1. Introduction

Noise problems are one of the most frequently discussed impacts of wind turbines (WT) on residents. Indeed, several studies provide empirical evidence for WT noise to be a potential source of annoyance. However, while about three dozen field studies on the noise effects of large WT (e.g., Health Canada, 2014; Michaud et al., 2016a, 2016b, 2016c, Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009; Pedersen and Persson-Waye, 2004, 2007; Pohl et al., 1999, 2012) and small WT (Taylor et al., 2013) indicate noise annoyance, the reported prevalence of annoyed residents is inconsistent and varies between 4.1% (Pedersen and Persson Waye, 2007) and 21.8% (Pohl and Hübner, 2012). One possible explanation for these different findings is that annoyance is not influenced solely by noise. For example, significant relations between noise levels from < 28 dB(A) to > 45 dB(A) – estimated by diffusion models – and annoyance repeatedly were found. However, the sound level explained only 12–26% of the annoyance variance (Pedersen and Persson-Waye, 2004, 2007; Pedersen et al., 2009), leaving more than 70% to be explained. Consequently, annoyance is influenced by further factors, so-called moderator variables such as visibility and financial participation. However, despite some knowledge on the moderating factors, it remains an open question under what conditions WT noise can lead to strong annoyance. Most of the mentioned studies calculated sound levels and used not local sound measurement at recipient locations, which may contribute to unexplained variance because in diffusion models local acoustical specificities were not considered.

Former studies provided valuable insight into the relation between WT noise and annoyance (e.g., Health Canada, 2014; Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009; Pedersen and Persson-Waye, 2004, 2007). However, they relied on a smaller range of stress indicators and moderators. Additionally, these studies remain descriptive and the indicators are not embedded in a larger stress concept. The benefit of a stress concept is to derive specific strategies for stress reduction on different stages of the stress process. Therefore, we rely on the well-established model of Lazarus (e.g., Lazarus and Cohen, 1977) enlarged by Baum et al. (1984) and Bell et al. (1990). This approach starts with the perception of a possible stressor (e.g., WT noise), followed by evaluation of the stressor (e.g., threatening), psychological and physical reactions (e.g., symptoms) and cognitive, emotional and behavioral coping (e.g., closing the window). Acoustic (e.g., sound pressure level), psychological (e.g., experiences during the planning process) and situational (e.g., distance to the nearest WT) moderators of the stress reaction were also considered.

The present study provides an interdisciplinary approach for a differentiated analysis of WT noise. This approach integrates noise

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measurement, weather and operational information connected with the WT and psychological concepts on social acceptance as well as stress psychology. To develop this integrated approach a field study was conducted involving 212 residents living in the vicinity of a wind farm in Lower Saxony, Germany. Finally, this approach offers a systematic background for recommendations regarding noise mitigation and on how to deal with WT noise.

2. Factors influencing noise annoyance by WT and stress effects

2.1. Influencing factors

Citizens and wind project operators refer to several influencing factors to explain noise annoyance. Some of these lay explanations are not mirrored by empirical evidence such as noise sensitivity, which has a rather weak impact on annoyance (e.g., Hübner and Löffler, 2013; Pedersen and Persson-Waye, 2004; Pohl et al., 2012). Socio-demographic variables such as age, gender and emotional lability, have not been proven to show significant impact (e.g., Pedersen and Larsman, 2008; Pedersen et al., 2010; Pohl et al., 2012).

A well-known moderator of noise annoyance due to WT is the visibility of WT from the property or homes of residents living nearby: on average, residents are significantly more annoyed when the WT are visible from their dwellings (e.g., Arezes et al., 2014; Pedersen et al., 2009, 2010; Pedersen and Persson Waye, 2007). This effect can be explained by the higher salience of the WT in case of visibility. In line with the explanation seems to be the finding that residents in rural and flatland regions reported higher noise annoyance than residents living in a more urban and hilly region (Pedersen and Larsman, 2008; Pedersen and Persson-Waye, 2007, 2008; Pedersen et al., 2009).

Additional relevant moderating variables that have the ability to decrease annoyance are financial participation in the wind farm (e.g., Arezes et al., 2014; Health Canada, 2014; Pohl et al., 1999; Pedersen et al., 2010), positive attitudes towards wind energy (e.g., Pawlaczyk-Luszczynska et al., 2014; Pedersen and Persson Waye, 2008; Pohl et al., 1999, 2012), and positive attitudes towards the local wind farm (e.g., Pohl et al., 1999, 2012). On the other hand, annoyance during planning and construction (e.g., Hübner and Löffler, 2013; Pohl et al., 2012) and a negative visual impact of WT on the landscape (e.g., Health Canada, 2014; Pawlaczyk-Luszczynska et al., 2014; Pedersen and Larsman, 2008; Pedersen et al., 2009) increase annoyance.

Additionally, noise annoyance is influenced by situational factors, such as weather conditions and time of day (e.g., Health Canada, 2014; Hübner and Löffler, 2013; Pawlaczyk-Luszczynska et al., 2014; Pedersen and Persson-Waye, 2004; Pedersen et al., 2009). The strongest noise annoyance occurs in the evening and night hours, especially when wind blows constantly from WT towards the dwellings or during periods of strong wind. Furthermore, residents experience higher noise annoyance outside rather than inside the home. Overall, however, the source directivity of wind turbines is still an under-researched topic especially in situations with strong amplitude modulation (AM).

In summary, moderator variables seem to better predict the annoyance caused by WT than, e.g., sound pressure level or distance to the nearest WT (e.g., Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009). Additionally, WT are rated more annoying than other noise sources with a similar sound level (Janssen et al., 2011; Pedersen and Persson-Waye, 2004; Pedersen et al., 2009). This finding also indicates that other factors contribute to the annoyance, such as some factors mentioned so far in combination with e.g., specific noise patterns and qualities. For example, residents felt most strongly annoyed by a noise pattern described as "swishing" (Pedersen and Persson-Waye, 2004, 2008).

2.2. Stress effects of WT noise

Sleep disturbance due to WT noise was reported in some studies (e.g., Bakker et al., 2012; Hübner and Löffler, 2013; Pedersen and Persson-Waye, 2004; Pohl et al., 1999). The proportion ranged from 6% (Bakker et al., 2012) to 11% of the residents (Pohl et al., 1999). Further symptoms caused by WT noise, such as negative mood, nervousness and irritability, occurred only to a small extent (up to 5.8% affected residents) and so far have been demonstrated in two earlier studies (Pohl et al., 1999; Wolsink et al., 1993). Further, there are only a few studies − and with heterogeneous findings − on the relationship between WT noise annoyance and disturbed work, leisure activities and alternating whereabouts (e.g., Hübner and Löffler, 2013; Pohl et al., 1999, 2012). Likewise, cognitive and behavioral coping strategies of annoyed residents have been subject only to a few studies (e.g., Hübner and Löffler, 2013; Pedersen and Persson Waye, 2007; Pohl et al., 1999, 2012). Typical reported measures include closing the windows and turning up the volume of the TV/radio.

While the aforementioned research refers to the health impacts of WT noise, other studies compare residents living near WT (≤ 2 km) with those living further away (≥ 3.3 km) in general (e. g., Nissenbaum et al., 2012; Sheperd et al., 2011). Although deteriorating health characteristics were reported for nearby residents, these studies are to be strongly criticized for their methods. They exclude the impacts of specific emissions, moderator variables or possible previous illness, and they do not control for the possible impact of additional noise sources (Nissenbaum et al., 2012; Sheperd et al., 2011).

2.3. Present research

The present research aims to provide a deeper understanding of the causes and consequences of WT noise stress effects. This knowledge is the base to derive recommendations for noise mitigation.

While existing research provides a basic understanding of the WT noise phenomenon, at least three open questions remain:

First, is there a greater proportion of residents living in the vicinity of a wind farm that is not only annoyed by noise but that also suffers from stress effects or even adverse health effects related to WT noise? To answer this question it is useful to assess possible stress effects by several indicators based on stress psychology concepts (Baum et al., 1984; Bell et al., 1990; Lazarus and Cohen, 1977). Further, it is unclear whether the proportion is stable over the time, since longitudinal studies thus far are missing.

Second, due to the chosen assessment methods, it is still uncertain whether the reported symptoms are directly attributed to WT noise or confounded by others stressors. The link is lacking in most studies. A first attempt to assess and directly link to WT noise was made in the late 1990s (Pohl et al., 1999). This study was mainly directed to analyse the stress impact of periodical shadow-casting but also included several items concerning noise.

Third, we need a deeper understanding of the conditions contributing to substantial annoyance.

Previous research results, illustrated above, suggest that physical factors (e.g., sound pressure level, sound quality, visibility of the wind farm) and psychological factors (e.g., stress during the planning phase, attitude toward wind energy) contribute to this.

Due to our aim to disentangle the responsible factors for WT noise annoyance, we used a case study approach with several psychological stress indicators and physical parameters.

3. Methods

3.1. Design

A longitudinal study design was chosen to test if WT noise annoyance is a stable phenomenon over time or can annoyance be influenced by information about causes and effects of WT noise. The design was based on the methodology of environmental and stress psychology in combination with noise measurement and audio recordings (Baum et al., 1984; Bell et al., 1990; Lazarus and Cohen, 1977). Using a standardized questionnaire, residents of one wind farm were interviewed face-to-face twice over a two-year period (March through April 2012, February through March 2014). Interviewers were trained students who visited the participants in their homes. Furthermore, they were able to submit complaint sheets over several months and audiotape any disturbing noises. In order to assess the generalizability of the results, the central findings were compared to findings of a nationwide sample, including more than 400 residents living in the vicinity of 13 wind farms (Pohl et al., 2012).

The wind farm was located in a rural, flat area in the German state of Lower Saxony. There were nine WT with a power of 2 MW and a total height of 150 m each (Enercon E-82). At the time of the first survey (2012), the time in operation was 37 months.

3.2. Participants

3.2.1. Recruitment

After information about the project was disseminated via radio and press releases, the participants were recruited through letters and phone calls, and at a community meeting. Based on address lists of authorities and public phone directories, letters were sent to 590 people. About the same number lived in an area with predicted sound pressure level of 25–30 dB(A) and in an area with 30–35 dB(A). There are no residents living in an area with levels > 35 dB(A). A few days later, those who received letters were called and asked to participate. Additionally, 45 persons were contacted on-site during the interview days, of whom 14 were partners of previously recruited single persons.

In the study, therefore, both randomly selected persons and persons who had directly contacted us were included. The latter was done to increase the acceptance of the study in the community. To proof possible self-selection bias we have assessed in the Wilstedt and the nationwide study possible moderators and tested their influence on WT noise annoyance, e.g., age, gender, health state, noise sensitivity, distance.

A total of 212 persons participated in the first survey; nearly two-thirds (133 persons) remained in the second one. Accordingly, one-third dropped out (“drop-outs”; 79 participants). It was controlled whether these dropouts represented extreme opinions, indicating a self-selection bias. Indeed, the dropouts differed statistically from the other participants only in terms of education level and household size. The remaining participants had a relatively higher education level and slightly larger household, compared to the dropouts (small effect size each). These socio-demographic variables had no significant influence on the central stress and attitude indicators; significant differences in the central attitude and annoyance assessments did not appear. Accordingly, analysing longitudinal effects with the remaining sample size of the second measurement time is reliable and does not lead to misinterpretation.

3.2.2. Sample characteristics

The respondents’ age ranged from 19 to 88 years, averaging 55 years (SD = 13.19). Slightly more men than women participated (47.6% women, 52.4% men). A completed junior high school qualification was held by 34.3%, 42.9% held university entrance qualifications. The majority owned property, and was married and had children. On average, the participants lived in a three-person household and lived in their community for about two decades. More than half were pensioners or had been exempted from work, one-fifth each being public servant or self-employed. Two-fifths of respondents worked at home. Only a minority of 3.8% benefited financially from the local WT, and no participant was employed by the WT industry. Participants lived an average of 1.90 km to the closest WT (SD = .37, range 1.25—2.89 km). From their homes they saw an average of nearly four WT (M = 3.93, SD = 3.35).

3.2.3. Non-response analysis

104 residents contacted via phone call refused to participate in the survey but answered four short items. More of the non-respondents were women (60.6%) than men (39.4%), and less of them had a view of the WT compared to respondents (61.5% vs. 81.6%). Both groups rather strongly approved of wind farms in general (M > 3 each) but differed in their judgment of the local wind farm: On average, respondents approved of the local WT less (M = .98, SD = 2.14) than the non-respondents (M = 1.51, SD = 1.78, small effect size). Additionally, respondents felt more annoyed by WT noise than non-respondents (M = 1.57, SD = 1.28 versus M = .43, SD = .83, large effect size). This result indicates that residents were more likely to participate when they felt more negatively affected by the local wind farm.

3.3. Questionnaires, stress indicators and moderators

The survey questionnaire included 450 items adopted from previous studies on stress effects of WT emissions (Pohl et al., 1999, 2012). Four residents – two annoyed and two not – gave feedback on a draft version concerning whether it covered their experiences and concerns properly. Based to their statements we revised the questionnaire. The complaint sheet included 25 items self-rating to describe actual noise annoyance. Complaint sheets were offered to each respondent.

3.3.1. Several stress indicators were assessed

a) The general impact of the wind farm was assessed by five items (e.g., "I feel disturbed by the wind farm" or "I experience physical complaints due to the wind farm") on a 5-point scale ranging from “not at all (0)” to “very (4)”.
b) For a general evaluation of WT noise, a semantic differential with four pairs of adjectives was used. The scale ranged from −3 (e.g., „very unpleasant“) to +3 (e.g., „very pleasant“).
c) To assess the overall noise annoyance, participants were asked to rate their noise experience on a unipolar rating scale ranging from 0 ("not at all") to 4 ("very"). In addition, the ICBEN-scale Q. V. ranging from 0 ("not at all") to 4 ("extremely") as well as the ICBEN-scale Q. N. for noise annoyance in the past 12 months (ranging from 0 to 10) were used (Felscher-Suhr et al., 2000; Fields et al., 2001).
d) To indicate temporal changes of the experienced noise annoyance since the wind farm construction a 3-point bipolar scale ranging from −1 („decreasing “) to +1 („increasing “) was applied.
e) To analyse typical situations with WT noise annoyance, participants were asked to provide a description of the noise pattern (nine items; e.g., "rush" or “swishing”), their frequency, the extent of noise annoyance, the day time, weather conditions, impaired activity, arisen emotions, etc.
f) In addition to WT noise, respondents were asked to evaluate other wind farm emissions (12 items; e.g., periodical shadow-casting, aircraft obstruction markings, landscape change) and other local annoyance sources (14 items; e.g., traffic noise, noise from maize choppers), each on a unipolar rating scale ranging from 0 ("not at all") to 4 ("very").
g) A number of 39 psychological and somatic symptoms as well as distractions linked to WT noise were assessed. Symptoms belonged to the domains (a) general performance, e.g., fatigue, concentration, (b) emotions and mood, (c) somatic complaints, e.g., dizziness, nausea, (d) pain, (e) cardiovascular system, and (f) sleep. Additionally, the frequency of the respective complaints was rated, ranging from 0 ("never") to 4 ("about every day"). In the follow-up survey, the same symptoms due to traffic noise were assessed in order to compare the impact of both noise sources.
h) As indicators for low frequency noise, participants were asked to report annoyance due to feelings of pressure and vibrations related to the WT on a unipolar rating scale ranging from 0 ("not at all") to 4 ("very").

i) Cognitive and behavioral coping responses were assessed. Five items indicated four cognitive strategies (unipolar rating scale, from 0 ("not at all") to 4 ("very")), such as trivializing or accepting. Based on 24 items, participants reported if and which behavioral strategies they applied to reduce the annoyance impact, e.g., changing rooms, closing windows or complaints to authorities.

3.3.2. In addition to the stress indicators, several moderators were assessed

a) Physical features: number of visible WT, distance to the nearest wind farm, calculated A-weighted Leq-sound pressure level according to ISO 9613 (1993). The distance was determined using the WT's geographical coordinates, residents' mailing addresses, and Google Earth™.
b) Past passivity or activities either in favor or against the wind farm.
c) Evaluation of the planning and construction phase: Participants were asked about stress and fairness of these processes on eight unipolar rating scales ranging from 0 ("not at all") to 4 ("very").
d) General attitude towards the local wind farm and WT were assessed by two semantic differentials with six pairs of adjectives; each on a bipolar scale ranging from −3 (e.g., „very bad“) to +3 (e.g., „very good“). The two means over the items were used as attitude indicators (Cronbach's alpha .95 and .88). Additionally, residents were asked if they financially participated in the local wind farm and if they are working in the wind energy business.
e) Health indicators: The general health state was rated on a unipolar scale ranging from 0 ("bad“) to 4 ("excellent"). For the assessment of noise sensitivity the mean of six items inspired by Zimmer and Ellermeier (1997, 1998) were used. Emotional lability was evaluated by a six item test of Trautwein (2004).

3.3.3. Complaint sheet, audio recordings, emission and immission measures

Participants were instructed to fill out the complaint sheet in case of WT noise annoyance (25 items), including items to measure annoyance, noise pattern, disturbed activities, symptoms and weather conditions. Residents also could borrow an audio recorder in order to record annoying noises induced by WT. The audio recordings were evaluated by experienced specialists from DEWI and correlated with operating data from the wind farms (e.g., wind direction, wind speed at hub height and at 10 m height, rotor speed). In the period from March 2012 to January 2013 a total of 98 complaint sheets were filled in by 11 participants, two of whom made a total of 28 evaluable audio recordings. In addition, DEWI performed emission measurements according to IEC 61400-11 Ed. 2.1 and immission measurement on the property of a strongly annoyed resident.

3.4. Statistical analyses

To analyse group differences in the case of interval-scaled variables, descriptive statistical values were used such as the arithmetical mean (M), empirical standard deviation (SD), and standard error of mean (SEM). In the case of nominal-scaled variables, absolute and relative frequencies (%-values) were reported. Pearson-correlations were calculated to identify moderator variables – only coefficients equal to or greater than .30 were regarded as relevant (medium effect size according to Cohen (1988)).

Chi^2-tests were used for inferential analysis of frequency distributions. To analyse mean group differences, analysis of variance (ANOVA) with repeated measurement was conducted. Least significant difference *t*-tests (LSD) were used for post hoc comparisons for ANOVA's means. A priori planned mean comparisons of two groups were analysed by *t*-tests.

Data analysis and description followed the principles of Abt's (1987) “Descriptive Data Analysis.” Correspondingly, reported p-values (p) of the two-tailed significance tests only possess a descriptive function labelling the extent of group differences. Despite the multiplicity of significance tests, no alpha-adjustment was conducted, since the present analysis was not a confirmatory data analysis. P-values ≤ .05 were described as significant; p-values greater than .05 and less than .10 described as a trend. Additionally, the effect size parameters, d, and w were used to report practical significance (Cohen, 1988). The effect size categories (small, medium, large) mentioned in the results section always refer to significant group differences. Effect sizes d and w were calculated by Excel procedures. The statistical software SPSS was used for any other analysis.

4. Results

4.1. WT noise annoyance

Of all participants 69.3% perceived WT noise and 30.7% did not; 18.4% of total sample were not annoyed at all by WT noise (scale-point 0), 16.0% were slightly annoyed (scale-point 1), 17.9% were somewhat annoyed (scale-point 2), 10.9% were moderately annoyed (scale-point 3) and 6.1% very annoyed (scale-point 4). According to the scale criteria of Miedema and Vos (1998), 34.9% of all participants were annoyed (scale-points 2–4). However, from a stress psychological perspective, the possible appearance of symptoms should be considered as an additional criterion for strong annoyance. Therefore, we define participants with no symptoms and scale values 2–4 as “somewhat annoyed” (25.0%). If additionally, at least one symptom linked to WT noise occurred the participant was indicated as “strongly annoyed” (9.9%).

For the total sample in 2012, the average WT noise annoyance was between the levels “slightly” and “somewhat” (M = 1.58, SD = 1.28), mean score on the ICBEN-scale Q. V. was at the level “slightly” (M = 1.23, SD = 1.14) and on the ICBEN-scale Q. N. at the lower end at 3.26 (SD = 2.67). The group of strongly annoyed participants had slightly higher mean values than those of the somewhat annoyed (medium and large effect size). Since the three annoyance scales were strongly correlated (.84 to .91), only the values of the WT noise annoyance scale will be reported in the following. Until 2012, the participants on average had not observed any change of annoyance over the years of operation of the wind farm (M = .02, SD = .41). Between 2012 and 2014 there was a marginal perceived change. Only the somewhat annoyed participants experienced a slight decrease in annoyance (large effect size, Fig. 1).

4.2. WT noise annoyance in comparison to other local noise sources

For participants perceiving WT noise the wind farm was as annoying as local road traffic noise, maize choppers, and sand trucks, but marginally less annoying than balloon-wheel trucks (small effect size, Fig. 2). The annoyance caused by WT and sand trucks decreased marginally from 2012 to 2014 (small effect sizes) but not for road traffic noise and other sources.

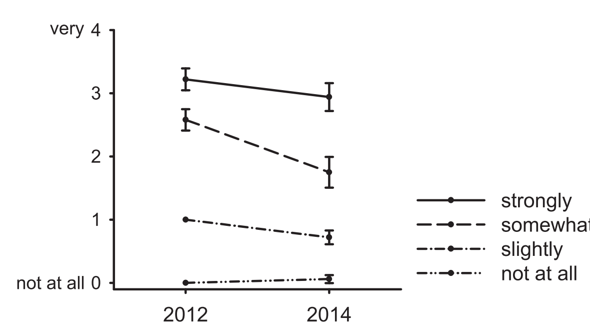

Fig. 1. Change of WT noise annoyance decrease for somewhat group only (M ± SEM, scale range: 0–4).

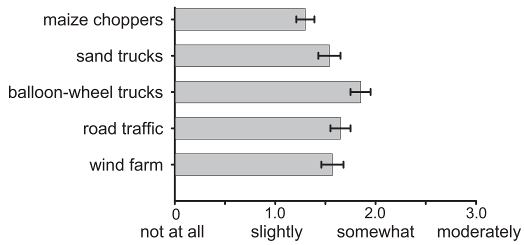

Fig. 2. WT noise annoyance lower compared to balloon-wheel trucks (2012, M ± SEM, scale range: 0–4).

4.3. Typical WT noise situation

About half of all participants (51.9%) reported in 2012 at least one typical annoying situation caused by WT noise. About half (53.6%) of this sub-sample experienced annoying noise about once a week, one-fifth (20.9%) about once a month, and 13.6% almost daily. Annoying noise occurred most frequently in the evening (33.6%) and at night (18.2%). This sub-sample felt most frequently disturbed while sleeping (30.0%), relaxation (24.5%) and leisure activities (19.1%). Most frequent emotional reactions were irritability or anger (39.1%). More than 10% of the sub-sample described WT noise as swooshing (76.4%), rumbling (72.7%), buzzing (23.6%) or grumbling (18.2%). Most frequently, the annoyance occurred during westerly winds (68.2%) – the local main wind direction – as well as during humid weather (30.9%) and frost (13.6%). The number of participants who reported a typical WT noise situation decreased clearly from 2012 to 2014 by about 22–29.3%. The pattern of noise effects remained comparable.

4.4. General impact of WT noise

In 2012, the somewhat and strongly annoyed residents assessed WT noise clearly to be more negative than the other groups (Fig. 3, medium or large effect sizes). Furthermore, the strongly annoyed participants rated WT noise more "threatening", "harmful" and "intolerable" than the somewhat annoyed residents (medium effect sizes). Significant changes over time were only detected for the group without annoyance, which rated WT noise in 2014 slightly less peaceful and harmless than in 2012 (medium effect sizes).

4.5. Psychological and somatic symptoms

As mentioned above, only a few participants reported (9.9%) psychological or physical symptoms that they attributed to WT noise and which they experienced at least once a month (Table 1). In 2014, this

Table 1
Percentage of symptoms caused by WT noise or traffic noise at least once a month.

Symptoms	WT noise 2012	WT noise 2014	traffic noise 2014
general mental indisposition	5.7%	0%	6.0%
reduced performance and work capacity	5.2%	0%	3.0%
fatigue	5.2%	0%	4.5%
lack of concentration, reduced sustained attention	4.7%	0%	3.8%
nervousness	4.2%	0%	4.5%
tenseness	5.3%	2.3%	6.8%
negative mood	6.6%	0%	7.5%
helplessness	4.2%	3.8%	6.0%
irritability, anger, hostility	5.7%	3.0%	7.5%
general somatic indisposition	5.3%	0%	.8%
hindered falling asleep	6.7%	3.0%	3.8%
multiple awakening	4.7%	1.5%	5.3%
reduced sleep quality	6.1%	2.3%	6.0%
reduced depth of sleep	5.7%	1.5%	4.5%
overall symptom carriers	9.9%	6.8%	15.8%

proportion decreased to 6.8%. With an average of 12 symptoms, these participants clearly reported more symptoms in 2012 (M = 12.33, SD = 8.03) than in 2014 (M = 3.00, SD = 1.94, large effect size). Furthermore, strongly annoyed participants rated their general health slightly better in 2014 (2012: M = 2.00, SD = .71; 2014: M = 2.59, SD = 1.06; medium effect size). The symptoms were related to general performance, emotion, mood and sleep. From 2012 to 2014, sleep disturbance decreased, and symptoms of impaired performance did not recur. Strongly annoyed participants were not affected more by acute or chronic diseases than the other groups.

Distraction due to noise can lead to stress experience. The strongly annoyed residents in 2012 felt somewhat distracted by WT noise (M = 1.88, SD = 1.01), clearly stronger than any other group (large effect sizes). For this group the distraction decreased slightly from 2012 to 2014 (medium effect size, Fig. 4), while it remained relatively low and unchanged in the other groups.

Only a few participants showed evidence for low-frequency WT noise effects (< 100 Hz): in 2012, 8.5% reported wind farm-related feelings of pressure and 6.1% experienced vibrations in the body. Over time, these proportions decreased to 6.8% and 3.8%, respectively. The experienced annoyance induced by pressure feelings or vibrations was somewhat (2012: M = 2.17, SD = .86; M = 1.85, SD = 1.07 respectively; 2014: M = 2.00, SD = 1.12; M = 2.40, SD = 1.52 respectively). The symptom "dizziness" was not observed. Therefore, no indicator for a negative vegetative effect of low-frequency noise could be detected (Krahé et al., 2014).

In order to evaluate stress effects appropriately, WT noise was compared with traffic noise. More participants experienced symptoms induced by traffic noise (15.8% of total sample) than WT noise; in 2014 only three participants reported complaints induced by both sources. In

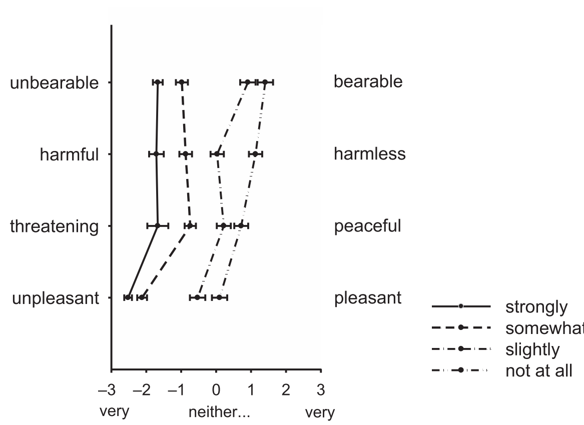

Fig. 3. WT noise impact most negative for strongly annoyed group (2012, M ± SEM, scale range: −3 – +3).

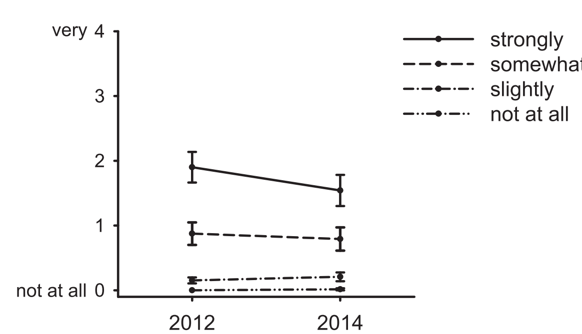

Fig. 4. Decrease of distraction induced by WT noise in the strongly annoyed group (M ± SEM, scale range: 0–4).

Fig. 5. Inefficient coping strategies in the strongly annoyed group (2012, M ± SEM, scale range: 0–4).

2014 about one-third (34.9%) of all participants was somewhat annoyed by traffic noise and 21.2% by WT noise. The pattern of symptoms for WT noise (2012) and traffic noise (2014) is very similar (Table 1).

4.6. Coping responses

Somewhat and strongly annoyed residents reported only little acceptance ("made peace", "all that bad") of WT noise in 2012 and observed it more critically than the other groups (Fig. 5, small to large effect sizes). Compared to the other groups, the somewhat annoyed participants showed a stronger emotional reassurance (i.e., had "stopped getting excited"; small to large effect sizes), which slightly increased from 2012 to 2014 (small or medium effect sizes). In contrast, cognitive coping for the strongly annoyed participants remained relatively stable. Thoughts of moving due to WT noise were only weak, even among the strongly annoyed residents (M = .81, SD = 1.25).

The most commonly used measures to reduce noise effects in 2012 were conversations with family members, friends and neighbors (32.1% of all participants), closing windows (25.9%), place leaving inside and outside the house(11.8%, 7.1%), and turning up the volume of the radio/TV (7.5%). In the groups of the somewhat and strongly annoyed participants, relatively more residents participated in conversations and closed their windows relatively more often (large effect sizes). Other measures taken were collecting signatures (13.7%) and demonstrating (9.4%), gathering information on WT noise (9.9%), and engaging in an environmental group/citizens' action committee (6.1%).

4.7. Analysis of complaint sheets and audio recordings

Ninety-five complaint sheets from 11 residents were included in the analysis, as well as 28 evaluable sound recordings from two participants. Almost all the records were made at night. WT operating data and measurements of wind speed and wind direction at hub height as well as at 10 m above ground level were included in the analysis. For the full report of this part of the project, see DEWI RS14-00017-01 (Gabriel and Vogl, 2014). Most of the complaints occurred during a southwesterly wind, which is the main wind direction, and at wind speeds at hub height of 6–9 m/s. There was a slight tendency to annoyance when the wind blew from the direction of the wind farm (downwind). The complaints occurred mainly during the night and early morning hours (83%), accumulating in the period from midnight to 3 a.m. The large number of nocturnal complaints can be explained by low background noise at nighttime, because Wilstedt is located far from any main road. Therefore, there is almost no nighttime traffic noise masking the relatively low level of sound from the WT.

Regarding the performed sound analyses, neither loudness of the broadband acoustic noise from the WT nor tonality or impulsivity is responsible for the documented complaints. Annoying WT noise has been characterized as predominantly irregular and fluctuating in loudness (71.6% pulsating swooshing). Thus – as opposed to national noise immission control regulation – it is not an absolute value of loudness, but the variation of loudness with the frequency of the rotating rotor blades, that primarily causes complaints. The perceived changes of sound are directly associated with the rotating blades. This noise characteristic is called amplitude modulation (AM). Special algorithms developed by DEWI (Vogl, 2013) were used to quantify AM in the sound recordings of perceived annoying WT noise. Examples are shown in Figs. 6 and 7 with AM for minutes or sporadic AM lasting a few seconds (typically < 10 s). This method of analysis is described in detail in report DEWI RS14-00017-01 (Gabriel and Vogl, 2014). The first algorithm calculated the physical modulation depth ΔL in dB after A-filtering. This measure is defined as the difference between the maximum and the following minimum of the sound pressure level (lower line). The second algorithm calculates the level of the pure psychoacoustic loudness variation F* (upper line) which is very similar to the fluctuation strength F developed by Zwicker and Fastl (1999).

The highest modulation depth ΔL was found in the frequency range 160–200 Hz, at wind speeds at hub height between 6 to 9.5 m/s, and WT rotational speed in the range of 14–18 U/min (average 16.2 U/min). Therefore, it can be concluded that maximum modulation occurred just below nominal rotational speed of the WT. A significant correlation of AM and wind direction could not be detected. The highest ΔL and F* values were found during nighttime.

AM can be used to explain the annoyance of WT noise (Fig. 7). We get used to regular stimuli and do not pay attention to them. New, unexpected and irregular stimuli attract attention. They trigger an orientation reaction and an alarm reaction in the case of a danger signal. The attention is directed unconsciously to such signals. This process can lead to a distraction of actions that are taking place.

4.8. General attitude towards WT and the local wind farm

In 2012 respondents reported on average a positive general attitude towards WT (M = 1.51, SD = 1.02) which remained positive with increasing annoyance level. The somewhat (M = 1.00, SD = 1.02) and strongly annoyed participants (M = .44, SD = .94) differed clearly from each other and the other three groups (medium and large effect sizes). For the somewhat annoyed residents, the attitude was marginally more positive in 2014 compared to 2012 (small effect size). No significant change was detected for the other groups. Participants reported strong involvement for the topic of wind energy (M = 3.09, SD = .78) – without significant differences between strongly annoyed (M = 3.22, SD = .76) and non-annoyed residents (M = 3.34, SD = .66).

Also regarding the local wind farm, participants reported on average a positive general attitude in 2012 (M = .73, SD = 1.64). Accordingly, attitudes towards wind energy and the local wind farm were highly

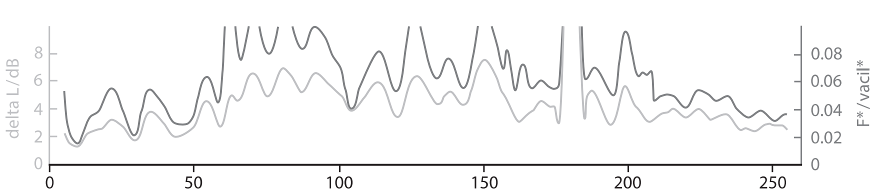

Fig. 6. Example for AM with strong modulation for minutes.

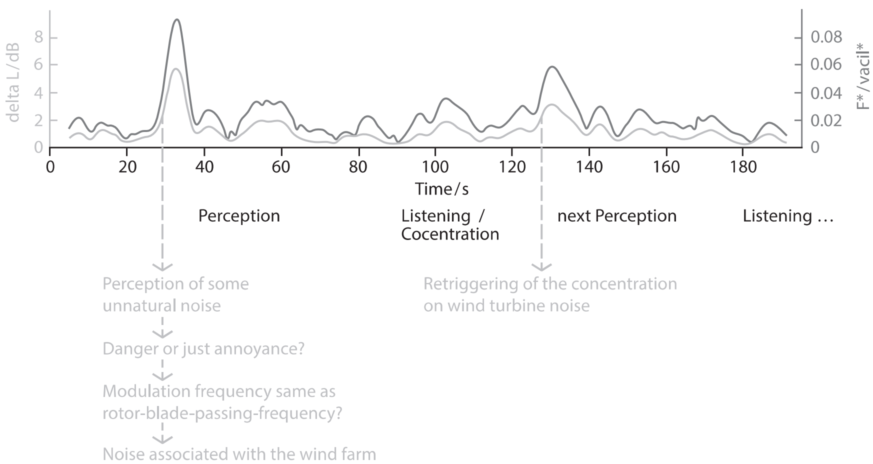

Fig. 7. Example for AM with short time perceptible modulation (upper part) and a description of the perception process of WT AM (lower part).

correlated (r = .83). In contrast, the somewhat and strongly annoyed residents showed a slightly negative attitude towards the local wind farm (M = −.60, SD = 1.42; M = −1.12, SD = 1.13 respectively) and differed clearly from each other and from the other three groups (small or large effect sizes).

Additionally, the participants were explicitly asked whether they had been wind farm opponents or proponents. Proponents (40.2%) were slightly more often represented than opponents (35.8%). Only a minority of 16.7% was ambivalent; 7.4% had no opinion on the wind farm. A further subdivision by active versus passive showed that opponents were more often active than the proponents: 30.4% of respondents indeed had been in favor of the wind farm but remained passive, and only a small proportion turned to be active (9.8%). Conversely, 26.5% had been active opponents and only 9.3% remained passive. It is noticeable that the majority of strongly annoyed residents (75.0%) had been passively or actively against the wind farm, whereas only 34.2% of the other participants showed active or passive behavior against the wind farm (small effect size).

4.9. Moderators

The analysis of relations between physical features and WT noise annoyance showed only small correlations for “distance to the closest WT“ (r = –.13) and “calculated A-weighted sound pressure level (SPL)” according to ISO 9613-2 (1993, r = .27). The SPL was on average 29.29 dB(A) (SD = 2.58, minimum = 10.23, maximum = 36.40). The correlation with “number of visible WT” was slightly stronger (r = .40).

There was a moderately negative relation between general attitude towards the local wind farm and WT noise annoyance (r = –.71). Further relevant correlations were found between “strain during the planning phase” (r = .37), “strain during the construction phase” (r = .34), “planning has been fair concerning one's own interests“ (r = –.52), “planning has been fair concerning community's interests” (r = –.52) and WT noise annoyance.

There were only small correlations between health indicators and WT noise annoyance (general health state, r = –.12; noise sensitivity, r = .26; emotional lability, r = .05), age (r = .20), and occupancy (r = .08). Women reported slightly stronger WT noise annoyance than men (M = 1.80, SD = 1.27 versus M = 1.36, SD = 1.25, small effect size).

4.10. Wilstedt sample in comparison with nationwide sample of residents of 13 wind farms

Overall, both groups rated the level of annoyance of the different WT emissions as very low to somewhat (Fig. 8). Concerning WT noise annoyance, the two groups did not differ significantly. Compared to the nationwide sample (Pohl et al., 2012), the Wilstedt sample reported

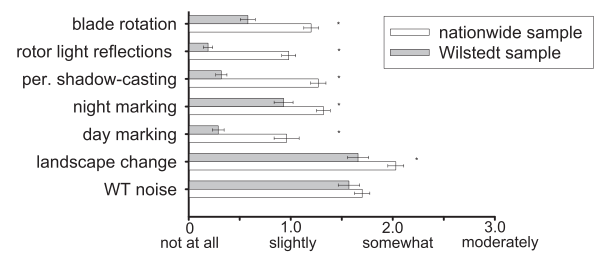

Fig. 8. Annoyance due to WT emissions comparing a nationwide and case sample (M ± SEM, scale range: 0–4, * p < .05).

significantly less annoyance due to landscape change, day and night obstruction marking, periodical shadow- casting, rotor light reflections and blade rotation (small and medium effect sizes). For both samples no statistically significant correlations were found between annoyance induced by different emissions and the distance to the nearest WT (all r < absolute value .25).

The general attitude towards the local wind farm was rated slightly positive in both groups without significant difference (Wilstedt sample: M = .43, SD = 1.67; nationwide sample: M= .30, SD = 1.92).

The general attitude towards WT was clearly positive in both groups. In the Wilstedt sample (M = 1.95, SD = .95) the attitude was slightly more positive than the comparison group (M = 1.43, SD = 1.61, small effect size). For the nationwide sample there was a strong correlation between the general attitude towards wind energy and the local wind farm (r = .78).

The gender distribution was comparable in both surveys. On average, respondents of the comparison group were four years younger than respondents of the Wilstedt sample. This difference, however, is too small to invalidate the interpretation of group differences in the mentioned features.

In conclusion, the comparison between both samples indicates Wilstedt to be a typical sample regarding WT noise annoyance. Therefore, the results regarding WT noise annoyance can be generalized. The other WT emission sources were rated more positively in the Wilstedt sample than in the nationwide sample. Therefore, the Wilstedt results for those other sources should not be generalized.

5. Discussion and recommendations

The present study is the first to extensively and differentially analyse the impact of WT noise on the experience and behavior of wind farm residents using an inter- and transdisciplinary approach. We have included a systematic approach to analyse stress effects in combination with noise audio recordings by residents and calculated sound pressure levels. It is also the first study to explore possible stress effects due to WT noise over the course of two years.

Only for a small percentage of all residents could strong WT noise annoyance be observed, which even decreased over time: in 2012 one-tenth (9.9%) was strongly annoyed, and two years later, this was true for only 6.8% of the residents. However, the WT were by no means the most potent local noise source – local traffic noise was strongly annoying for 15.8% of all participants. Residents belonging to one of the groups of strongly annoyed participants not only felt at least somewhat annoyed but also reported stress symptoms. Both noise sources – WT and traffic – led to a similar pattern of symptoms that is typical of noise effects (reduction in performance, concentration, and the incidence of irritability/anger, negative mood and disturbed sleep; Stansfeld and Matheson, 2003; Stansfeld et al., 2012). A similar pattern has already been shown in a previous study (Pohl et al., 1999). Regarding disturbed sleep, a comparable percentage (4–6%) was found in the large Dutch study by Bakker and colleagues – in this study they also found a very similar percentage of symptom-carriers due to traffic and engine noise (15%; Bakker et al., 2012). The similar results give a hint that the results could be generalize. Furthermore, the percentage of strongly WT noise-annoyed participants in Wilstedt is between the percentage of strongly annoyed residents in Switzerland (4.5%; Hübner and Löffler, 2013) and in the German state Schleswig-Holstein (15.7%; Pohl et al., 1999). The higher percentage of the Schleswig-Holstein sample is likely due to the older design of the WT and the differences regarding official directives – here the directives regarding the limitation of periodically shadow-casting of WT which was put into effect, taking into account the results of the study. The present results not being a special case is additionally proven by the comparison the Wilstedt-sample with a nationwide German sample of residents of 13 wind farms (Pohl et al., 2012). Thus, the present results suggest a generalization. The results of both studies were not distorted by extreme opinions (e.g., the general attitude towards the local wind farm or annoyance ratings). WT noise annoyance was not significantly correlated to age, general health state, emotional lability, and noise sensitivity. Overall, we concluded that our results are not influenced by a strong self-selection bias.

To better understand why some residents feel more annoyed by emissions of WT than others, we divided the participants into subgroups regarding noise perception and the level of annoyance. Compared to other groups, the strongly annoyed residents showed the strongest stress effects due to WT noise and an overall more negative evaluation of the wind farm. It can be assumed that stress began during the planning phase of the wind farm and was maintained throughout. This assumption is supported by the findings that this group had perceived a stronger annoyance due to the planning, approval and construction phase of the wind farm. Furthermore, 75% of the strongly annoyed residents reported to be actively or passively against the wind farm in the past. They showed comparatively less positive cognitive coping in terms of WT noise. As part of a stress management training, positive cognitive coping could be supported, as existing approaches show (Leventhall et al., 2008, 2012). However, the affected residents in our study responded with limited interest to such a remedial offer. Rather, a positive implementation of the planning and construction phase is more urgently recommended. There are positive experiences with early and informal resident participation (Devine-Wright, 2011; Rand and Hoen, 2017; Rau et al., 2012).

Even informal participation cannot guarantee that residents will experienced the planning process positively. Without serious resident participation, however, additional problems are more likely. For, as proven by the present results, the majority of the residents showed a positive attitude towards WT on the condition that their concerns are taken seriously. An often recurring concern by residents is the noise impact of WT. The present study was a response to the residents' complaints in Wilstedt. Their implementation and results are likely to have contributed to a decline in annoyance. Only little change in the evaluation of the wind farm was observed from 2012 to 2014. For the somewhat annoyed residents, noise annoyance decreased slightly and cognitive coping improved. For the strongly annoyed participants there was a reduction in WT noise-related distraction. The reduction of residents with noise related symptoms from 10% to 7%, and the decrease in the average number of symptoms from 12 to 3, can be interpreted as a significant change. We attribute the positive change – even after talking to some complainants – to the residents' positive evaluation of the study and the chosen approach and to the residents' active support and involvement.

For instance, the disturbing noises were independently recorded by residents and later analysed by us. Residents were informed about preliminary results (community meeting, letter with presentation of results). Additionally, plausible explanations for WT noise annoyance were offered and discussed in the plenum (e.g., AM). The aforementioned participation regarding the research process may have contributed to the positive changes. For the reported results reduced uncertainties and possible alternating interpretations of the findings and thus somewhat indirectly decreased WT noise annoyance. To our knowledge it is the first known field experiment showing that empirical information helps residents to reduce stress induced by WT noise.

This study does not provide any empirical evidence for the repeatedly asserted relationship between annoyance or acceptance of WT and distance to the residence. There is no numerically strong relationship between noise annoyance and the distance to the nearest WT or the estimated sound pressure level. Additionally, studies by Pohl et al., (1999, 2012) and Hübner and Löffler (2013) proved WT noise annoyance to be independent from the distance ($r = .03$; –.07; –.10), suggesting the existing emission protection laws are effective in general. For example, the German emission protection law determines the limits for permissible sound levels, which, among other features, determines the minimum distance.

However, an important indicator regarding the analysis of the causes was provided by the acoustic analysis of the disturbing WT noise, which has been recorded by the residents. A cause for the WT noise annoyance might be the amplitude modulation (AM), which explains the origin of certain annoying noise patterns. One explanation why AM cause annoyance is, that short-term amplitude changes may attract the residents' attention and thus disturbs current behavior. Research should be deepened in order to better understand the mechanism of action and develop technical solutions.

It became clear that there is detectable disturbing noise associated with the AM (from an acoustic point of view), but not with infrasound. Today, the data base of freely available AM data is very small (e.g., Cand et al., 2013). Further studies on AM of WT noise should broaden the database. For this, a long-term monitoring station needs to be developed that continuously records WT noise and residents' complaints.

Parallel to the sound detection, wind farm operating data and the wind speed profile (LIDAR) should be recorded in high solution, in order to improve understanding of the mechanisms of AM and check for possible dependency of the AM from the wind profile. Another interesting aspect is the overall interaction of WT in a wind farm with sporadic short modulation periods. For instance it is unknown whether AM is supported by the turbulent wake or the interaction of several WT. From the synopsis of meteorology data and WT operating data as well as sound data, knowledge regarding the causes of AM and their possible mitigation strategies can be derived.

For the development of noise mitigation strategies, the measurability of AM with an appropriate assessment tool is a necessary condition. The used algorithm must be improved because e.g., currently only the sinusoidal modulation is considered (for other methods proposed see e.g., Amplitude Modulation Working Group, 2016; Fukushima et al., 2013; Tachibana et al., 2014). To validate the evaluation of non-sinusoidal modulations and other tool modifications (in order to provide an AM-evaluation standard), hearing tests should be performed.

Overall, it appears promising to further develop the research approach used to understand in a more differentiated manner the psychological and acoustic causes and their interaction in the development and maintenance of WT noise annoyance. The present study provides insight into the mechanisms causing noise annoyance. However, replication studies are needed to further explore why some residents are strongly annoyed by WT noise and others are not, especially in comparison to traffic noise. Furthermore, the long-term effects are to be probed, e.g., whether or not and under what conditions habituation or sensitization occurs. To explore the influence of WT noise on sleep the method of ambulatory sleep monitoring would be useful. In this respect, first steps were made in the Health Canada study (2014) and in a study by Jalali et al. (2016). Both field studies did not find any relation between objective sleep parameters and WT noise exposure. Additionally it would be possible to supplement the research by including seismological studies in order to explore the transmission of low-frequency noise (< 100 Hz) through soil layers. Although no evidence of symptoms that would indicate low-frequency noise were reported by the participants, in order to address the concerns of WT opponents, low-frequency noise measurements are recommended for further studies. Overall the installation of a long-term monitoring station for WT noise as well as further studies on the effects on local residents (in the meaning of "Homo sapiens monitoring") seem to be advisable. Homo sapiens monitoring is not recommended by the authors only but encouraged by the local residents.

Finally, it should be noted that strongly annoyed residents and explanations for the causes of their annoyance could be identified by means of the presented research paradigm. This approach complements the previous, rather epidemiological research on this subject (e.g., Pedersen and Persson Waye, 2004; Pedersen et al., 2009).

The most important and immediately realizable recommendation is to make the planning and construction process more of a positive experience for the residents. Thereby operators and authorities can preventatively reduce the likelihood of complaints after construction of the wind farm. Creating a more positive planning process includes the early and informal participation of residents and the consideration of their concerns. Although more residents seem to be strongly annoyed by traffic noise than by WT noise, a further improvement of WT technology is desirable. After all, the present study shows that citizens are not only in favor of wind energy in general but also support local installations, as long as they are developed sustainably.

Most important, the present results shows that noise annoyance can be reduced by providing empirical information to the residents.

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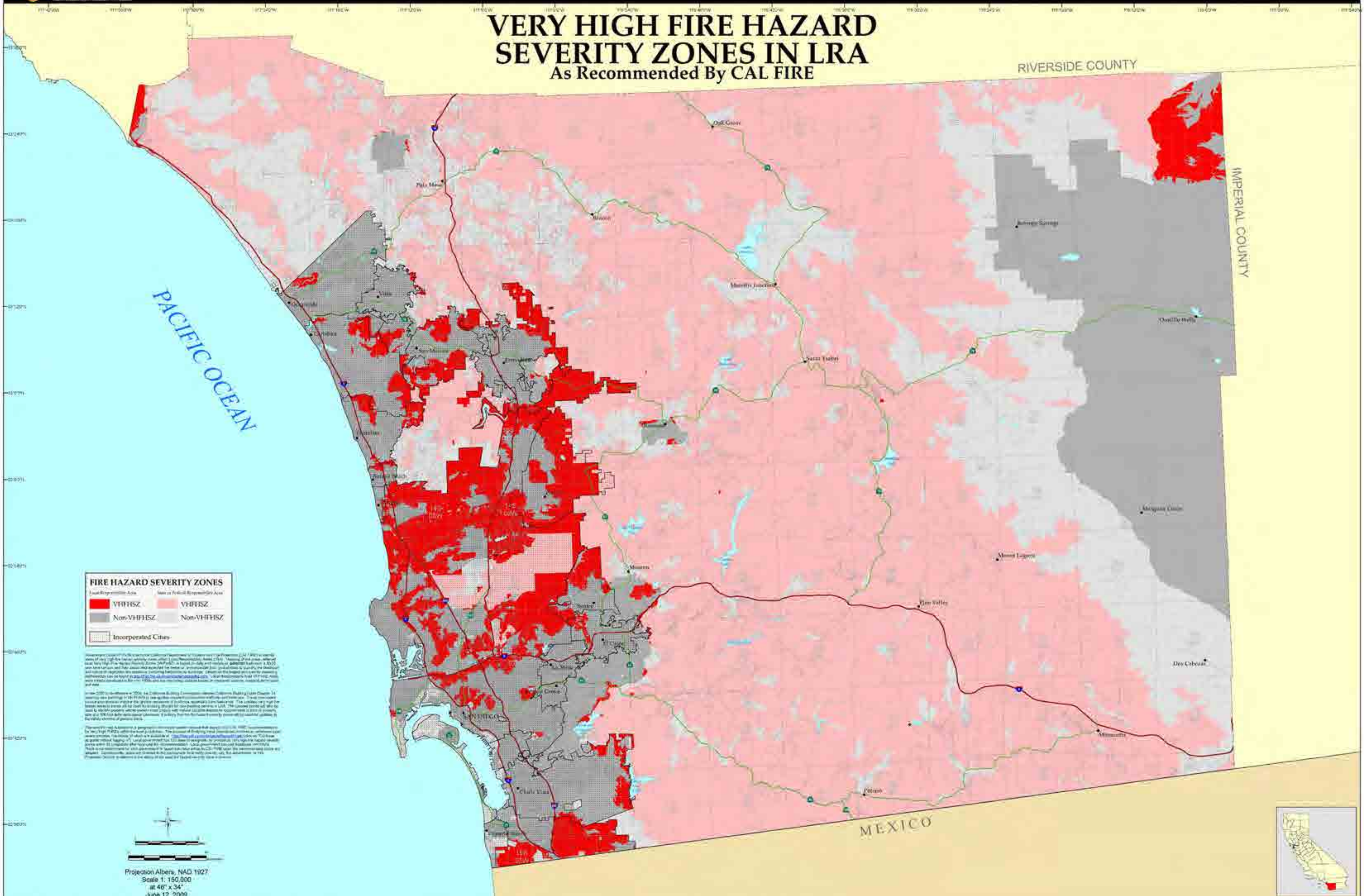
EXHIBIT
4

SAN DIEGO COUNTY



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Research Paper

Influence of visibility of wind farms on noise annoyance – A laboratory experiment with audio-visual simulations

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ABSTRACT

Noise annoyance reactions in the population due to wind farms are related to visual as well as noise-related impacts of the farms. Improved understanding of these effects may support the planning of better accepted wind farms. Recently, tools for visualization and auralization of wind farms have been developed that allow mutually studying audio-visual effects on annoyance. The objective of this study was to investigate the audio-visual effects of different wind turbine noise situations on short-term noise annoyance in a psychophysical laboratory experiment, considering serial position effects (simple order and differential carryover effects). A set of 24 audio-visual situations covering a range of acoustical characteristics (sound pressure level, periodic amplitude modulation) and visual settings (landscape with visible wind turbine, landscape only, grey background) was created. The factorial design of the experiment allowed separating audio-visual effects from serial position effects on noise annoyance. Both visual and acoustical characteristics were found to affect noise annoyance, besides the participants' attitude towards wind farms. Sound pressure level and amplitude modulation increased annoyance, the presence of a visualized landscape decreased annoyance, and the visibility of a wind turbine increased annoyance. While simple order effects could be eliminated by counterbalancing, the initial visual setting strongly affected the annoyance ratings of the subsequent settings. Due to this differential carryover effect, visual effects could be assessed reliably only as long as the participants saw the initial visual setting. Therefore, the presentation order of audio-visual stimuli should be carefully considered in experimental studies and in participatory landscape planning.

1. Introduction

The production of wind energy is growing worldwide. Between 2001 and 2016, the wind power capacity increased by a factor of 20, from some 24 to 487 GW (GWEC, 2017). As a result, landscapes suffer growing visual impacts, and increasing portions of the population are exposed to wind turbine (WT) noise. The visual and noise-related impacts of wind farms have therefore been much discussed in recent years. Regarding health effects of WT noise, noise annoyance seems most prevalent (van Kamp & van den Berg, 2018).

Literature from field surveys suggests that annoyance reactions to WT noise are often stronger than to transportation noise at comparable noise levels (van Kamp & van den Berg, 2018). Annoyance to WT noise was therefore extensively studied in field surveys (e.g., Hongisto, Oliva, & Keränen, 2017; Janssen, Vos, Eisses, & Pedersen, 2011; Klæboe & Sundfør, 2016; Michaud et al., 2016) as well as in laboratory experiments (e.g., Ioannidou, Santurette, & Jeong, 2016; Lee, Kim, Choi, & Lee, 2011; Schäffer et al., 2016; Schäffer, Pieren, Schlittmeier, & Brink, 2018). The studies reveal that annoyance reactions depend on various factors. First, specific acoustical characteristics of WT noise, which mainly consists of aerodynamic broadband noise, contribute to annoyance. Here, periodic amplitude modulation (AM), i.e., quasi-periodic temporal level fluctuations sometimes encountered, is particularly important. Periodic AM occurs at the blade passing frequency (~ 1 Hz). It comprises high-frequency "swishing" sound, sometimes also referred to as "Normal Amplitude Modulation", and more impulsive, mid- to low-frequency "thumping" sound ("Other Amplitude Modulation") (Bowdler, 2008; Oerlemans, 2015). It was found to be particularly annoying (Ioannidou et al., 2016; Lee et al., 2011), possibly by provoking the subjective hearing sensation "fluctuation strength" (Fastl & Zwicker, 2007). But also spectral characteristics such as low-frequency components may affect annoyance (Møller & Pedersen, 2011; Schäffer et al., 2018). Second, the visibility of WTs plays a crucial role (Janssen et al., 2011; Michaud et al., 2016; Pedersen & Larsman, 2008). Third, the living environment of residents (hilly vs. flat terrain) may affect reactions to noise

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(Pedersen & Larsman, 2008). Finally, also personal factors such as noise sensitivity (Miedema & Vos, 2003), attitude (Pedersen & Persson Waye, 2004) or familiarity with WT noise (Maffei et al., 2015), situational factors such as economic benefit (Janssen et al., 2011), and even expectations on caused health effects (Chapman, St George, Waller, & Cakic, 2013) were shown to be linked to noise annoyance.

Specific effects on noise annoyance can be effectively studied in controlled laboratory experiments. Compared to field surveys, laboratory experiments have the advantage of high control of the (noise) exposure as well as exclusion/control of effect modifiers (e.g., visibility of WTs or living environment, see above). In the past, such experiments often focussed either on the effects of acoustical characteristics of WT noise (classically in psychoacoustic studies where visual impacts may be deliberately excluded; see, e.g., Schäffer et al., 2016) or on visual impacts of wind farms (classically in landscape and environmental sciences and planning, focusing on social acceptance and visual preferences for WTs; see, e.g., Molnarova et al., 2012; Betakova, Vojar, & Sklenicka, 2015; and Scherhaufer, Höltinger, Salak, Schauppenlehner, & Schmidt, 2018). Besides the scientific interest, the results of these studies suggest practical recommendations for site planning of wind farms, such as regarding number, height, and placement of wind turbines in a landscape. However, considering audio-visual aspects mutually in such laboratory studies is important as both contribute to the perception of the studied situations (Lindquist, Lange, & Kang, 2016).

In recent years, laboratory experiments on mutual audio-visual effects on (noise) annoyance were conducted (He, Leickel, & Krahé, 2015; Maffei et al., 2013; Preis, Hafke-Dys, Szychowska, Kociński, & Felcyn, 2016; Ruotolo et al., 2012; Sun, De Coensel, Echevarria Sanchez, Van Renterghem, & Botteldooren, 2018; Szychowska, Hafke-Dys, Preis, Kociński, & Kleka, 2018; Yu, Behm, Bill, & Kang, 2017). The studies revealed that both, acoustical characteristics and visual settings, including the visibility of the noise source, affect (noise) annoyance. Here, one should consider that the experimental design, in particular the presentation order, may strongly affect the outcomes. When a number of stimuli is subsequently presented, two serial position effects may appear: simple order and/or differential carryover effects (Cohen, 2013). Simple order effects may result, e.g., from fatigue or practice. They can be averaged out and thus eliminated by counterbalancing (Cohen, 2013), either completely or partially (Latin squares), or by randomization if samples are large. For pure psychoacoustic experiments with a large number of stimuli, randomization is common practice (e.g., Nordtest, 2002). For psychophysical experiments involving also visual stimuli, in contrast, the effect of playback order may be less straightforward. Here, differential carryover effects may occur, where the rating of the stimulus is affected by previous stimuli. Differential carryover effects differ depending on the order of the stimuli. They cannot be eliminated by counterbalancing (Cohen, 2013). Here, either a sufficiently large time delay between treatments, putting a neutral task between stimuli for distraction, or a between-subjects design (i.e., assigning different participants to different stimuli) may be necessary (Cohen, 2013). As far as we know, however, studies on audio-visual effects of environmental noise sources (including WTs) did not systematically account for this effect to date.

The objective of the present study therefore was to investigate the audio-visual effects of WT noise situations on short-term noise annoyance, considering also possible serial position effects. Our hypotheses were that (i) acoustical characteristics alone contribute to noise annoyance, and that (ii) visual settings may act as effect modifiers for noise annoyance. To test these hypotheses, different situations with WT sound covering a range of acoustical characteristics (sound pressure level, periodic AM) and visual settings (landscape with a single visible WT, landscape only, grey background) were studied in a psychophysical laboratory experiment, which allowed separating the effects of the studied variables on noise annoyance.

Table 1
Factorial design of the psychophysical tests with 24 audio-visual wind turbine (WT) stimuli covering a range of sound pressure levels (L_{Aeq}) of 33.0–49.4 dB, two situations ("no" and "with") of periodic amplitude modulation (AM) of the sound, and three visual settings (WT = landscape with WT; LS = landscape only, Grey = grey background). The table shows the L_{Aeq} in dB per variable combination (same values for the three visual settings), resulting from observer distances to the WT of 100–600 m.

Distance to WT [m]	Periodic AM					
	no			with		
	Visual setting					
	WT	LS	Grey	WT	LS	Grey
100	48.6			49.4		
200	43.6			44.6		
350	38.2			39.2		
600	33.0			34.0		

2. Methods

2.1. Experimental concept and design

In this study, 24 audio-visual stimuli were systematically varied (full factorial design) with respect to three variables: distance to the WT, periodic AM of the sound (with, without) and visual setting (landscape with visible WT, landscape only, grey background) to study their individual contribution to short-term noise annoyance (Table 1). In the following, we refer to the noise annoyance studied here as "(noise) annoyance rating" (for the individual ratings) or "short-term (noise) annoyance", sometimes omitting the term "noise" in this context for sake of brevity.

The acoustical situations were similar to those studied by Schäffer et al. (2016): The distances of the observers to the WT cover a relevant sound pressure level (L_{Aeq}) range of WT noise to which residents may be exposed (Janssen et al., 2011; Tachibana, Yano, Fukushima, & Sueoka, 2014). The situations without periodic AM represent quasi-stationary WT noise, while those with periodic AM comprise "swishing" and "thumping" sound (see above).

For the stimuli with the visual settings "Landscape only" and "Landscape with WT", a hilly, rural landscape without buildings was chosen. Hilly terrain is a major landscape type of Switzerland, besides plains and mountains (Szerencsits et al., 2009). Such a setting was found to increase the risk of annoyance to WT noise, compared to urban areas or flat terrain (Pedersen & Persson Waye, 2007). Also, WTs were found to be more visible in rural than in urban areas (Pedersen, van den Berg, Bakker, & Bouma, 2009). For the case without visible landscape, a grey background ("Grey" in Table 1) was chosen, as grey is a neutral colour with respect to feelings (Heller, 2009).

2.2. Audio-visual stimuli

The audio-visual stimuli of Table 1 were synthetized using GIS-based 3D simulations with the tools of Manyoky, Wissen Hayek, Heutschi, Pieren, and Grêt-Regamey (2014), Pieren, Heutschi, Müller, Manyoky, and Eggenschwiler (2014) and Heutschi et al. (2014), as described below. For the current study, a location in a typical Swiss hilly landscape type was chosen for simulation. In this virtual environment, a single 2.0 MW Vestas V90 turbine (three blades, hub height = 95 m, rotor diameter = 90 m) was placed. The observer was set at 1.7 m above ground and at four positions situated 100–600 m away from the WT position (Table 1). The meteorological conditions were chosen as a sunny day with strong wind conditions resulting in a rotational speed of the WT of 15 rpm.

2.2.1. Visualization

Computer-generated imagery animations were created using the game engine CRYENGINE by Crytek GmbH (2015) as described in

Manyoky et al. (2014). The procedure involved (i) import of a digital elevation model and an orthophoto of an existing landscape, (ii) removing striking and recognizable landscape elements (e.g., characteristic mountain ranges) from the background to obtain a more generic setting (Ribe et al., 2018), (iii) adding 3D models for vegetation and infrastructures (e.g., road, WT), (iv) definition of a wind speed profile for movement of the WT blades and the vegetation, and (v) visual optimisations, e.g., of the colorization of the orthophoto and vegetation models and of the lighting settings, to obtain a higher level of realism.

For the current study, the landscape type "hills" of Ribe et al. (2018), which had been created in an older CRYENGINE version, was re-established in the more recent Version 3.4.8. Into the resulting visual setting, a 3D model of the WT was either placed and animated ("Landscape with WT" in Table 1), or not ("Landscape only" in Table 1). For these two settings, images were rendered for videos (Section 2.2.3) for the four observer positions (Table 1) with a widescreen aspect ratio of 16:9 (Fig. 1). The observer direction was chosen such as to see the WT to the right hand side of the visual field, to avoid a too strong focus on the WT during the experiments. In the videos both the 3D models of moving vegetation and WT with rotating blades (in clockwise direction) were animated. The rendered sets of images were complemented with a grey background image ("grey" in Table 1).

2.2.2. Auralization

The acoustical stimuli were artificially generated using digital sound synthesis as described in Pieren et al. (2014) and Heutschi et al. (2014), with the parameter settings similar to those of Schäffer et al. (2016).

The auralization process consists of three main steps, namely, emission synthesis, propagation filtering, and reproduction rendering. The synthesis of the sound emissions of the WT was done for strong wind conditions. Periodic AM of the sound was realized with a standard deviation of the level fluctuation of 3 dB and a modulation frequency of 0.75 Hz, corresponding to the rotational speed of 15 rpm. Sound propagation effects from the source to the observer locations were simulated by digital filtering (Heutschi et al., 2014), accounting for the propagation effects geometrical spreading, air absorption, ground reflection on a grassy terrain and atmospheric turbulence. The propagation situations with distances of 100–600 m resulted in a L_{Aeq} range of ~33–49 dB (Table 1).

In a final step, the synthesized sound pressure signals were rendered for surround sound reproduction with a five-channel loudspeaker setup (cf. Section 2.3.1) to generate a realistic hearing impression with directional information. Reproduction rendering was accomplished as described in Wissen Hayek, Pieren, Heutschi, Manyoky, and Grêt-Regamey (2018), using Vector Base Amplitude Panning by Pulkki (1997). This technique allows virtual sound source positioning with a loudspeaker array by calculating the individual loudspeaker feeds. In addition to the stimuli, a reference signal with a predefined sound pressure level was created for level calibration of the playback system.

To get an audio impression of the resulting stimuli with and without periodic AM, audio examples provided as supplementary material by Schäffer et al. (2016), which are very similar to those used here, may be consulted. Fig. 2 shows exemplary level-time histories, and Fig. 3 the spectra of the resulting acoustical stimuli. The standard deviations of the FAST time-weighted level fluctuations amount to ~0.8 dB and ~2.3 dB in the situations without and with periodic AM, respectively (Fig. 2), independent of the propagation distance. Due to the distinctly stronger level fluctuations and correspondingly higher L_{AF} peaks in situations with periodic AM compared to without AM (Fig. 2), the resulting L_{Aeq} of the former are ~1 dB larger than the latter (Table 1, Fig. 3).

The WT spectra reveal considerable energy at low frequencies, with spectral variations due to the ground effect (Fig. 3). As atmospheric attenuation increases with frequency, the low-frequency content becomes more pronounced with increasing propagation distance. Accordingly, the level difference $L_{C\text{-}A}$ between the C-weighted and A-weighted sound pressure level increases from 9 dB at 100 m to 14 dB at 600 m, and the spectral slope, i.e., the L_{eq} of the unweighted sound pressure level vs. octave band, from −2.6 dB/oct at 100 m to −5.1 dB/oct at 600 m (Fig. 3a). The slope of −4.1 dB/oct at 350 m coincides with the value observed by Tachibana et al. (2014) for residential areas around wind farms.

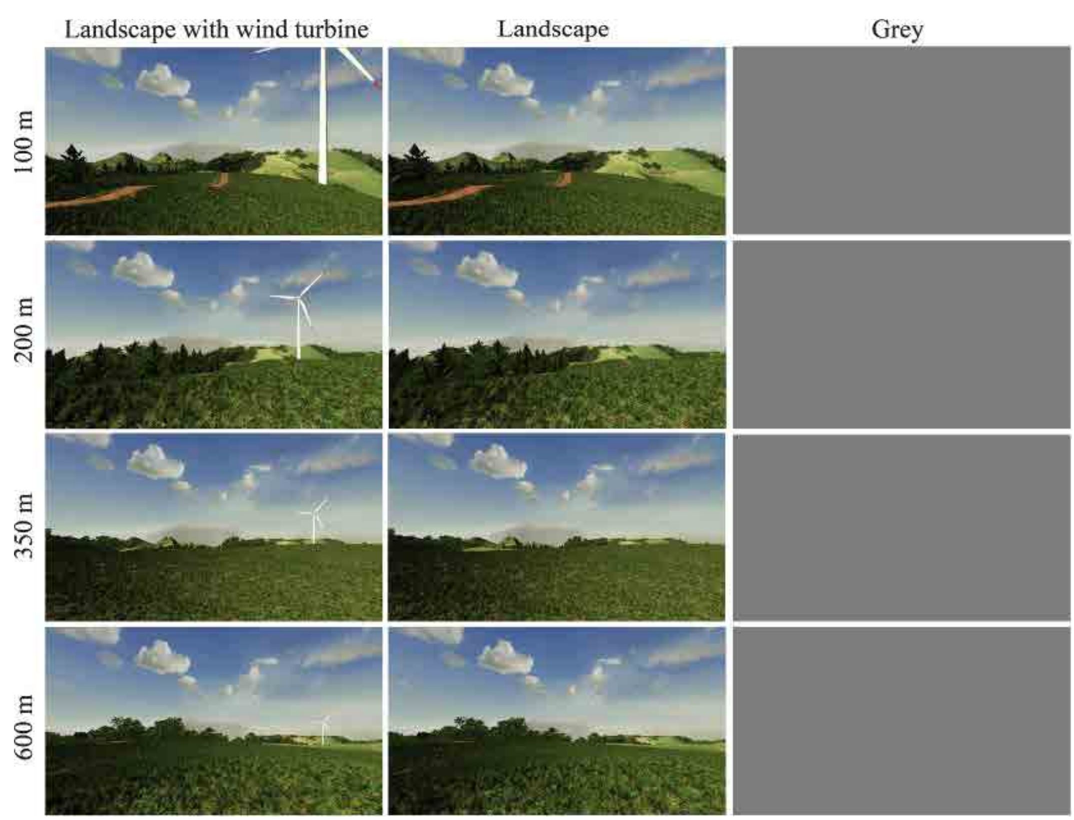

Fig. 1. Images of the visual stimuli covering three visual settings (landscape with visible wind turbine, landscape only, grey background) for distances of 100–600 m.

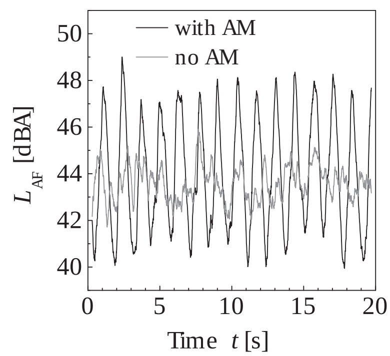

Fig. 2. Level-time histories of the A-weighted and FAST-time-weighted sound pressure level (L_{AF}) of the stimuli without ("no") and with amplitude modulation (AM), for a distance of 200 m.

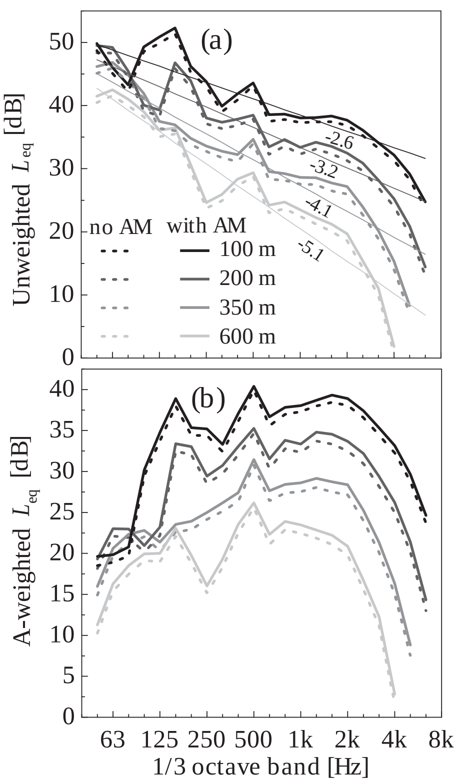

Fig. 3. (a) Unweighted and (b) A-weighted 1/3 octave band spectra (in L_{eq}) of the stimuli without ("no") and with amplitude modulation (AM), for distances of 100–600 m, in (a) with mean spectral slopes (thin solid lines: regressions per distance of the L_{eq} on 1/3 octave band) with the numbers below the lines indicating the slope in dB/oct.

2.2.3. Combination to acoustic-visual stimuli

The rendered images were stitched and encoded to videos of 21.5 s duration (stimuli of 20 s plus fade-in and fade-out), and the rendered audio data were time synchronised and linked to the videos as described in Manyoky et al. (2014) and Ribe et al. (2018). Each of the three visual settings of Table 1 was linked with two acoustical situations (with and without AM). This resulted in a total of 24 compressed videos (Multimedia container format MP4, video codec H.264, frame rate 60 fps, audio codec MPEG AAC, audio sampling rate 44.1 kHz) for playback.

2.3. Psychophysical experiments

2.3.1. Laboratory setup

The listening tests were carried out in the "Mobile Visual-Acoustic Lab" (MVAL), which is described in detail in Manyoky, Wissen Hayek, Pieren, Heutschi, and Grêt-Regamey (2016). For the experiment, the MVAL was built up in a room with low background noise and a carpet floor at the authors' institution ETH. MVAL consists of an aluminium construction (5 m × 5 m × 2.5 m) carrying black, sound absorbing curtains as walls and ceiling to exclude light and to obtain a favourable sound field. Within MVAL, five active loudspeakers (Focal CMS 50, Focal-JMlab) were arranged in a pentagon setting in a distance of 210 cm from the centre, along with a low-noise projector (Acer H6500, Acer Group) and a micro-perforated projection screen sized 2.70 m × 1.65 m. The videos were played using the VLC media player Version 2.2.4 on a laptop connected to the projector and the loudspeakers via a multichannel audio interface (Motu 896mk3, MOTU). Up to three persons simultaneously participated in the experiment. The seats were arranged at the centre of the pentagon. The audio playback chain was calibrated in level with the reference signal (Section 2.2.2) and a sound level meter located at the centre of the pentagon.

2.3.2. Experimental procedure

The experiments were conducted as a within-subject design, where all participants were exposed to all stimuli. Prior to the experiment, the participants were introduced to the research topic and task (noise annoyance rating of different situations with WT sounds). After signing a consent form to participate in the study, they answered questions on hearing and well-being as criterions for inclusion in the experiments.

The experiments were done as focused tests. The participants watched and listened to the videos, and rated them regarding noise annoyance after play-back by means of a paper-and-pencil questionnaire (supplementary data, see Appendix A). An investigator, situated at the back of the MVAL, played back the stimuli (once only), one by one, turning off the light during play back and turning it on between the stimuli for the participants to enter the ratings. Annoyance was rated with the ICBEN 11-point scale (Fields et al., 2001), where 0 represents the lowest and 10 the highest noise annoyance rating, by answering the following question (in German, modified from Fields et al., 2001): "You will be subsequently presented with 24 different situations of wind turbine sounds, which you are to rate regarding your annoyance by the sounds. What number from 0 to 10 represents best how much you felt bothered, disturbed or annoyed by the played back situation?" The experiments consisted of (i) an orientation with two stimuli to set the frame of reference, (ii) two exercise ratings to get accustomed to the task with the 11-point scale, and (iii) the actual ratings of the 24 stimuli from Table 1.

After the experiment, the participants completed a pen-and-pencil questionnaire, which assessed noise sensitivity, attitude towards wind farms, gender, age, highest educational degree achieved, landscape most frequently used for recreation, and questions about the experiment. Noise sensitivity was measured with the NoiSeQ-R by Griefahn, Marks, Gjestland, and Preis (2007) (the short form of the NoiSeQ by Schütte, Marks, Wenning, & Griefahn, 2007), which covers values of 0 (noise-insensitive) to 3 (highly noise-sensitive), and attitude towards wind farms with the questionnaire of Schäffer et al. (2016), which covers values of 0 (very negative) to 4 (very positive).

The whole test procedure lasted about one hour. Participants were compensated with 20 Swiss Francs (about 18 Euro) after completing the experiments.

2.3.3. Playback order of the stimuli

Special attention was paid to the playback order of the stimuli. Randomization is a successful strategy in many psychoacoustic experiments, including those of Schäffer et al. (2016; 2018). However for visual stimuli, some authors balanced the order of the stimuli (Ferris, Kempton, Deary, Austin, & Shotter, 2001; Maffei et al., 2013), while others randomized them, either within the same session (Szychowska et al., 2018) or over different days (Sun et al., 2018).

In a preliminary experiment preceding the present study, we played back the audio-visual stimuli of Table 1 to 40 participants (22 females, 18 males) in fully randomized order, using the same laboratory setup and experimental procedure as described above. The results are presented in Appendix B (Fig. B1). The experiment revealed that noise annoyance increases with the acoustical characteristics L_{Aeq} and periodic AM, as well as with the playback number ($p < 0.001$), which is in accordance with the findings of Schäffer et al. (2016). Further, annoyance tended to decrease with more positive attitude toward wind farms ($p = 0.051$), which corroborates the results of Schäffer et al. (2018). The visual setting, in contrast, apparently had no effect ($p = 0.15$). This finding was unexpected insofar as the visual setting differed strongly (Fig. 1) and as some participants felt that it influenced their noise annoyance rating.

For the main experiment, we therefore used a completely counterbalanced design regarding the visual setting (Cohen, 2013). The three visual settings of Table 1 were presented in three blocks in completely counterbalanced order, and the eight acoustical situations per visual setting in randomized order. With this design, the annoyance ratings of the first block correspond to a between-subject design (see above) and are free from potential visual differential carryover effects, while those of the subsequent blocks may contain such effects.

2.3.4. Participants

Forty-three participants (22 females, 21 males), all with self-declared normal hearing and feeling well and healthy, were included in the study. A large part studied or worked at the authors' institution ETH. Accordingly, the panel was quite young (19–52 years; median of 25 years) and well educated, with 67% possessing an academic degree (BSc, MSc, MAS or PhD), and another 30% studying to obtain one. The panel was moderately noise sensitive (noise sensitivity values of 0.4–2.9, median of 1.7). Further, with attitude values of 1.2–4.0 (median of 2.9), the panel was largely positive towards wind farms. The participants spent most of their spare time rather in hilly regions (50%) than in plains (35%) or mountains (15%), and somewhat more in urban (58%) than in rural areas (42%). Thus, the visual setting of the stimuli (hilly rural) corresponded to the preference of a large part of the participants. 67% of the participants had heard WT noise before.

2.4. Statistical analysis

Statistical analysis was done in IBM SPSS Version 23 and 25.

The consistency of the annoyance ratings between participants was assessed with the inter-rater reliability (Hallgren, 2012), doing a two-way random, consistency, average-measures intraclass correlation (ICC) (McGraw & Wong, 1996), where large ICC values indicate high agreement between individuals.

The noise annoyance ratings were analysed by means of linear mixed-effects models (see, e.g., West, Welch, & Gałecki, 2015), using the SPSS procedure MIXED. To that aim, the variables of Table 1 were included as fixed effects, namely, the L_{Aeq} resulting from the distance to the WT as a continuous variable, and periodic AM and visual setting as categorical variables. Potential differential carryover effects of the visual information were also considered with the variable visual setting, which describes the current visual setting and the preceding settings ("the visual history"; cf. Section 3). Given the experimental design, the variables of Table 1, as well as their interactions, were a priori tested. In addition, simple order effects (aside from differential carryover effects) of the playback number of the stimuli (continuous variable), as well as the link of the participants' characteristics to noise annoyance were studied. Finally, repeated observations (24 ratings per participant) were accounted for with a random effect for the participants. Different models of different degrees of complexity (with respect to fixed and random effects) were tested to find the optimal model with respect to completeness (include all relevant variables), performance (data representation, significance of effects) and parsimony (simplicity of the model). The goodness-of-fit of the final model was assessed with the marginal (R^2_m for the fixed effects) and conditional coefficient of determination (R^2_c for the fixed and random effects) (Johnson, 2014; Nakagawa & Schielzeth, 2013). Model assumptions were confirmed by means of residual plots, which did not reveal any obvious deviation from normality, and suggested constant variance as well as independence of the observations (except within participants, which was accounted for by the mixed-effect model).

3. Results and discussion

The observed annoyance ratings have an ICC of 0.989. This value lies in the excellent range (Cicchetti, 1994), indicating a high degree of agreement between participants (Hallgren, 2012). In the following account (Sections 3.1–3.3), the observed short-term noise annoyance is discussed. All effects discussed here were confirmed with the mixed-effects model analysis, the results of which are presented graphically along with the observations in Figs. 4–7, as well as described in more detail in Section 3.4. In Section 3.5, the study is brought into broader context.

3.1. Audio-visual effects

Fig. 4 shows the effects of the audio-visual stimuli on noise annoyance, for the first block (first 8 stimuli, free from potential visual differential carryover effects) as well as for the whole experiment (all 24 stimuli). Noise annoyance is strongly linked with the L_{Aeq}, increasing linearly by 1.7 units per 5 dB increase of the L_{Aeq} (Fig. 4a). This corroborates the well-known crucial role of the L_{Aeq} to be a determinant for annoyance in the laboratory (e.g., Lee et al., 2011; Schäffer et al., 2016) and also that an A-weighted metric is appropriate to predict (WT noise) annoyance reactions (Bolin, Bluhm, & Nilsson, 2014). Besides, periodic AM increases annoyance by about 0.6 units on the 11-point scale (Fig. 4b), which would also be evoked by a ~2 dB increase of the L_{Aeq}. This effect has also been amply observed in the laboratory (Hafke-Dys, Preis, Kaczmarek, Biniakowski, & Kleka, 2016; Ioannidou et al., 2016; Lee et al., 2011; Schäffer et al., 2016; 2018) as well as in the field (Bockstael et al., 2012; Pohl, Gabriel, & Hübner, 2018). The results on L_{Aeq} and periodic AM are also in line with the preliminary experiment (Section 2.3.3). The link of the annoyance to the L_{Aeq} and AM is similar in the first block and the whole experiment, except that annoyance tends to increase in the course of the experiment (Fig. 4a and b: 24 vs. 8 stimuli). This suggests a simple order effect.

Finally, the visual setting strongly affects annoyance (Fig. 4c), i.e., it acts as an effect modifier for noise annoyance. For the first block, annoyance increases in the order landscape only < landscape with WT < grey, by 1.2 units on the 11-point scale, which corresponds to ~4 dB increase of the L_{Aeq}. Increased annoyance to situations with visible noise source was also observed in a laboratory study of Yu et al. (2017) and a field experiment by Bangjun, Lili, and Guoqing (2003), while Sun et al. (2018) found the effect of visibility to depend on the participants' noise sensitivity. This corroborates findings of field surveys that the visibility of wind farms increases annoyance (Klæboe & Sundfør, 2016; Pedersen & Larsman, 2008; Pedersen & Persson Waye, 2007; Pedersen et al., 2009). It is also in line with the finding of Maffei et al. (2013) that the number of WTs increases annoyance (although the authors did not investigate the case without visible WT). In the laboratory, the visibility of the WT may have led to (conscious) recognition of WT noise as such, which in turn may increase annoyance (Szychowska et al., 2018; Van Renterghem, Bockstael, De Weirt, & Botteldooren, 2013). Also, it may have shifted the participants' focus to the WT noise, while the landscape alone distracted the participants from the sound. Such focussing apparently was strongest in the grey setting, which did not offer any visual distraction from the sound. Besides, the strong reactions to the grey setting might by caused by the fact that purely auditory situations are emotionally more engaging than videos (Richardson et al., 2018). Our results of the grey vs. landscape setting are also corroborated by Preis, Kociński, Hafke-Dys, and Wrzosek (2015), who for some of their tested cases found audio-visual stimuli of urban places to be linked with a higher comfort feeling than acoustical stimuli alone.

The strong effect of the visual setting on noise annoyance observed for the first block (Fig. 4c, left) is lost when averaging over the whole experiment (Fig. 4c, right). In the latter case, the annoyance varied only by 0.3 points on the 11-point scale between settings, and in a different order (landscape only > landscape with WT ≈ grey). This change was likely to be evoked by a differential carryover effect, which is not eliminated by (complete) counterbalancing and thus may change the overall results (cf. Section 1). The above indicated simple order and differential carryover effects are discussed in Section 3.3.

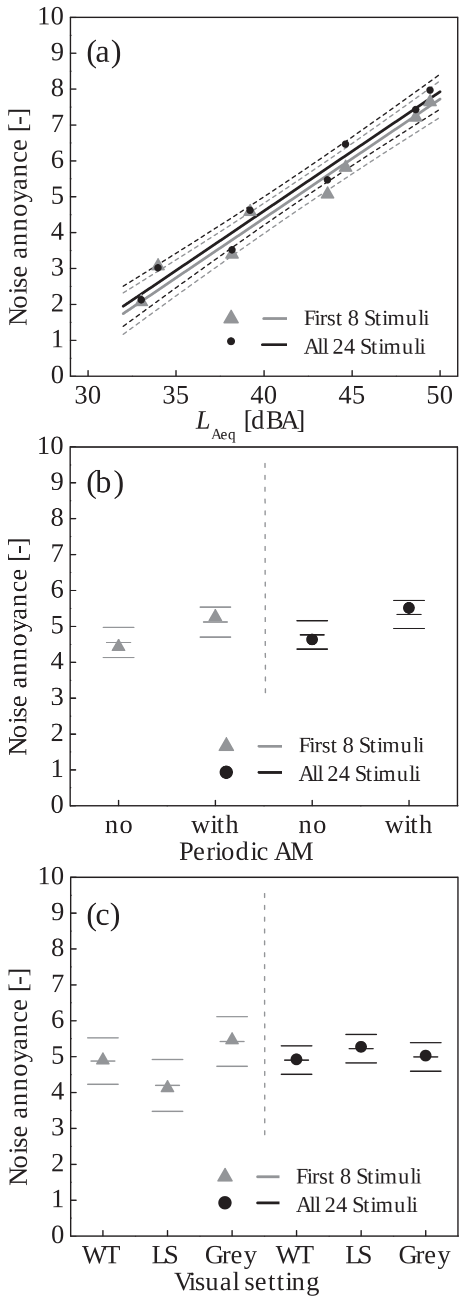

Fig. 4. Mean short-term noise annoyance as a function of the audio-visual characteristics (a) equivalent continuous sound pressure level (L_{Aeq}) (pooled data of different situations of amplitude modulation (AM) and visual settings), (b) AM (without ("no") or with; pooled data of different L_{Aeq} and visual settings) and (c) visual settings (landscape with wind turbine (WT), landscape only (LS) and grey; pooled data of different L_{Aeq} and AM), for the first block of visual setting (first 8 stimuli) and for all three blocks (all 24 stimuli). Symbols represent observations, and lines the corresponding mixed-effects model (Eq. (1)) with 95% confidence intervals, in (b) and (c) as horizontal lines. The annoyance ratings are shown at the mean playback number of either the first 8 stimuli or all 24 stimuli.

3.2. Influence of personal characteristics

The annoyance ratings were found to be lower the more positive the attitude towards wind farms, although scattering is relatively large (Fig. 5). On the 11-point scale, the ratings differ by 2.4 units within the observed range of attitude values of 1.2–4.0, corresponding to a L_{Aeq} difference of more than 7 dB. The importance of attitude was also observed by Ribe, Manyoky, Wissen Hayek, and Grêt-Regamey (2016) and Schäffer et al. (2018), as well as in the preliminary experiment (Section 2.3.3), and is also known from field surveys (Klæboe & Sundfør, 2016; Pedersen & Larsman, 2008; Pedersen & Persson Waye, 2004).

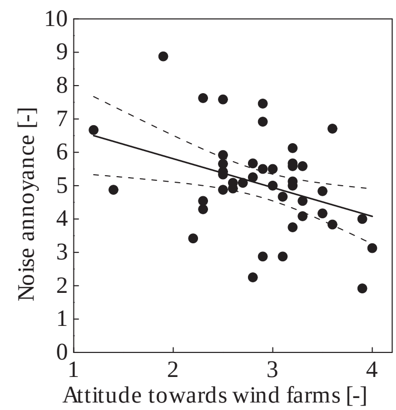

Fig. 5. Mean short-term noise annoyance (mean of all ratings per participant) as a function of the attitude towards wind farms (with values of 0 = very negative to 4 = very positive) according to Schäffer et al. (2016). Symbols represent observations, and lines the corresponding mixed-effects model (Eq. (1)) with 95% confidence intervals.

Annoyance was not linked to any other of the participants' tested characteristics (gender, age or noise sensitivity). Other laboratory studies, in contrast, found a dependency on noise sensitivity (Crichton, Dodd, Schmid, & Petrie, 2015; Sun et al., 2018) or no dependency on personal variables at all (Schäffer et al., 2016). These discrepancies may be due to the fact that in the laboratory, participants' ratings are closer to their sensory perception (corroborated also by the high ICC value found here), while in the field, personal and situational factors become much more important (Janssen et al., 2011; Michaud et al., 2016).

3.3. Simple order and differential carryover effects

Annoyance increased with the playback number of the stimuli, by about 0.6 units on the 11-point scale from the first to the twenty-fourth stimulus (Fig. 6). The same effect would also be evoked by a ∼2 dB increase of the L_{Aeq}. Possibly, the participants became increasingly annoyed and/or fatigued by the stimuli, and rated the stimuli ever quicker as they got used to the sounds (practice or fatigue effect: Cohen, 2013). An increase in annoyance with playback number was also observed in the preliminary experiment (Section 2.3.3) as well as in previous laboratory experiments on noise annoyance by Schäffer et al. (2016; 2018). In contrast, an experiment with a pairwise comparison task to evaluate the subjectively perceived sound quality of speech did not reveal such effect (Sanavi, Schäffer, Heutschi, & Eggenschwiler, 2017). In fact, simple order effects were found to depend on the task and to be particularly important for simple tasks (Malhotra, 2009). This corroborates the importance of counterbalancing to eliminate such effects (Cohen, 2013).

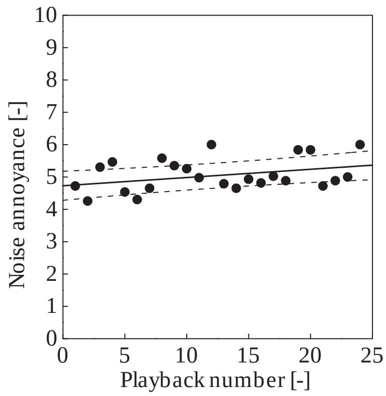

Fig. 6. Simple order effect: Mean short-term noise annoyance vs. playback number. Symbols represent observations (mean of all ratings per playback number), and lines the corresponding mixed-effects model (Eq. (1)) with 95% confidence intervals.

The potential differential carryover effects of the visual setting indicated by Fig. 4c are further presented in Fig. 7, which shows the mean annoyances per visual setting, separately for the first block of visual settings ("between-subject design", thus no visual differential carryover effect), for the second plus third block (with potential differential carryover effects), and for all three blocks. The results of the first block and of the mean of all three blocks correspond to Fig. 4c, except that the simple order effect was excluded in Fig. 7. The data of the second and third block were pooled, because the change between them was smaller than between the first and second block. This indicates that the initial and current visual settings are both determinant for ratings. This observation is congruent with findings from literature on memory, referred to as primacy and recency effect (Li, 2010; Murdock, 1962). The magnitude of annoyance of the first block strongly determines the annoyance of the following blocks. This effect of the first visual setting on annoyance seems even stronger than the effect of the current setting. Accordingly, the order of annoyance to the visual settings in the second/third block differs from the first block. This is likely to be caused by anchoring, where the magnitude of the first rating determines the magnitude of subsequent ratings (Sawyer & Wesensten, 1994). Of the possible carryover effects assimilation and contrast (Ferris et al., 2001), assimilation, i.e., bias towards the rating of the preceding (here, first) visual setting, was apparently the dominant effect here. Assimilation was also found, e.g., by Ward (1973) in a psychoacoustic experiment on loudness evaluation. As a consequence, the effect of the visual setting on the mean annoyance over the whole experiment is lost (Fig. 7, right), which was also observed in the preliminary experiment (Section 2.3.3). Even worse, the data pooled over the whole experiment suggests significant differences between visual settings in a different order than the first, unbiased block (Fig. 7). The observed carryover effect is in line with results from literature for visual assessment (Ferris et al., 2001).

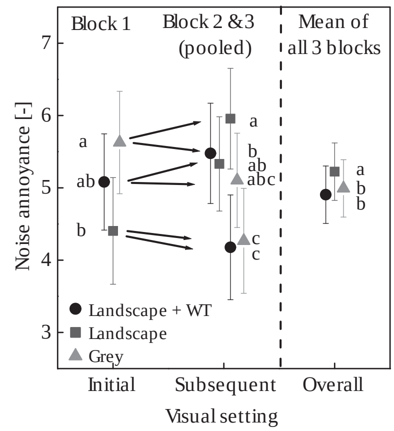

Fig. 7. Differential carryover effect: Mean short-term noise annoyance with 95% confidence intervals (mixed-effects model, Eq. (1)) as a function of the visual setting and the blocks of visual settings (initial = first block only; subsequent = second plus third block; overall = all three blocks). The data of the first block is free from differential carryover effects, while the data of the second/third block also depends on the first block, as indicated by the arrows. Values are shown at the mean playback number of all 24 stimuli to exclude the dependence on playback number (Fig. 6). For presentation purposes (better visibility of the overlapping confidence intervals) the data are slightly shifted on the x-axis. The observed mean annoyance values are very similar to the modelled values shown here except that it implicitly contains the dependency on playback number. Different letters indicate significant differences within blocks, as obtained from estimated marginal means (initial block, subsequent second plus third block) and contras analysis (overall).

Thus, the simple order effect influenced the annoyance to both, acoustical characteristics and visual setting, while a differential carryover effect was observed for the visual setting only. However, this finding cannot be generalized. First, differential carryover effects cannot be excluded a priori for acoustical stimuli. As an example, Sun et al. (2018) in their experiment presented the stimuli in different blocks over four consecutive days to minimize auditory memory of the participants. Second, the studied visual settings were either similar (landscape with vs. without WT) or without (much) information (grey). Thus, the current setting will not or only partially have erased the memory of the preceding setting(s), which might have promoted differential carryover effects. Also Maffei et al. (2013) used similar visual settings and observed only a weak effect of the number of WTs on annoyance (possibly diminished by differential carryover effects). In contrast, Szychowska et al. (2018) and Sun et al. (2018) (cf. Section 2.3.3) used very different visual settings. Here, the memory of the previous setting was probably erased by the current setting, which might have inhibited or at least reduced differential carryover effects, so that visual effects were observed over the whole experiment (contrary to our study). In conclusion, both types of serial position effects may play a role in psychophysical experiments and should be considered in experimental designs.

3.4. Statistical model

To describe the above observed effects on annoyance, the following mixed-effects model was found to be adequate:

$$Annoy_{ijk} = \mu + \beta \cdot L_{\mathrm{Aeq},ijk} + \tau_{\mathrm{AM},i} + \tau_{\mathrm{vis},j} + \gamma \cdot Ord_{ijk} + \delta \cdot Att_k + u_{0k} + u_{1k} \cdot L_{\mathrm{Aeq},ijk} + \varepsilon_{ijk}. \quad (1)$$

In Eq. (1), $Annoy_{ijk}$ is the dependent variable short-term annoyance, μ is the overall mean, τ_{AM} and τ_{vis} are the categorical variables AM (2 levels: $i = 1, 2$) and visual setting (current and first setting, described by 9 levels: $j = 1, \ldots, 9$), L_{Aeq}, *Ord* and *Att* are the continuous variables L_{Aeq}, order (playback number) and attitude towards wind farms, and β, γ and δ are their regression coefficients. The random effect terms u_{0k} and u_{1k} are the participants' random intercept and slope ($k = 1, \ldots, 43$), describing the dependence of the individual annoyance ratings on the L_{Aeq} (same model approach as by Schäffer et al., 2016), and ε_{ijk} is the error term. The index *ijk* represents the *k*th replicate observation of the *i*th AM with the *j*th visual setting. All variables of Eq. (1) are significantly linked to annoyance ($p < 0.001$ to $p = 0.01$). The model parameters are presented in Appendix C. The model explains more than 80% of the variance ($R^2_m = 0.60$, $R^2_c = 0.82$), indicating that it may reproduce the observations highly accurately.

3.5. Broader study context

This section aims at bringing the present study into broader context regarding (i) reproduction techniques, (ii) differences between laboratory experiments and field surveys, and (iii) practical implications.

First, our study revealed that visual impressions may strongly affect the participants' noise annoyance. However, although the audio-visual stimuli used here provided a high level of realism, the projection of the visualizations on a screen with a limited field of view does not meet human viewing habits, which may have influenced the participants' responses. For a more realistic simulation of the multisensory way in which the real environment is perceived, head-mounted displays or a Cave Automatic Virtual Environment (CAVE; e.g., Sahai et al., 2016) to present immersive virtual realities (IVR) are promising tools. They foster the participants' feeling of being present in the virtual environment (Maffei, Masullo, Pascale, Ruggiero, & Romero, 2016; Puyana-Romero, Lopez-Segura, Maffei, Hernández-Molina, & Masullo, 2017; Ruotolo et al., 2013; Yu et al., 2017). Also augmented reality (e.g., Botella et al., 2016) may provide such immersiveness. However, wearable devices such as head-mounted displays are intrusive, which in turn may affect results. Acoustically, immersiveness could be further improved by adding ambient sounds. Systematic studies on differences in results from experiments using different reproduction techniques would therefore be desirable.

Second, in interpreting the results, one should consider the inherent differences between field surveys and laboratory experiments, as discussed in detail for psychoacoustic experiments on WT noise annoyance by Schäffer et al. (2016; 2018). Laboratory experiments as performed here are an important complement to field surveys, because they allow isolating specific variables and thus systematically studying and developing a better understanding of their effects on noise annoyance (e.g., Szychowska et al., 2018; see above). However, at the same time, due to the focus on only few variables, laboratory experiments fall short of providing the whole environmental context, and hence, certain findings might not be confirmed by field surveys. For example, we observed the well-known crucial role of the L_{Aeq} in the laboratory (see Section 3.1), while its effect is weaker in the field (Brink, 2014), where other factors may play a more prominent role (e.g., Janssen et al., 2011; Michaud et al., 2016). Also, the short-term noise annoyance assessed in the laboratory is inherently different from long-term exposure in the field (Guski & Bosshardt, 1992). Therefore, it is crucial to bear in mind that results of single experiments are only revealing certain aspects of a more complex model, which needs to be built upon series of studies and meta-analyses, as proposed by Szychowska et al. (2018). The present study provides a valuable input for enhanced models, which may subsequently be validated in field surveys to prove the generalizability of the results.

Finally, the identified differential carryover effect of the first visual setting on the subsequent annoyance ratings may also have implications for planning practice, as audio-visual simulations are regarded a valuable tool for public participation in environmental planning (Maffei et al., 2016; Manyoky et al., 2016; Ribe et al., 2018). When these techniques are used, for example, to evaluate wind farm scenarios in different landscape contexts or as communication tools for residents of potential future wind parks, the presentation order of the landscapes and/or elements such as WTs (e.g., with/without) might affect the people's perception and noise annoyance, too. Hence, users of audio-visual simulations need to be aware of possible unwanted effects and of methods to avoid them. Focusing in training and teaching courses of 3D landscape simulation not only on technical but also on practical implementation aspects is, therefore, mandatory. Likewise, the presentation order should be rigorously considered in psychophysical laboratory experiments. It would be interesting to know if/how much the results of previous studies (Ferris et al., 2001; Maffei et al., 2013; Sun et al., 2018; Szychowska et al., 2018) (cf. Section 2.3.3) would have changed if the presentation order had been different.

4. Conclusions

In this study, audio-visual stimuli were systematically varied with respect to the distance of the observer from the WT, periodic AM of the sound and visual setting, accounting also for participants' personal characteristics, as well as for simple order and differential carryover effects. We are not aware of any other study on audio-visual effects of WTs, where also the playback order was explicitly accounted for.

We found that both acoustical characteristics and the visual setting affect noise annoyance, besides the participants' attitude towards wind farms. The visual setting may thus act as an effect modifier on noise annoyance. The investigated variables and their variation within the experiment (L_{Aeq} = 33–49 dB; two situations of AM; three visual settings, playback number = 1–24; attitude value = 1.2–4.0) caused annoyance variations decreasing in the order L_{Aeq} (5.4 points on the ICBEN 11-point scale) > attitude (2.4 points) > unbiased visual setting (1.2 points, first block) > periodic AM ≈ playback number (both 0.6 points).

Our results further show that serial position effects (playback order) may affect the outcomes of psychophysical experiments. Simple order effects influenced the annoyance to both, acoustical characteristics and visual setting, while a differential carryover effect was observed for the latter only. Thus, the association of noise annoyance with acoustical characteristics can (usually) be reliably assessed by counterbalancing, eliminating simple order effects. The presentation order of visual stimuli, in contrast, needs more attention and should be explicitly accounted for in experimental designs (Nonyane & Theobald, 2007). The strength of the current study is the full control to separate the "primary" effects (Table 1) from simple order and differential carryover effects. To our knowledge, available studies from literature on audio-visual effects of environmental noise on annoyance did not explicitly investigate the latter effects to date. Whether and to what degree differential carryover effects affected their results thus cannot be answered.

In conclusion, audio-visual characteristics were found to mutually affect noise annoyance. The sound pressure level and amplitude modulation increased annoyance, the presence of a visualized landscape decreased annoyance, and the visibility of a wind turbine increased annoyance. To obtain unbiased experimental results, however, the presentation order of audio-visual stimuli needs to be carefully considered in experimental studies as well as in participatory landscape planning. As the number of audio-visual studies is increasing and findings are thought to support landscape planning and design decisions, it is essential to give these topics more consideration in future studies.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data (authors' questionnaire) associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landurbplan.2019.01.014.

Appendix B. Results of the preliminary experiment

See Fig. B1.

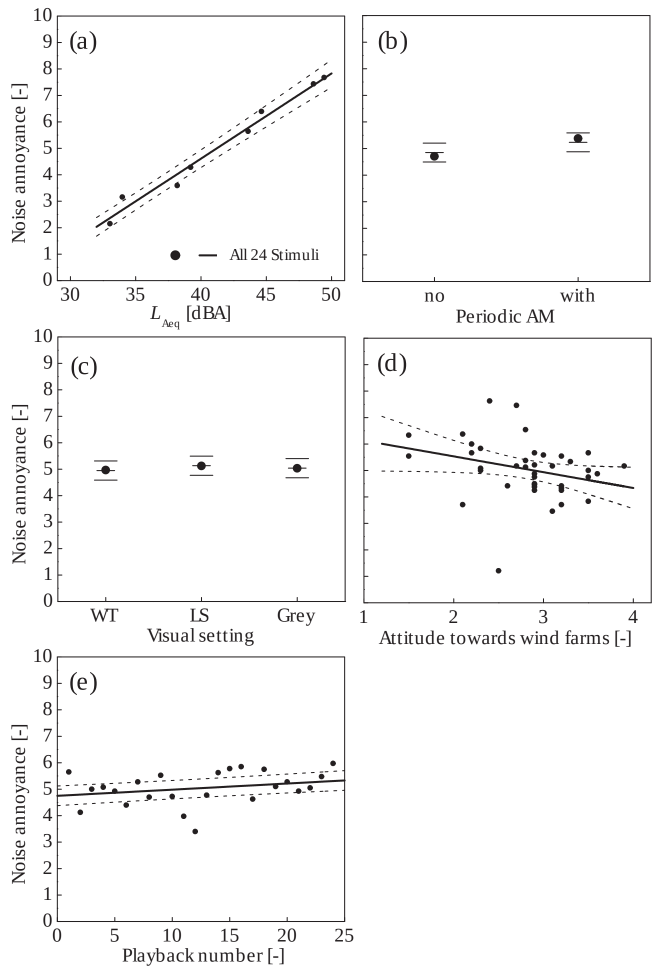

Fig. B1. Mean short-term noise annoyance as a function of (a) the equivalent continuous sound pressure level (L_{Aeq}) (pooled data of different situations of amplitude modulation (AM) and visual settings), (b) AM (without ("no") or with; pooled data of different L_{Aeq} and visual settings), (c) visual settings (landscape with wind turbine (WT), landscape only (LS) and grey; pooled data of different L_{Aeq} and AM), (d) attitude towards wind farms (mean of all ratings per participant, with values of 0 = very negative to 4 = very positive) according to Schäffer et al. (2016), and (e) playback number (mean of all ratings per playback number). Symbols represent observations, and lines the corresponding mixed-effects model with 95% confidence intervals, in (b) and (c) as horizontal lines. The annoyance ratings of (a)–(d) are shown at the mean playback number of all 24 stimuli. Note that an analogous statistical model was used here as for the main experiment (cf. Eq. (1) and Table C1), except that the visual setting was modelled simpler (3 categories only: WT, LS and grey), without accounting for differential carryover effects.

Appendix C. Linear mixed-effect model

See Table C1.

Table C1
Model coefficients with 95% confidence intervals (CI) and probability values (p) of the linear mixed-effects model for the annoyance ratings. The parameters symbols are explained in Eq. (1) in Section 3.4.

Parameter	Symbol	Coefficient	95% CI	p
Intercept	μ	−7.4373	[−10.0772; −4.7973]	< 0.001
L_{Aeq}	β	0.3322	[0.2930; 0.3713]	< 0.001
AM	$\tau_{AM,i=with}$	0.5703	[0.4201; 0.7205]	< 0.001
	$\tau_{AM,i=no}$	0[a]		
Visual setting (current; first)	$\tau_{vis,j=WT;none}$	0.6773	[−0.3008; 1.6554]	0.17
	$\tau_{vis,j=WT;LS}$	−0.2270	[−0.6274; 0.1733]	0.27
	$\tau_{vis,j=WT;Grey}$	1.0733	[0.0454; 2.1012]	0.04
	$\tau_{vis,j=LS;none}$	0[a]		
	$\tau_{vis,j=LS;WT}$	0.9265	[−0.0761; 1.929]	0.07
	$\tau_{vis,j=LS;Grey}$	1.5532	[0.5208; 2.5856]	< 0.01
	$\tau_{vis,j=Grey;none}$	1.2232	[0.2164; 2.2301]	0.02
	$\tau_{vis,j=Grey;WT}$	0.6999	[−0.3027; 1.7025]	0.17
	$\tau_{vis,j=Grey;LS}$	−0.1369	[−0.5438; 0.2700]	0.51
Playback number	γ	0.0255	[0.0065; 0.0444]	< 0.01
Attitude towards wind farms	δ	−0.8647	[−1.5207; −0.2086]	0.01
Random intercept	u_{0k}^2	27.3095	[16.891; 44.1541]	< 0.001
Random slope	u_{1k}^2	0.0143	[0.0088; 0.0232]	< 0.001
Residual	ε^2_{ijk}	1.4951	[1.3656; 1.6369]	< 0.001

[a] Redundant coefficients are set to zero.

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EXHIBIT
5

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SEE COMMENTARY

Anthropogenic warming has increased drought risk in California

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California is currently in the midst of a record-setting drought. The drought began in 2012 and now includes the lowest calendar-year and 12-mo precipitation, the highest annual temperature, and the most extreme drought indicators on record. The extremely warm and dry conditions have led to acute water shortages, groundwater overdraft, critically low streamflow, and enhanced wildfire risk. Analyzing historical climate observations from California, we find that precipitation deficits in California were more than twice as likely to yield drought years if they occurred when conditions were warm. We find that although there has not been a substantial change in the probability of either negative or moderately negative precipitation anomalies in recent decades, the occurrence of drought years has been greater in the past two decades than in the preceding century. In addition, the probability that precipitation deficits co-occur with warm conditions and the probability that precipitation deficits produce drought have both increased. Climate model experiments with and without anthropogenic forcings reveal that human activities have increased the probability that dry precipitation years are also warm. Further, a large ensemble of climate model realizations reveals that additional global warming over the next few decades is very likely to create ∼100% probability that any annual-scale dry period is also extremely warm. We therefore conclude that anthropogenic warming is increasing the probability of co-occurring warm–dry conditions like those that have created the acute human and ecosystem impacts associated with the "exceptional" 2012–2014 drought in California.

drought | climate extremes | climate change detection | event attribution | CMIP5

The state of California is the largest contributor to the economic and agricultural activity of the United States, accounting for a greater share of population (12%) (1), gross domestic product (12%) (2), and cash farm receipts (11%) (3) than any other state. California also includes a diverse array of marine and terrestrial ecosystems that span a wide range of climatic tolerances and together encompass a global biodiversity "hotspot" (4). These human and natural systems face a complex web of competing demands for freshwater (5). The state's agricultural sector accounts for 77% of California water use (5), and hydroelectric power provides more than 9% of the state's electricity (6). Because the majority of California's precipitation occurs far from its urban centers and primary agricultural zones, California maintains a vast and complex water management, storage, and distribution/conveyance infrastructure that has been the focus of nearly constant legislative, legal, and political battles (5). As a result, many riverine ecosystems depend on mandated "environmental flows" released by upstream dams, which become a point of contention during critically dry periods (5).

California is currently in the midst of a multiyear drought (7). The event encompasses the lowest calendar-year and 12-mo precipitation on record (8), and almost every month between December 2011 and September 2014 exhibited multiple indicators of drought (Fig. S1). The proximal cause of the precipitation deficits was the recurring poleward deflection of the cool-season storm track by a region of persistently high atmospheric pressure, which steered Pacific storms away from California over consecutive seasons (8–11). Although the extremely persistent high pressure is at least a century-scale occurrence (8), anthropogenic global warming has very likely increased the probability of such conditions (8, 9).

Despite insights into the causes and historical context of precipitation deficits (8–11), the influence of historical temperature changes on the probability of individual droughts has—until recently—received less attention (12–14). Although precipitation deficits are a prerequisite for the moisture deficits that constitute "drought" (by any definition) (15), elevated temperatures can greatly amplify evaporative demand, thereby increasing overall drought intensity and impact (16, 17). Temperature is especially important in California, where water storage and distribution systems are critically dependent on winter/spring snowpack, and excess demand is typically met by groundwater withdrawal (18–20). The impacts of runoff and soil moisture deficits associated with warm temperatures can be acute, including enhanced wildfire risk (21), land subsidence from excessive groundwater withdrawals (22), decreased hydropower production (23), and damage to habitat of vulnerable riparian species (24).

Recent work suggests that the aggregate combination of extremely high temperatures and very low precipitation during the 2012–2014 event is the most severe in over a millennium (12). Given the known influence of temperature on drought, the fact that the 2012–2014 record drought severity has co-occurred with record statewide warmth (7) raises the question of whether long-term warming has altered the probability that precipitation deficits yield extreme drought in California.

Significance

California ranks first in the United States in population, economic activity, and agricultural value. The state is currently experiencing a record-setting drought, which has led to acute water shortages, groundwater overdraft, critically low streamflow, and enhanced wildfire risk. Our analyses show that California has historically been more likely to experience drought if precipitation deficits co-occur with warm conditions and that such confluences have increased in recent decades, leading to increases in the fraction of low-precipitation years that yield drought. In addition, we find that human emissions have increased the probability that low-precipitation years are also warm, suggesting that anthropogenic warming is increasing the probability of the co-occurring warm–dry conditions that have created the current California drought.

Author contributions: N.S.D., D.L.S., and D.T. designed research, performed research, contributed new reagents/analytic tools, analyzed data, and wrote the paper.

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SUSTAINABILITY SCIENCE

Results

We analyze the "Palmer" drought metrics available from the US National Climatic Data Center (NCDC) (25). The NCDC Palmer metrics are based on the Palmer Drought Severity Index (PDSI), which uses monthly precipitation and temperature to calculate moisture balance using a simple "supply-and-demand" model (26) (*Materials and Methods*). We focus on the Palmer Modified Drought Index (PMDI), which moderates transitions between wet and dry periods (compared with the PDSI) (27). However, we note that the long-term time series of the PMDI is similar to that of other Palmer drought indicators, particularly at the annual scale (Figs. S1 and S2).

Because multiple drought indicators reached historic lows in July 2014 (Figs. S1–S3), we initially focus on statewide PMDI, temperature, and precipitation averaged over the August–July 12-mo period. We find that years with a negative PMDI anomaly exceeding –1.0 SDs (hereafter "1-SD drought") have occurred approximately twice as often in the past two decades as in the preceding century (six events in 1995–2014 = 30% of years; 14 events in 1896–1994 = 14% of years) (Fig. 1*A* and Fig. S4). This increase in the occurrence of 1-SD drought years has taken place without a substantial change in the probability of negative precipitation anomalies (53% in 1896–2014 and 55% in 1995–2014) (Figs. 1*B* and 2 *A* and *B*). Rather, the observed doubling of the occurrence of 1-SD drought years has coincided with a doubling of the frequency with which a negative precipitation year produces a 1-SD drought, with 55% of negative precipitation years in 1995–2014 co-occurring with a –1.0 SD PMDI anomaly, compared with 27% in 1896–1994 (Fig. 1 *A* and *B*).

Most 1-SD drought years have occurred when conditions were both dry (precipitation anomaly < 0) and warm (temperature anomaly > 0), including 15 of 20 1-SD drought years during 1896–2014 (Fig. 2*A* and Fig. S4) and 6 of 6 during 1995–2014 (Fig. 2*B* and Fig. S4). Similarly, negative precipitation anomalies are much more likely to produce 1-SD drought if they co-occur with a positive temperature anomaly. For example, of the 63 negative precipitation years during 1896–2014, 15 of the 32 warm–dry years (47%) produced 1-SD drought, compared with only 5 of the 31 cool–dry years (16%) (Fig. 2*A*). (During 1896–1994, 41% of warm–dry years produced 1-SD droughts, compared with 17% of cool–dry years.) The probability that a negative precipitation anomaly co-occurs with a positive temperature anomaly has increased recently, with warm–dry years occurring more than twice as often in the past two decades (91%) as in the preceding century (42%) (Fig. 1*B*).

All 20 August–July 12-mo periods that exhibited a –1.0 SD PMDI anomaly also exhibited a –0.5 SD precipitation anomaly (Fig. 1*B* and 2*E*), suggesting that moderately low precipitation is prerequisite for a 1-SD drought year. However, the occurrence of –0.5 SD precipitation anomalies has not increased in recent years (40% in 1896–2014 and 40% in 1995–2014) (Fig. 2 *A* and *B*). Rather, these moderate precipitation deficits have been far more likely to produce 1-SD drought when they occur in a warm year. For example, during 1896–2014, 1-SD drought occurred in 15 of the 28 years (54%) that exhibited both a –0.5 SD precipitation anomaly and a positive temperature anomaly, but in only 5 of the 20 years (25%) that exhibited a –0.5 SD precipitation anomaly and a negative temperature anomaly (Fig. 2*A*). During 1995–2014, 6 of the 8 moderately dry years produced 1-SD drought (Fig. 1*A*), with all 6 occurring in years in which the precipitation anomaly exceeded –0.5 SD and the temperature anomaly exceeded 0.5 SD (Fig. 1*C*).

Taken together, the observed record from California suggests that (*i*) precipitation deficits are more likely to yield 1-SD PMDI droughts if they occur when conditions are warm and (*ii*) the occurrence of 1-SD PMDI droughts, the probability of precipitation deficits producing 1-SD PMDI droughts, and the probability of precipitation deficits co-occurring with warm conditions have all been greater in the past two decades than in the preceding century.

These increases in drought risk have occurred despite a lack of substantial change in the occurrence of low or moderately low precipitation years (Figs. 1*B* and 2 *A* and *B*). In contrast, statewide warming (Fig. 1*C*) has led to a substantial increase in warm conditions, with 80% of years in 1995–2014 exhibiting a positive temperature anomaly (Fig. 2*B*), compared with 45% of years in 1896–2014 (Fig. 2*A*). As a result, whereas 58% of moderately dry years were warm during 1896–2014 (Fig. 2*A*) and 50% were warm during 1896–1994, 100% of the 8 moderately dry years in 1995–2014 co-occurred with a positive temperature anomaly (Fig. 2*B*). The observed statewide warming (Fig. 1*C*) has therefore substantially increased the probability that when moderate precipitation deficits occur, they occur during warm years.

The recent statewide warming clearly occurs in climate model simulations that include both natural and human forcings ("Historical" experiment), but not in simulations that include only natural forcings ("Natural" experiment) (Fig. 3*B*). In particular, the Historical and Natural temperatures are found to be different at the 0.001 significance level during the most recent 20-, 30-, and 40-y periods of the historical simulations (using the block bootstrap resampling applied in ref. 28). In contrast, although the Historical experiment exhibits a slightly higher mean annual precipitation (0.023 significance level), there is no statistically

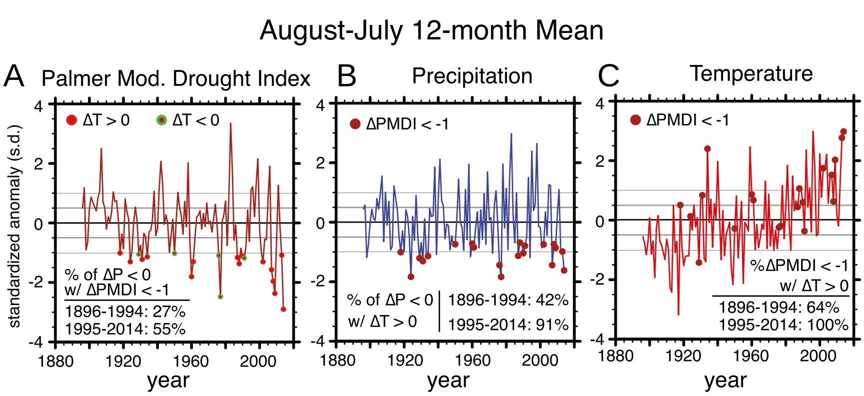

Fig. 1. Historical time series of drought (*A*), precipitation (*B*), and temperature (*C*) in California. Values are calculated for the August–July 12-mo mean in each year of the observed record, beginning in August 1895. In each year, the standardized anomaly is expressed as the magnitude of the anomaly from the long-term annual mean, divided by the SD of the detrended historical annual anomaly time series. The PMDI is used as the primary drought indicator, although the other Palmer indicators exhibit similar historical time series (Figs. S1 and S2). Circles show the years in which the PMDI exhibited a negative anomaly exceeding –1.0 SDs, which are referred to as 1-SD drought years in the text.

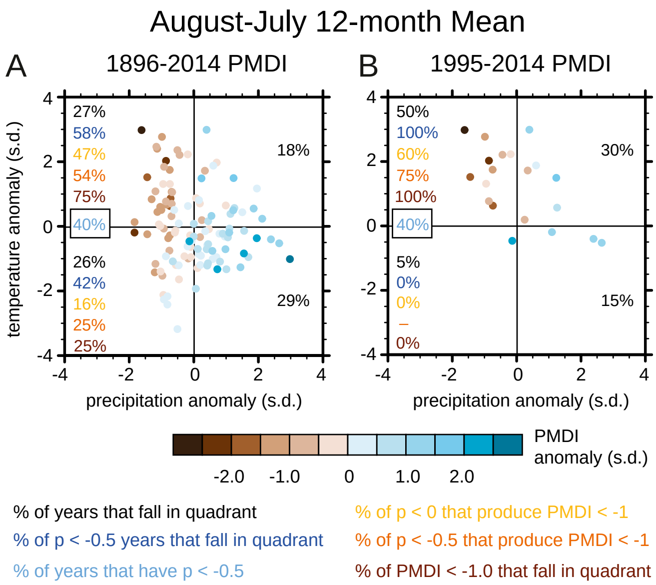

Fig. 2. Historical occurrence of drought, precipitation, and temperature in California. Standardized anomalies are shown for each August–July 12-mo period in the historical record (calculated as in Fig. 1). Anomalies are shown for the full historical record (*A*) and for the most recent two decades (*B*). Percentage values show the percentage of years meeting different precipitation and drought criteria that fall in each quadrant of the temperature–precipitation space. The respective criteria are identified by different colors of text.

significant difference in probability of a –0.5 SD precipitation anomaly (Fig. 3 *A* and *C*). However, the Historical experiment exhibits greater probability of a –0.5 SD precipitation anomaly co-occurring with a positive temperature anomaly (0.001 significance level) (Fig. 3*D*), suggesting that human forcing has caused the observed increase in probability that moderately dry precipitation years are also warm.

The fact that the occurrence of warm and moderately dry years approaches that of moderately dry years in the last decades of the Historical experiment (Fig. 3 *B* and *C*) and that 91% of negative precipitation years in 1995–2014 co-occurred with warm anomalies (Fig. 1*B*) suggests possible emergence of a regime in which nearly all dry years co-occur with warm conditions. We assess this possibility using an ensemble of 30 realizations of a single global climate model [the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM1) Large Ensemble experiment ("LENS")] (29) (*Materials and Methods*). Before ~1980, the simulated probability of a warm–dry year is approximately half that of a dry year (Fig. 4*B*), similar to observations (Figs. 1*B* and 2). However, the simulated probability of a warm–dry year becomes equal to that of a dry year by ~2030 of RCP8.5. Likewise, the probabilities of co-occurring 0.5, 1.0 and 1.5 SD warm–dry anomalies become approximately equal to those of 0.5, 1.0, and 1.5 SD dry anomalies (respectively) by ~2030 (Fig. 4*B*).

The probability of co-occurring extremely warm and extremely dry conditions (1.5 SD anomaly) remains greatly elevated throughout the 21st century (Fig. 4*B*). In addition, the number of multiyear periods in which a –0.5 SD precipitation anomaly co-occurs with a 0.5 SD temperature anomaly more than doubles between the Historical and RCP8.5 experiments (Fig. 4*A*). We find similar results using a 12-mo moving average (Fig. 4*C*). As with the August–July 12-mo mean (Fig. 4*B*), the probability of a dry year is approximately twice the probability of a warm–dry year for all 12-mo periods before ~1980 (Fig. 4*C*). However, the occurrence of warm years (including +1.5 SD temperature anomalies) increases after ~1980, reaching 1.0 by ~2030. This increase implies a transition to a permanent condition of ~100% risk that any negative—or extremely negative—12-mo precipitation anomaly is also extremely warm.

The overall occurrence of dry years declines after ~2040 (Fig. 4*C*). However, the occurrence of extreme 12-mo precipitation deficits (–1.5 SD) is greater in 2006–2080 than in 1920–2005 (<0.03 significance level). This detectable increase in extremely low-precipitation years adds to the effect of rising temperatures and contributes to the increasing occurrence of extremely warm–dry 12-mo periods during the 21st century.

All four 3-mo seasons likewise show higher probability of co-occurring 1.5 SD warm–dry anomalies after ~1980, with the probability of an extremely warm–dry season equaling that of an extremely dry season by ~2030 for spring, summer, and autumn, and by ~2060 for winter (Fig. 4*D*). In addition, the probability of a –1.5 SD precipitation anomaly increases in spring ($P < 0.001$) and autumn ($P = 0.01$) in 2006–2080 relative to 1920–2005, with spring occurrence increasing by ~75% and autumn occurrence increasing by ~44%—which represents a substantial and statistically significant increase in the risk of extremely low-precipitation events at both margins of California's wet season. In contrast, there is no statistically significant difference in the probability of a –1.5 SD precipitation anomaly for winter.

Discussion

A recent report by Seager et al. (30) found no significant long-term trend in cool-season precipitation in California during the 20th and early 21st centuries, which is consistent with our

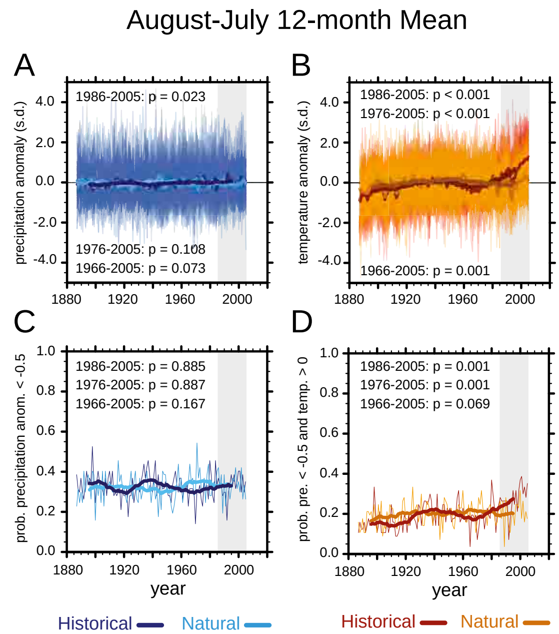

Fig. 3. Influence of anthropogenic forcing on the probability of warm–dry years in California. Temperature and precipitation values are calculated for the August–July 12-mo mean in each year of the CMIP5 Historical and Natural forcing experiments (*Materials and Methods*). The *Top* panels (*A* and *B*) show the time series of ensemble–mean standardized temperature and precipitation anomalies. The *Bottom* panels (*C* and *D*) show the unconditional probability (across the ensemble) that the annual precipitation anomaly is less than –0.5 SDs, and the conditional probability that both the annual precipitation anomaly is less than –0.5 SDs and the temperature anomaly is greater than 0. The bold curves show the 20-y running mean of each annual time series. The CMIP5 Historical and Natural forcing experiments were run until the year 2005. *P* values are shown for the difference between the Historical and Natural experiments for the most recent 20-y (1986–2005; gray band), 30-y (1976–2005), and 40-y (1966–2005) periods of the CMIP5 protocol. *P* values are calculated using the block bootstrap resampling approach of ref. 28 (*Materials and Methods*).

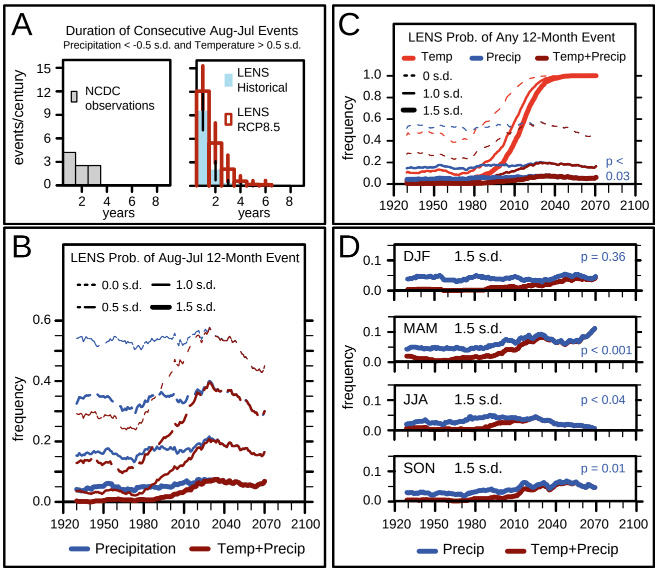

Fig. 4. Projected changes in the probability of co-occurring warm–dry conditions in the 21st century. (*A*) Histogram of the frequency of occurrence of consecutive August–July 12-mo periods in which the 12-mo precipitation anomaly is less than –0.5 SDs and the 12-mo temperature anomaly is at least 0.5 SDs, in historical observations and the LENS large ensemble experiment. (*B*) The probability that a negative 12-mo precipitation anomaly and a positive 12-mo temperature anomaly equal to or exceeding a given magnitude occur in the same August–July 12-mo period, for varying severity of anomalies. (*C*) The probability that a negative precipitation anomaly and a positive temperature anomaly equal to or exceeding a given magnitude occur in the same 12-mo period, for all possible 12-mo periods (using a 12-mo running mean; see *Materials and Methods*), for varying severity of anomalies. (*D*) The unconditional probability of a –1.5 SD seasonal precipitation anomaly (blue curve) and the conditional probability that a –1.5 SD seasonal precipitation anomaly occurs in conjunction with a 1.5 SD seasonal temperature anomaly (red curve), for each of the four 3-mo seasons. Time series show the 20-y running mean of each annual time series. *P* values are shown for the difference in occurrence of –1.5 SD precipitation anomalies between the Historical period (1920–2005) and the RCP8.5 period (2006–2080).

findings. Further, under a scenario of strongly elevated greenhouse forcing, Neelin et al. (31) found a modest increase in California mean December–January–February (DJF) precipitation associated with a local eastward extension of the mean subtropical jet stream west of California. However, considerable evidence (8–11, 31–33) simultaneously suggests that the response of northeastern Pacific atmospheric circulation to anthropogenic warming is likely to be complex and spatiotemporally inhomogeneous, and that changes in the atmospheric mean state may not be reflective of changes in the risk of extreme events (including atmospheric configurations conducive to precipitation extremes). Although there is clearly value in understanding possible changes in precipitation, our results highlight the fact that efforts to understand drought without examining the role of temperature miss a critical contributor to drought risk. Indeed, our results show that even in the absence of trends in mean precipitation—or trends in the occurrence of extremely low-precipitation events—the risk of severe drought in California has already increased due to extremely warm conditions induced by anthropogenic global warming.

We note that the interplay between the existence of a well-defined summer dry period and the historical prevalence of a substantial high-elevation snowpack may create particular susceptibility to temperature-driven increases in drought duration and/or intensity in California. In regions where precipitation exhibits a distinct seasonal cycle, recovery from preexisting drought conditions is unlikely during the characteristic yearly dry spell (34). Because California's dry season occurs during the warm summer months, soil moisture loss through evapotranspiration (ET) is typically high—meaning that soil moisture deficits that exist at the beginning of the dry season are exacerbated by the warm conditions that develop during the dry season, as occurred during the summers of 2013 and 2014 (7).

Further, California's seasonal snowpack (which resides almost entirely in the Sierra Nevada Mountains) provides a critical source of runoff during the low-precipitation spring and summer months. Trends toward earlier runoff in the Sierra Nevada have already been detected in observations (e.g., ref. 35), and continued global warming is likely to result in earlier snowmelt and increased rain-to-snow ratios (35, 36). As a result, the peaks in California's snowmelt and surface runoff are likely to be more pronounced and to occur earlier in the calendar year (35, 36), increasing the duration of the warm-season low-runoff period (36) and potentially reducing montane surface soil moisture (37). Although these hydrological changes could potentially increase soil water availability in previously snow-covered regions during the cool low-ET season (34), this effect would likely be outweighed by the influence of warming temperatures (and decreased runoff) during the warm high-ET season (36, 38), as well as by the increasing occurrence of consecutive years with low precipitation and high temperature (Fig. 4*A*).

The increasing risk of consecutive warm–dry years (Fig. 4*A*) raises the possibility of extended drought periods such as those found in the paleoclimate record (14, 39, 40). Recent work suggests that record warmth could have made the current event the most severe annual-scale drought of the past millennium (12). However, numerous paleoclimate records also suggest that the region has experienced multidecadal periods in which most years were in a drought state (14, 39, 41, 42), albeit less acute than the current California event (12, 39, 41). Although multidecadal ocean variability was a primary cause of the megadroughts of the last millenium (41), the emergence of a condition in which there is ~100% probability of an extremely warm year (Fig. 4) substantially increases the risk of prolonged drought conditions in the region (14, 39, 40).

A number of caveats should be considered. For example, ours is an implicit approach that analyzes the temperature and precipitation conditions that have historically occurred with low PMDI years, but does not explicitly explore the physical processes that produce drought. The impact of increasing temperatures on the processes governing runoff, baseflow, groundwater, soil moisture, and land-atmosphere evaporative feedbacks over both the historical period and in response to further global warming remains a critical uncertainty (43). Likewise, our analyses of anthropogenic forcing rely on global climate models that do not resolve the topographic complexity that strongly influences California's precipitation and temperature. Further investigation using high-resolution modeling approaches that better resolve the boundary conditions and fine-scale physical processes (44–46) and/or using analyses that focus on the underlying large-scale climate dynamics of individual extreme events (8) could help to overcome the limitations of simulated precipitation and temperature in the current generation of global climate models.

Conclusions

Our results suggest that anthropogenic warming has increased the probability of the co-occurring temperature and precipitation conditions that have historically led to drought in California. In addition, continued global warming is likely to cause a transition to a regime in which essentially every seasonal, annual, and multiannual precipitation deficit co-occurs with historically warm conditions. The current warm–dry event in California—as well as historical observations of previous seasonal, annual, and multiannual warm–dry events—suggests such a regime would substantially increase the risk of severe impacts on human and natural systems. For example, the projected increase in extremely low precipitation and extremely high temperature during spring and autumn has substantial implications for snowpack water storage, wildfire risk, and terrestrial ecosystems (47). Likewise, the projected increase in annual and multiannual warm–dry periods implies increasing risk of the acute water shortages, critical groundwater overdraft, and species extinction potential that have been experienced during the 2012–2014 drought (5, 20).

California's human population (38.33 million as of 2013) has increased by nearly 72% since the much-remembered 1976–1977 drought (1). Gains in urban and agricultural water use efficiency have offset this rapid increase in the number of water users to the extent that overall water demand is nearly the same in 2013 as it was in 1977 (5). As a result, California's per capita water use has declined in recent decades, meaning that additional short-term water conservation in response to acute shortages during drought conditions has become increasingly challenging. Although a variety of opportunities exist to manage drought risk through long-term changes in water policy, management, and infrastructure (5), our results strongly suggest that global warming is already increasing the probability of conditions that have historically created high-impact drought in California.

Materials and Methods

We use historical time series of observed California statewide temperature, precipitation, and drought data from the National Oceanic and Atmospheric Administration's NCDC (7). The data are from the NCDC "nClimDiv" divisional temperature–precipitation–drought database, available at monthly time resolution from January 1895 to the present (7, 25). The NCDC nClimDiv database includes temperature, precipitation, and multiple Palmer drought indicators, aggregated at statewide and substate climate division levels for the United States. The available Palmer drought indicators include PDSI, the Palmer Hydrological Drought Index (PHDI), and PMDI.

PMDI and PHDI are variants of PDSI (25–27, 48, 49). PDSI is an index that measures the severity of wet and dry anomalies (26). The NCDC nClimDiv PDSI calculation is reported at the monthly scale, based on monthly temperature and precipitation (49). Together, the monthly temperature and precipitation values are used to compute the net moisture balance, based on a simple supply-and-demand model that uses potential evapotranspiration (PET) calculated using the Thornthwaite method. Calculated PET values can be very different when using other methods (e.g., Penman–Monteith), with the Thornthwaite method's dependence on surface temperature creating the potential for overestimation of PET (e.g., ref. 43). However, it has been found that the choice of methods in the calculation of PET does not critically influence the outcome of historical PDSI estimates in the vicinity of California (15, 43, 50). In contrast, the sensitivity of the PET calculation to large increases in temperature could make the PDSI inappropriate for calculating the response of drought to high levels of greenhouse forcing (15). As a result, we analyze the NCDC Palmer indicators in conjunction with observed temperature and precipitation data for the historical period, but we do not calculate the Palmer indicators for the future (for future projections of the PDSI, refer to refs. 15 and 40).

Because the PDSI is based on recent temperature and precipitation conditions (and does not include human demand for water), it is considered an indicator of "meterological" drought (25). The PDSI calculates "wet," "dry," and "transition" indices, using the wet or dry index when the probability is 100% and the transition index when the probability is less than 100% (26). Because the PMDI always calculates a probability-weighted average of the wet and dry indices (27), the PDSI and PMDI will give equal values in periods that are clearly wet or dry, but the PMDI will yield smoother transitions between wet and dry periods (25). In this work, we use the PMDI as our primary drought indicator, although we note that the long-term time series of the PMDI is similar to that of the PDSI and PHDI, particularly at the annual scale considered here (Figs. S1 and S2).

We analyze global climate model simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5) (51). We compare two of the CMIP5 multimodel historical experiments (which were run through 2005): (*i*) the Historical experiment, in which the climate models are prescribed both anthropogenic and nonanthropogenic historical climate forcings, and (*ii*) the Natural experiment, in which the climate models are prescribed only the nonanthropogenic historical climate forcings. We analyze those realizations for which both temperature and precipitation were available from both experiments at the time of data acquisition. We calculate the temperature and precipitation values over the state of California at each model's native resolution using all grid points that overlap with the geographical borders of California, as defined by a high-resolution shapefile (vector digital data obtained from the US Geological Survey via the National Weather Service at www.nws.noaa.gov/geodata/catalog/national/html/us_state.htm).

We also analyze NCAR's large ensemble ("LENS") climate model experiment (29). The LENS experiment includes 30 realizations of the NCAR CESM1. This large single-model experiment enables quantification of the uncertainty arising from internal climate system variability. Although the calculation of this "irreducible" uncertainty likely varies between climate models, it exists independent of uncertainty arising from model structure, model parameter values, and climate forcing pathway. At the time of acquisition, LENS results were available for 1920–2005 in the Historical experiment and 2006–2080 in the RCP8.5 (Representative Concentration Pathway) experiment. The four RCPs are mostly indistinguishable over the first half of the 21st century (52). RCP8.5 has the highest forcing in the second half of the 21st century and reaches ∼4 °C of global warming by the year 2100 (52).

Given that the ongoing California drought encompasses the most extreme 12-mo precipitation deficit on record (8) and that both temperature and many drought indicators reached their most extreme historical values for California in July 2014 (7) (Fig. 1 and Figs. S1 and S2), we use the 12-mo August–July period as one period of analysis. However, because severe conditions can manifest at both multiannual and subannual timescales, we also analyze the probability of occurrence of co-occurring warm and dry conditions for multiannual periods, for all possible 12-mo periods, and for the winter (DJF), spring (March–April–May), summer (June–July–August), and autumn (September–October–November) seasons.

We use the monthly-mean time series from NCDC to calculate observed time series of statewide 12-mo values of temperature, precipitation, and PMDI. Likewise, we use the monthly-mean time series from CMIP5 and LENS to calculate simulated time series of statewide 12-mo and seasonal values of temperature and precipitation. From the time series of annual-mean values for each observed or simulated realization, we calculate (*i*) the baseline mean value over the length of the record, (*ii*) the annual anomaly from the baseline mean value, (*iii*) the SD of the detrended baseline annual anomaly time series, and (*iv*) the ratio of each individual annual anomaly value to the SD of the detrended baseline annual anomaly time series. (For the 21st-century simulations, we use the Historical simulation as the baseline.) Our time series of standardized values are thereby derived from the time series of 12-mo annual (or 3-mo seasonal) mean anomaly values that occur in each year.

For the multiannual analysis, we calculate consecutive occurrences of August–July 12-mo values. For the analysis of all possible 12-mo periods, we generate the annual time series of each 12-mo period (January–December, February–January, etc.) using a 12-mo running mean. For the seasonal analysis, we generate the time series by calculating the mean of the respective 3-mo season in each year.

We quantify the statistical significance of differences in the populations of different time periods using the block bootstrap resampling approach of ref. 28. For the CMIP5 Historical and Natural ensembles, we compare the populations of the August–July values in the two experiments for the 1986–2005, 1976–2005, and 1966–2005 periods. For the LENS seasonal analysis, we compare the respective populations of DJF, March–April–May, June–July–August, and September–October–November values in the 1920–2005 and 2006–2080 periods. For the LENS 12-mo analysis, we compare the populations of 12-mo values in the 1920–2005 and 2006–2080 periods, testing block lengths up to 16 to account for temporal autocorrelation out to 16 mo for the 12-mo running mean data. (Autocorrelations beyond 16 mo are found to be negligible.)

Throughout the text, we consider drought to be those years in which negative 12-mo PMDI anomalies exceed –1.0 SDs of the historical interannual PMDI variability. We stress that this value is indicative of the variability of the annual (12-mo) PMDI, rather than of the monthly values (compare Fig. 1 and Figs. S1 and S2). We consider "moderate" temperature and precipitation anomalies to be those that exceed 0.5 SDs ("0.5 SD") and "extreme" temperature and precipitation anomalies to be those that exceed 1.5 SDs ("1.5 SD").

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EXHIBIT 5

Environmental effects on flying migrants revealed by radar

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Abstract

Migratory animals are affected by various factors during their journeys, and the study of animal movement by radars has been instrumental in revealing key influences of the environment on flying migrants. Radars enable the simultaneous tracking of many individuals of almost all sizes within the radar range during day and night, and under low visibility conditions. We review how atmospheric conditions, geographic features and human development affect the behavior of migrating insects and birds as recorded by radars. We focus on flight initiation and termination, as well as in-flight behavior that includes changes in animal flight direction, speed and altitude. Several similarities and differences in the behavioral responses of different aerial migrants include an overlooked similarity in the use of thermal updrafts by very small (e.g., aphids) and very large (e.g., vultures) migrants. We propose that many aerial migrants modulate their migratory flights in relation to the interaction between atmospheric conditions and geographic features. For example, aerial migrants that encounter crosswind during flight may terminate their flight or continue their migration and may also drift or compensate for lateral displacement depending on their position (over land, near the coast or over sea). We propose several promising directions for future research, including the development and application of algorithms for tracking insects, bats and large aggregations of animals in weather radars. Additionally, an important contribution will be the spatial expansion of aeroecological radar studies to Africa, most of Asia and South America where no such studies have been undertaken. Quantifying the role of migrants in ecosystems and specifically estimating the number of departing birds from stopover sites using low-elevation radar scans is important for quantifying migrant-habitat relationships. This information, together with estimates of population demographics and migrant abundance, can help resolve the long-term dynamics of migrant populations that face large-scale environmental changes.

Keywords

Behavioral responses, Bird migration, Flight behavior, Geographic features, Human development, Insect migration, Meteorological conditions, Radar aeroecology.

1. Introduction

Migratory animals are affected by various environmental factors before, during and after their journeys. Specifically, flying migrants have evolved different mechanisms to accomplish their travels by sensing and responding (Bauer et al. 2011, Reynolds et al. 2016) to their dynamic aerial habitat (Womack et al. 2010, Diehl 2013, Reynolds et al. 2018). Inappropriate response to environmental heterogeneity and dynamics could strongly jeopardize migrant fitness due to direct mortality or through carry over effects that may lower reproductive output (Newton 2008). Although some important progress has been made in recent years (e.g. Krauel et al. 2015, Shamoun-Baranes et al. 2017, Reynolds et al. 2018), we still lack good understanding of how aerial migrants sense and respond to their dynamic habitat.

The study of aerial migratory movements using radar has been instrumental in revealing how environmental factors affect migrants (Kerlinger and Gauthreaux 1985, Riley et al. 1999, Kelly et al. 2012, Bauer et al. 2017). This is because radars may simultaneously track the movement of all animals (that could be as small as aphids of ~0.5 mg) in their range and may operate for decades (Hu et al. 2016, Stepanian and Wainwright 2018). Nevertheless, radars alone cannot usually identify individual species and track migrants for their entire route. Other tracking methods, such as miniaturized GPSs and light-level geolocators, can track a limited number of individual birds and bats for their entire journeys, but cannot track most flying insects (Kissling et al. 2014, but see Wikelski et al. 2006). Due to their size, GPS devices can usually be applied only to relatively large-bodied species, excluding many bird and bat species that are too small to bear the device's weight (Bridge et al. 2011). Geolocators (Bridge et al. 2011) are characterized by a low spatial resolution (dozens to hundreds of kilometers) and a low measurement frequency (one position point per day, at most) (McKinnon et al. 2013). Therefore, radars are an important tool for exploring how environmental conditions affect the behavioral ecology of aerial migrants of almost all sizes at a high rate and spatial resolution (Drake and Reynolds 2012, Chilson et al. 2018, Drake and Bruderer

2018; see also list of radar types that are being used to track the movement of aerial migrants in Hüppop et al. 2019).

To this end, the present review aims: 1) to synthetize how radar research has contributed to our understanding of behavioral responses of migrants to environmental factors, thereby promoting our knowledge of the causes, mechanisms, patterns and consequences of migratory movements, 2) to identify gaps in our understanding of animal aeroecology that could be addressed using radar technology, and 3) to offer promising future research directions in radar aeroecology of animal migration. We specifically explore how atmospheric conditions, geographic factors and human development facilitate the initiation and termination of migratory flights, as well as affecting flight speed, direction and altitude choice of migrating insects and birds (but not bats, see Box 1). In addition, we discuss similarities and differences in behavioral responses to environmental conditions between different taxa of migrating animals. We further highlight the importance of interactions between geographic features and atmospheric conditions that modulate the behavior of aerial migrants and suggest that improved radar technology, data analysis and increased geographic coverage of radar studies may advance our understanding of animal-habitat relationships and the role of migrants in ecosystems. Furthermore, we highlight the need for future research to be directed towards long-term and large-scale studies that can reveal the combined effects of large-scale environmental changes on migrant populations.

2. Behavioral responses to environmental conditions

The migration journey includes specific sequential stages: initiation or departure, cross-country flight or 'transmigration', and termination. This sequence is repeated if migration is suspended at intermittent stopover sites. Each of these stages presumably requires the sensing of specific cues under a variety of environmental conditions and necessitates the application of specific decision rules to be accomplished (Bauer et al. 2011). The decision by animals to initiate flight, to terminate it, and to behave in a certain way during in-flight migratory phases by changing their speed, direction and altitude depends on several endogenous and exogenous factors. These factors include the animal's state, the properties of the resting site and the ambient meteorological conditions. The animal's behavioral decisions have consequences for fitness through their effects on survival, metabolism, navigation and the timing of migration (Alerstam 1991, Liechti 2006, Chapman et al. 2010, Mouritsen 2018), as well as on reproduction which often follows migration periods within the animal's annual routine (McNamara et al. 1998). In this section, we discuss the migrants' behavioral responses as recorded by radars. These responses are broadly divided to two categories: (1) flight initiation, termination and migration intensity; and (2) in-flight behavior, which includes changes in speed, direction and altitude. We review these responses for insects and birds, highlighting similarities and differences in the responses of these two taxa while noting the extent of available empirical information about these responses. Behavioral responses of migrants acquired by radar are discussed in relation to atmospheric conditions, grouped into three meteorological categories: (1) wind, (2) precipitation, clouds and fog, and (3) temperature and thermal updrafts. Additionally, the responses of aerial migrants are discussed with regards to three geographic features: (1) topography, (2) water-land interface, and (3) human and infrastructure development (Table 1 and 2). Furthermore, we provide an online Appendix with detailed information on behavioral responses of insects and birds, in relation to the aforementioned environmental attributes.

2.1 Flight initiation, termination and migration intensity

When to begin or end a migratory flight is an important decision for animal fitness. This decision may consider prevailing and expected external factors such as ambient temperature and wind direction, internal factors such the animal's fuel stores and innate motivation, as well as the geographical context, for example the position of the animal in relation to wide ecological barriers such as seas and deserts. We discuss below how flight initiation, termination and migration intensity varies in response to different atmospheric and geographic factors (Table 1; Appendix).

Atmospheric conditions

Atmospheric conditions may constrain but could also assist migrating insects and birds. Using information regarding current and expected atmospheric conditions when deciding to depart or land may increase the survival and the chance to land in a suitable area while decreasing the animal's metabolic cost of transport. Wind speed and direction have pronounced effects on migratory departure and landing in insects and birds, and consequently these may affect the intensity of migration aloft (Rose et al. 1985, Dokter et al. 2011, Chapman et al. 2015a, Chapter 11 in Drake and Reynolds 2012, Hu et al. 2016, Nilsson et al. 2019).

Precipitation inhibits take-off in both insects and birds, and induces flight termination in many cases (Chapter 11 in Drake and Reynolds 2012, but see Drake et al. 1981). Precipitation is a term that ranges from drizzle to cloudburst events, including hail precipitation and snow. How flying migrants react to these different types of precipitation is not well documented, mostly because recording the behavioral responses of migrants flying under almost any type of precipitation is nearly impossible using radars (Box 2). Large insects and birds can keep flying under light rain and drizzle, but heavy rain physically hampers the flight for insects by inflicting high forces of the rain drops on their bodies and wings. Heavy, widespread rainfall also inhibits bird flight initiation and induces its termination (Richardson 1978a, 1990). Yet, one must bear in mind that radars are limited in their ability to detect biological targets under rainfall and thus their usefulness for studying animal behavior under rainy conditions is low (see Box 2). The effects of fog on flight initiation and termination are not well understood, and despite its potential significance on migration timing, hardly any empirical data exist (but see Feng et al. 2006).

Temperature variations can be critical for take-off and maintenance of flight in insects. Because insects are poikilotherms, temperature requirements for flight must be satisfied before flight can be commenced (Chapter 9 in Drake and Reynolds 2012) and insects usually have a threshold temperature below which flight cannot be initiated and/or maintained (e.g., Dudley 2000, Chapter 9 in Drake and Reynolds 2012). In nocturnally migrating birds, flight ability is not limited by temperature, but increasing temperatures in spring and decreasing temperatures in autumn promote departure from staging sites and increase migration intensity (Richardson 1978a, 1990, Van Doren and Horton 2018). Soaring birds depend on thermal updrafts forming in the boundary layer during the day (Spaar and Bruderer 1996, 1997), and thermal convection is probably important for some butterflies that are adapted to soaring flight (e.g., Gibo and Pallett 1979). Yet, there are currently no empirical data from radar studies regarding the effect of thermal updrafts on flight initiation and termination of soaring birds and insects.

Geographical features

Empirical studies regarding the effects of geographic features, including topography, the water-land interface and man-made structures, on the initiation, termination and intensity of migration, are rare. Direct effects of topography are not well documented, largely because of the limitations of scanning radar technology in recording meaningful data in mountainous areas (Box 2). However, the use of other types of radars and the combination of radars and other measuring devices might allow better exploring such effects in the future. For example, the funneling of passerine migration through mountain passes and other topographic corridors has been recorded in the Appalachians (Williams et al. 2001) and the Alps (Bruderer and Jenni 1990). To the best of our knowledge, no similar radar data from insects is available. In addition to mountain ranges, wide waterbodies that are located within migration flyways may also affect the intensity of migration. Although nocturnal insect migration is usually halted by the onset of dawn (Drake and Reynolds 2012), this termination of movement is overridden if insect migrants find themselves over water. Accordingly, the range of insect movement under these circumstances may be considerably extended (Drake et al. 1981, Feng et al. 2009), with associated elevated risks of exhaustion and drowning. Similarly, birds may decide whether to stop, follow the coast or cross the sea by considering the possible fatal consequences of drifting over the sea (Alerstam and Pettersson 1977, Horton et al. 2016a).

In recent centuries, anthropogenic landscape modification has influenced much of the Earth's surface, and light pollution is one of the clearest examples (Cabrera-Cruz et al. 2018). Insects and birds are mostly attracted to artificial light and some incidental radar observations recorded concentrations of insects around lights of large towns (e.g. Wad Madani in Sudan, see p. 275 in Drake and Reynolds 2012). Similarly, birds stop over at a disproportionately high rate in large city parks (Buler and Dawson 2014) and nearby highly light-polluted areas (Van Doren et al. 2017, McLaren et al. 2018).

2.2 In-flight behavior: speed, direction and altitude

In-flight behavioral responses to different environmental conditions can have direct (e.g., reducing the chance of mortality during flight) or indirect (e.g., improving the physiological state of the individual before reproducing) fitness consequences. These behavioral responses can include changing speed, direction and altitude during flight (Table 2). Insects and birds are subject to physical constraints when it comes to changing their airspeed, and the animal may be able to fully compensate for drift only when its airspeed is higher than that of the surrounding airflow (see Box 3). In addition to changes in flight speed and direction, flight altitude selection may facilitate migration by selecting specific atmospheric layers with airflows that align with seasonally preferred migration directions.

Atmospheric conditions

Wind is one of the most important atmospheric factors that affect the flight behavior of insects and birds (Shamoun-Baranes et al. 2017, Reynolds et al. 2018). The optimal response of a flapping migrant to tailwinds is airspeed reduction, to decrease the metabolic cost of flight, while increased airspeed is expected in headwind conditions (Pennycuick 1978). The response of insects to wind conditions is strongly constrained by their low airspeeds (Schaefer 1976, Larkin 1991), which is virtually negligible in small insects. Beside this, overall responses to wind by insects and birds are comparable (Table 2). Migrating insects experiencing crosswinds show a variety of responses, including complete and partial drift (Chapman et al. 2010, 2015a,b, Reynolds et al. 2016). However, the variation of responses depends on the size and flight power of the species and the speed of the airflow (Hu et al. 2016). A variety of responses to crosswinds was also observed in birds. Such response depends on bird morphology and its preferred flight mode, as well as the geographic context, for example depending on the proximity to the coast (Green 2001, Horton et al. 2016b, Becciu et al. 2018). Selection of specific flight altitudes is related to strong wind support both in insects and birds (insects: Drake 1985, Wood et al. 2006, Drake and Reynolds 2012; birds: Bruderer and Liechti 1995, Green 2004, Dokter et al. 2011, Kemp et al. 2013).

Despite the limitations of radar technology to track flying birds and insects in rain (Box 2), some data exist regarding flight behavior in precipitating conditions. Under convective rain, insect flight can continue outside the precipitating cumulonimbus cells (Leskinen et al. 2011, Browning et al. 2011, Drake and Reynolds 2012). Moreover, large insects can continue flying in light rain (Drake et al. 1981). The mechanisms by which precipitation affects the flight of insects and birds are not well understood, and most of our knowledge regarding these mechanisms is based on laboratory studies (Webb and King 1984, Ortega-Jimenez and Dudley 2012, Dickerson et al. 2014). The effects of fog and low clouds on in-flight behavior of migrating animals are poorly studied. We note that due to associated reduced visibility, flight within fog may directly affect orientation and could indirectly alter animal speed and altitude.

Insects and birds can tolerate a broad range of temperatures once they are in flight, but temperature itself does not affect flight speed and direction. Several groups of diurnal migrating insects and birds exploit convective thermals that are columns of ascending air which lift insects and birds to higher altitude above ground (Box 3, but see Geerts and Miao 2005). These include mainly, but not exclusively, small insects (e.g., aphids) and large birds (e.g., vultures).

Geographical features

The effects of topography on insect flight behavior are understudied in radar research (but see Chapter 11 in Drake and Reynolds 2012), probably because entomological radars may not be suitable for recording insect echoes in mountainous environments (see Box 2). In ornithology, the use of tracking radars, and marine scanning radar in some cases, allowed recording migrants passing in a complex terrain. It seems that, in some cases, migrating birds deviate from their regular flight direction to follow local topography through mountain passes (Williams et al. 2001).

Flight over the sea could be risky for many insects and birds, particularly under harsh weather conditions and specifically when strong winds are blowing from land towards the sea. Insects have a predisposition to resist being carried over the sea (Russell and Wilson 1996, Shashar et al. 2005; but see Chapman et al. 2010), unless they are habitual transoceanic migrants (e.g. Drake et al. 1981, Feng et al. 2006, 2009). The flight behavior of terrestrial birds is variable in response to the water-land interface, depending on body size, flight mode and prevailing winds (Table 2). Seabirds usually migrate across open waters without apparent barriers to their movements. Yet, in some occasions, such as those experienced when crossing a strait, seabirds may benefit from coastal orographic features during flight (Mateos-Rodríguez and Arroyo 2011). Notably, the flight behavior of seabirds near coasts may vary depending on their flight mode and the direction of the wind (Mateos-Rodríguez and Arroyo 2011).

Despite the well-known attraction of many insects towards artificial lights, insects engaged in steady high altitude nocturnal migration do not appear to be affected by lights on the ground (see p. 276 in Drake and Reynolds 2012), with some exceptions (Feng et al. 2009). On-the-ground anthropogenic development has well-known consequences on birds engaged in active migration, and radars have been widely used to study the effect of wind turbines and light pollution on the movement of migrating birds (Table 2). Nocturnal migrating birds adjust flight directions, altitudes and speeds near wind turbine facilities (e.g. Mabee et al. 2006, Cabrera-Cruz et al. 2017). Artificial lights also disrupt the flight of migrating birds (Bruderer et al. 1999, Van Doren et al. 2017, Cabrera-Cruz et al. 2018), particularly under poor weather and low visibility conditions (Larkin and Frase 1988). Flight disruption could have implications for migrant conservation (Hüppop et al. 2019).

3. Integration and synthesis

Similarities and differences in behavioral responses to environmental conditions

Migrating insects and birds present similarities and differences when responding to environmental factors (Tables 1 and 2). Wind is likely to be the most important factor affecting the migration of both insects and birds (see Box 3), although the evidence is not unequivocal (e.g., Van Doren and Horton 2018). Despite large variations in body size and wing morphology within and between insects and birds, there are shared preferable atmospheric conditions. Winds that blow in the intended direction of migration (i.e., tailwinds) trigger take-off for migratory flights and probably cause peaks of migration intensity aloft (Hu et al. 2016). The capacity of an individual to reach high airspeed while flying dictates its ability to overcome unwanted movement of the airflow, such that the accomplishment of migration for small insects like aphids is much more dependent on airflow blowing towards the intended goal than for larger insects or birds (Chapman et al. 2011). Among birds, wing morphology, body mass and flight mode are important factors that affect flight flexibility in changing wind conditions (Newton 2008), and the behavioral response to wind permits broad categorization of aerial migrants (Box 3).

In birds, the effects of rain may be indirect via wetting the plumage, leading to increased weight, and by impeding visibility (Emlen and Demong 1978, Liechti 1986). Insects, and probably birds as well, avoid heavy rain events by tumbling downward before reaching thunderstorm's powerful updrafts that can lead them to mortality by freezing (Browning et al. 2011). Precipitation is known to induce flight termination in migrating insects (Chapter 11 in Drake and Reynolds 2012, Reynolds et al. 2018), but evidence from birds is rare.

The effects of fog and low clouds on aerial migrants have rarely been studied. Fog is usually found in calm weather conditions (e.g., weak or no winds) at the ground level and its development might be associated with good conditions for insect migration (Feng et al. 2006). Although birds may benefit from the calm weather that is associated with the formation of fog, the low visibility associated with fog may cause disorientation and avoidance of travelling within the fog (Pastorino et al. 2017, Panuccio et al. 2019). We note that precipitation, clouds and fog usually coincide with specific conditions of other atmospheric parameters (e.g. temperature, humidity and wind speed) such that it is often difficult to disentangle their single effects on migrating insects and birds (see below).

How temperature affects insect and bird migration has been investigated much more extensively. Insects need warm temperatures to take-off although when flying they can tolerate somewhat lower temperatures, whereas birds are generally more tolerant to both low and high temperatures. A general pattern observed in both insects and birds is that migration is triggered by rising temperature in spring and dropping temperature in autumn (Richardson 1978a, 1990, Mikkola 2003). A consequence of solar radiation is the formation of thermal convection in the diurnal boundary layer, which is exploited by diurnal migrating insects and birds. Soaring landbirds are the most evident example of adaptation to such atmospheric phenomenon (Spaar and Bruderer 1996), but also smaller migrants such as aphids and several butterfly species use thermal updrafts to gain altitude during their migration flights (Schaefer 1976, Box 3).

We note that behavioral responses to weather conditions can be complex. Migratory decisions are often based on multilevel input from the atmosphere. For instance, limited visibility, changes in temperature, wind speed and direction, and the limited availability of convective thermals are all associated with rainy weather. One or more of these factors may cause migrants to descend or land. In insects, ambient temperatures falling below the flight threshold, cessation of convection (which many diurnal insect migrants require to remain aloft) and strong downdraughts associated with convective rainstorms can force insects to descend or land (Russell 1999, Reynolds et al. 2018). Nocturnal birds in migration reach higher altitude taking advantage of vertical wind shear, which arises in particular synoptic situations related to the magnitude and direction of large-scale horizontal temperature gradients (Dokter et al. 2013). The crossing of large water bodies may challenge flying migrants, invoking various behavioral responses. When flying insects and birds migrate over a large water body, they may react quite differently to cues that normally cause flight termination. Insects usually disregard these cues and continue flying while birds reorient to the closest coast to stop over. This takes place mostly around dawn for nocturnal migrants, and dusk for diurnal ones (Richardson 1978b, Drake et al. 1981, Feng et al. 2009, Archibald et al. 2017).

The interaction between atmospheric conditions and geographic features in the response of flying migrants

In the case of aerial migrants, several behavioral responses to atmospheric conditions are modulated by geographic features, constituting interactions, for example crosswinds (Fig. 1). Migrating land-birds may drift laterally under crosswind conditions when flying over land far from the coast. Yet, under similar wind conditions, the birds will try overcoming lateral drift when they are found close to the shoreline, presumably to reduce the chances of being carried over the sea which could be fatal (Horton et al. 2016b, Becciu et al. 2018). Interestingly, nocturnally migrating insects that usually terminate their flight at dawn continue flying at that time when found over water (Drake et al. 1981, Feng et al. 2006, 2009). Yet, evidence for the modulation of insect flight behavior in relation to wind over land and when flying close or over the sea has not been documented to date. In any case the low airspeed of insects may result in a low capacity to resist the wind (Drake and Reynolds 2012). Diurnally-migrating dragonflies have also been documented flying in the dark under foggy conditions, which are common during migration events. The insects, which usually halt their migration at or near sunset, probably continued flying because the fog prevented them from seeing the ground and specifically the coastline (Feng et al. 2006).

A different interaction between atmospheric conditions and geographic features relates to bird flight behavior in relation to wind in mountainous areas. Wind was found to modulate the tendency of low-flying birds to circumvent mountains instead of crossing them (Williams et al. 2001), which is more prevalent under headwind conditions when most birds fly at relatively low altitudes (Liechti 1986). Under tailwind conditions, birds usually cross mountain ranges in higher numbers and disregard local topography (Lack and Lack 1951). We note that high resolution wind flow description and simulation of movement over complex terrain could provide deeper understanding of the environmental factors faced by travelling birds. In a recent simulation study based on radar data, topography was found to guide the wind flow and consequently changed the profitability of different flight paths due to its effect on flight energy costs (Aurbach et al. 2018). This combined effect of wind and topography therefore leads to concentrations of bird migration at specific flyways under certain meteorological conditions (Aurbach et al. 2018). Although the seasonal near-ground passage of hordes of insects through high mountain passes is well known (e.g., Lack and Lack 1951, Aubert et al. 1976; see Box 2), no radar studies have documented this phenomenon, nor insect concentration in response to lee waves, topographic wind eddies and rotors, when migrating through mountainous terrain (Chapter 11 in Drake and Reynolds 2012).

The response of aerial migrants to interactions between atmospheric conditions and man-made structures are largely understudied by radars. Such studies are important for understanding the mechanisms by which anthropogenic structures cause mortality of aerial migrants (Hüppop et al. 2019), for example the attraction of nocturnally migrating birds to lights of tall towers when flying within low clouds (Larkin and Frase 1988; Fig. 1). Given the abundance of tall anthropogenic structures in many regions in the world, it is important to characterize this interaction and determine measures to mitigate the consequences (Hüppop et al. 2019).

4. Future directions

Despite the advancement of our understanding of the migrants' behavioral responses in relation to meteorology and geographic features as revealed by radars, there are still substantial gaps in our knowledge that warrant future investigation. In particular, the effects of several environmental factors such as precipitation and fog, landscape topography and man-made structures, are currently understudied. Beyond the need to address the effects of specific environmental factors, we discuss several promising research directions that may be investigated using radars, and which could broadly contribute to our understanding of migrants' aeroecology.

Identifying and tracking of additional taxa by radars

Recently, weather radar networks in Europe and the U.S.A. have been successfully applied to study the broad front migration of birds, of which most are songbirds (Dokter et al. 2018, Van Doren and Horton 2018, Nilsson et al. 2019). The application of algorithms to study the movement of birds that congregate in flocks during migration, including waterbirds (e.g., geese and herons) and soaring migrants (e.g., storks and eagles) using weather radars data are currently largely missing (but see Buler et al. 2012 for a study of over-wintering waterfowl). One of the most important gaps in knowledge relates to the unfortunate scarcity of bat migration research (Box 1), particularly given the importance of migratory bats in various ecosystems and their role in insect pest control (McCracken et al. 2012). Another set of algorithms that have already been developed (Chilson et al. 2012, Stepanian et al. 2014, 2016), but have not been largely implemented in data analysis from weather radar networks relates to the detection of insect movements. The future development and implementation of algorithms that will extract data from a wider diversity of aerial taxa may substantially improve our ability to study how these animals are affected by environmental conditions. Specifically, the development and application of algorithms to detect insects in weather radars is expected to revolutionize our capacity to quantify insect migration by allowing a spatially expansive investigation of insect movement across entire continents. Such development will enhance our abilities to quantify their flux and roles in various natural and agricultural systems (Hu et al. 2016). Notably, the development and application of the aforementioned algorithms will allow comprehensive cross-taxa comparisons of the responses of aerial migrants to environmental conditions. Moreover, algorithms that will detect and track bird flocks at real time using data from weather radars may improve existing warning systems and will further reduce the collisions of aerial migrants with civil and military aviation (e.g., van Gasteren et al. 2019).

Increasing the coverage of aeroecological radar studies

Unlike the study of migrant aeroecology using local radars and large-scale networks of weather radars in the United States (i.e., NEXRAD) and Europe (i.e., OPERA), which successfully monitor mass movements of aerial organisms over regional (e.g., Dokter et al. 2011, Farnsworth et al. 2016, Hu et al. 2016) and continental scales (Lowery and Newman 1966, Van Doren and Horton 2018, Nilsson et al. 2019), the scarcity of radar studies from the African continent, most of Asia and South America limits our knowledge of animal aeroecology in these vast areas. The development of processing and analytical methodologies, as well as knowledge sharing and inter-disciplinary data integration for identifying and tracking aerial migrants across Europe was conducted during the COST (European Cooperation in Science and Technology) action ENRAM (European Network for the Radar surveillance of Animal Movement in Europe; www.enram.eu) during 2013-2017. Using data from existing radar networks in additional regions of the world where such networks exist (e.g., India and China) is a promising way to increase the geographic coverage of animal migration research and for exploring migrant aeroecology in various systems (Hüppop et al. 2019). Nevertheless, we note that studies involving local radars are extremely useful for researching migration properties that cannot be studied using weather radars, including the identification of the species involved in some cases (e.g., Horvitz et al. 2014), the extraction of animal wingbeat frequency (Bruderer and Popa-Lisseanu 2005) and detailed flight trajectories (Larkin and Frase 1988). Local radars are also important for cross-calibrating weather radar systems (Nilsson et al.

2018, Liechti et al. 2019). Moreover, the use of additional existing meteorological measuring platforms, such as wind profilers, is a promising direction to substantially increase our knowledge of aerial migration in different parts of the world (Weisshaupt et al. 2018). We note that seabirds have been mostly tracked with radars from the coast, but recently a radar study showing seabird foraging movements and social interactions was done using radar on board a fishing vessel (Assali et al. 2017). The use of shipborne radars for tracking bird migration across seas could allow for the exploration of novel research questions, such as the effects of human-induced food resources on migrating seabirds far from the shore. Airborne radars can be an important tool which was used mostly to detect insect migration and successfully describe their behavioral responses to atmospheric conditions (Geerts and Miao 2005, but see also Chapter 11 in Drake and Reynolds 2012). This type of radar can be used to cover areas where it is not possible to use land-based radars (e.g., over sea).

Quantifying the role of migrants in ecosystems

We propose that quantifying the abundance and distribution of migrating animals using radars is a first critical step for better understanding their roles in ecosystem functions and services. This is because migrants interact with organisms in different ecosystems and participate in massive biological transport processes of nutrients and energy (Bauer and Hoye 2014, Bauer et al. 2017). Knowledge regarding the abundance and distribution of migrants is important for understanding their ecology and could be critical for their conservation (Hüppop et al. 2019). Recently, substantial progress has been made with radar-based calculations of transport phenomena involving both migrating insects (Hu et al. 2016) and birds (Dokter et al. 2018, Horton et al. 2019) , but such studies are still very rare.

Despite the importance of characterizing animal-habitat associations, only a few studies have so far estimated the densities of migrating birds departing from stopover sites using weather radars. These studies were done using low-elevation radar scans that allowed quantifying the number of departing birds from areas that are within the coverage range of the radar. To date, all these studies were made in North America (e.g., Bonter et al. 2009, Buler and Dawson 2014, Lafleur et al. 2016). Further application of this approach may help in assessing the importance of different land uses, habitat types and geographic features on migrating birds in different parts of the world. Importantly, quantifying large-scale habitat relationships of migrants may aid their conservation by assessing their habitat selection criteria (e.g., Buler and Dawson 2014). Moreover, these studies allow reconciling large-scale migration patterns of migrants that are tracked in mid-air with departure decisions of individual animals, thereby exposing the mechanisms by which environmental factors act on the decision of individual animals to depart from stopover sites and continue their migration aloft. In this context, it would be of interest to investigate if mass migration events are the consequence of a synchronized take-off of a huge number of migrants (for example, under certain atmospheric conditions). Interestingly, radar data, especially those collected over many years, may allow measuring the response of migrants to both habitat degradation and habitat restoration activities (Sieges et al. 2014). Furthermore, we note that forecasting high intensity insect (Hu et al. 2016) and bird (Van Doren and Horton 2018) migration over large spatial scales is important for characterizing the properties of migrant-related transport processes, including their dynamics, practical implications (e.g., mass migration of agricultural pests), and future fate under different environmental change scenarios.

Investigating the long-term and large-scale effects of environmental changes on migrant populations

Long-term radar data collection facilitates the investigation of migrant aeroecology at multiple scales in time (from hours to seasons, years and decades) and space (from a single site to a region and an entire continent). Using long-term data to infer about population properties over a continental scale is particularly important for analyzing population trends in the light of ongoing global environmental changes (Kelly et al. 2012, Stepanian and Wainwright 2018). A recent example for a successful application of this approach involves the quantification of population demography indices for the entire population of migrating birds in North America (Dokter et al. 2018). A different approach that produced interesting results combined estimates of future climates with knowledge regarding the response of migrants to atmospheric variables from radar data. This work was able to predict the future properties (e.g., spatial distribution and temporal characteristics) of land-bird migration over North America under projected climate change scenarios (La Sorte et al. 2018). Due to the overall scarcity of long-term analyses of phenological patterns and population dynamics across wide geographic areas, we suggest directing future research efforts towards the long-term and broad-scale investigation of migration patterns in areas where data from radar networks are readily available. Scientists can now use this research framework to investigate how future changes in major environmental conditions (e.g. warming air temperatures; Van Doren and Horton 2018) may influence migration properties, with potential consequences for reproductive output and hence population dynamics following the migration period.

A different aspect that can be modeled is the consequences of anthropogenic structures on aerial migrants. Data from radar-based spatially and temporally resolved migration metrics (e.g., Aurbach et al. 2018) combined with information about the proposed locality and size of structures such as wind farms, can help to model the impacts of future developments at continental and flyway scales. Furthermore, predictive modelling will facilitate the application of risk mitigation measures to, at least partially, overcome potential negative consequences of human development on migrant populations (Hüppop et al. 2019).

Box 1. Extent of radar research on different aerial animal taxa

Searching for keywords in the Scopus® (https://www.scopus.com) database, we found that bats are an under-studied taxonomic group in radar research, totaling only 78 records, with corresponding figures for insects and birds being 326 and 565 records, respectively. To obtain relevant studies we searched for the following terms in article titles, abstracts and keywords: “insect” AND “radar”; ” bird” AND “radar”; and ”bat” AND “radar”. Adding the term “migration” (e.g., “insect” AND “radar” AND “migration”) resulted in 31, 122, and 1 records of migration studies using radar of insects, birds and bats, respectively. The search period was from 1956 until 2018 (accessed: 20th March 2018). Since only a single published article deals with bat migration as detected by radar (Stepanian and Wainwright 2018), we could not include bats in the present review despite their important services and functions in various ecosystems, including seed dispersal, pollination and pest control (Shilton et al. 1999, Medellin and Gaona 1999, Aziz et al. 2017, Medellin et al. 2017). We hope that future advances in radar technology and data analysis will spur on future research on bat migration.

Box 2. Methodological challenges and limitations of radar technology to study environmental effects on animal migration

The effects of various meteorological conditions on migrating insects and birds is now much better understood than in the past, yet some important aspects are still unknown partly due to major methodological challenges. We outline several atmospheric conditions, geographic features and general limitations that currently limit our ability to better understand the aeroecology of migrating animals.

Atmospheric conditions:

1. Rain - The strong attenuation and masking effects of raindrops at typical radar frequencies makes it difficult to detect biological targets in anything other than the lightest precipitation.

2. Fog – The lack of data on the spatial and temporal properties of fog in meteorological databases limits broad-scale analysis of the effects of fog on migrating animals, and only a handful of small scale studies have been so far done to study these effects (e.g., Panuccio et al. 2019).

Geographic features:

1. Topography - Insect echoes on scanning radars at low altitudes are swamped by much stronger ‘clutter’ echoes from ground features in mountainous areas. However, entomological vertical-looking or tracking radars are generally less affected by ground clutter and may thus be applied in the future to address questions related to the effects of topography on migratory departure and termination. In addition, only very few radar studies have so far tracked migrating birds in mountainous areas, and such investigation is important for better understanding how the highly dynamic wind field in these areas affects migrants (Aurbach et al. 2018).

General limitations:

1. Detection of migration at low altitudes - Current dedicated entomological radars can only observe targets from ~150 m above ground level. This results in misrepresentation of a major part of migrating insects that fly at lower altitudes. To overcome this problem, insect radars need to implement a FM-CW, millimeter-wave radar system, which would detect insects flying closer to the ground. A different problem that hinders low elevation detection of flying migrants is the positioning of many radars on high mountains (e.g., Meron radar in Northern Israel; Liechti et al. 2019). It has become clear that much of the migration (e.g., 90% of migration traffic rates) goes undetected in these localities because migration mostly takes place close to the ground.

2. Taxonomic identification - A longstanding issue with radar detection is the lack of precision in identifying and categorizing flying animals. Newly developed radar systems implemented specific algorithms that may classify targets into several broad categories (e.g., insect, passerine, wader, bird flock). A finer identification at the level of a specific taxonomic group (e.g., swifts) or even at the species level will substantially advance our inferences regarding migrant aeroecology (see for

example Horvitz et al. 2014 for a radar study in which birds were identified to the species level using an optical device).

Box 3. Categorizing the response of flying animals to airflow

The response of flying animals to different airflow conditions based mostly on radar studies, permits the broad categorization of flying migrants to the following four categories:

1. Small insects (e.g., aphids) which can only influence movement by selecting whether to ascend into (and stay in) the atmosphere or not (Wainwright et al. 2017);
2. Large insects that can influence their track to a certain extent (e.g., Chapman et al. 2010), but are usually orientating and displacing roughly downwind (Chapman et al. 2016, Reynolds et al. 2016);
3. Birds and bats which may fly fast enough to overcome adverse winds, but due to the high metabolic cost of this behavior usually avoid such flights (Bruderer and Popa-Lisseanu 2005, Liechti 2006, Shamoun-Baranes et al. 2017, Horton et al. 2016b, 2018);
4. Soaring butterflies, birds and bats that use updrafts to gain altitude and then glide towards their destination (Spaar and Bruderer 1996, 1997, Lindhe-Norberg et al. 2000, Horvitz et al. 2014, Reynolds et al. 2018).

Some of the species included in the last category may switch to flapping flight when atmospheric conditions do not facilitate soaring (Meyer et al. 2000, 2003, Spaar and Bruderer 1997). In the marine environment, the flight modes of seabirds range from dynamic soaring in albatrosses and large petrels to pure flapping flight in auks (Mateos-Rodríguez and Bruderer 2012). Interestingly, the largest (i.e., eagles, vultures, pelicans, storks and albatrosses) and the smallest (i.e., aphids) flying animals mostly ascend on convection while most smaller birds such as passerines and larger insects such as moths, use flapping flight.

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ON-LINE APPENDIX - Details of the behavioral responses of migrants in relation to atmospheric conditions and geographic features

1. Flight initiation, termination and migration intensity

Insects

WIND: Radar studies have revealed that wind speed and direction have pronounced effects on migratory departure and landing and consequently on the intensity of migration aloft (Rose et al. 1985, Chapman et al. 2010, 2015a, Drake and Reynolds 2012). Favorable seasonal tailwinds (e.g. northerlies in autumn) are associated with high migration intensity of many insects over the southern UK (Hu et al. 2016). Specifically, seasonally advantageous high-altitude tailwinds promote the initiation and maintenance of migratory flight of autumn generation of the noctuid moth *Autographa gamma* heading south, from northern Europe to the wintering grounds around the Mediterranean Sea (Chapman et al. 2008, 2015b). Airflows associated with synoptic scale fronts can provide short term 'windows' for crucial, seasonally-adaptive movements in directions different from those in which the prevailing wind direction would take the migrants. For example, massive autumn insect migration was associated with the passage of synoptic-scale cold fronts, with insects flying in northerly winds immediately behind the leading edge of the front (e.g., Beerwinkle et al. 1994, Feng et al. 2009, Chapman et al. 2010). Drake et al. (1981) recorded spring movements of moths from the Australian mainland into Tasmania on warm northerly (anticyclonic) airflows *ahead* of an approaching cold front. These rapid seasonal migrations may account for large fluxes of insect biomass (Hu et al. 2016). Additionally, insects are often caught in the outflow boundaries of convective storms (e.g., Achtemeier 1991, Browning et al. 2011) that may disperse insects over long distances (e.g. Wilson and Schreiber 1986) and may also be trapped in the 'eye' or the rear of hurricanes and typhoons (Van den Broeke 2013, Ma et al. 2018).

PRECIPITATION, CLOUDS AND FOG: Responses to, and effects of, rain on insect migration are complex (Drake and Reynolds 2012, Reynolds et al. 2018). In temperate areas, rainy weather may inhibit insect flight because of the associated lower air temperatures (and/or the cessation of convection in the case of small day-flying insects, Russell 1999), and heavy, widespread rainfall inhibits insect flight initiation and induces its termination (Drake and Reynolds 2012, but see Drake et al. 1981). Interestingly, a sudden increase in nocturnal dragonfly migration over the Bohai Sea in northern China coincided with foggy weather (Feng et al. 2006). Probably the flight of this diurnal migrant *Pantala flavescens* were extended after dark because the insects found themselves over the sea, and the foggy conditions commonly associated with the migration events might have also interfered with visual detection of ground features (e.g. the coastline), which might otherwise have promoted landing (Feng et al. 2006). This could be because fog is usually associated with relatively calm conditions at the surface, as indeed found in these heavy-migration nights. The migrants were probably flying above the fog and likely departed for their journey at dusk before the fog formed.

TEMPERATURE AND THERMAL UPDRAFTS: Because insects are poikilotherms, temperature requirements for take-off and maintenance of flight must be satisfied first (Chapter 9 in Drake and Reynolds 2012). Consequently, insects usually have a threshold temperature below which flight cannot be initiated and/or maintained (e.g., Dudley 2000, Drake and Reynolds 2012). Temperature thresholds are highly variable depending on the species, but various radar studies report that insects are usually detected only when surface temperatures exceed 10°C (Wilson et al. 1994, Chapter 15 in Drake and Reynolds 2012), likely representing an approximate threshold temperature for flight initiation in insects. In autumn, falling temperatures promote the initiation of migratory flights in red admiral butterfly (Mikkola 2003), thus increasing the probability of windborne transport on cool northerlies. Although some butterflies use soaring flight (e.g., Gibo and Pallett 1979), we are not aware of any radar studies that explored it.

TOPOGRAPHY: To the best of our knowledge there are no radar studies on direct effects of topography on flight initiation and/or termination of insect migration, largely because insect echoes on scanning radars at low altitudes are swamped by much stronger ‘clutter’ echoes from ground features in mountainous areas. However, entomological vertical-looking or tracking radars are generally less affected by ground clutter and may thus be applied in the future to address questions related to the effects of topography on migratory departure and termination.

WATER-LAND INTERFACE: Usually, nocturnal insect migration is largely halted by the onset of dawn (Drake and Reynolds 2012). Yet, this termination of migratory movement is overridden if insect migrants find themselves over water. Accordingly, the range of insect movement under these circumstances may be considerably extended (Drake et al. 1981, Feng et al. 2009).

HUMAN AND INFRASTRUCTURE DEVELOPMENT: There are some incidental radar observations of concentrations of insects around lights of large towns (e.g. Wad Madani in Sudan, see p. 275 in Drake and Reynolds 2012) and additional studies reported the attraction of large numbers of radar-observed insect migrants to light traps following their descent from an overflying layer concentration and subsequent flight near the ground near the trap (Reynolds and Riley 1988, Drake and Reynolds 2012, see also Muirhead-Thompson 1991).

Birds

WIND: There is a balance between several endogenous and exogenous factors making up a bird's decision to take off, and these include the bird’s body condition, the quality of the resting site and the meteorological conditions. Radar data showed that birds migrating selectively during nights with favorable wind conditions speed up their flight by 30% (on average) compared to those disregarding the wind (Liechti and Bruderer 1998), with likely implications for energy conservation (Pennycuick 1978, Alerstam 1991). Several radar studies reported that flapping birds, such as waders, woodpigeons, starlings and geese, select tailwinds to initiate their migration (e.g. Richardson and Haight 1970, Alerstam and and Ulfstrand 1974, Green 2004). Migrating geese are selective in their choice of migration days and waders were found to migrate in days with strong tailwinds that may even exceed the birds' own airspeeds (Green 2004).

Synoptic patterns of bird migration are structured by the presence of cyclones and anticyclones at temperate latitudes, both in horizontal and altitudinal dimensions (Richardson 1978a, 1990). Early radar studies in North America (Nisbet and Drury 1968, Richardson and Haight 1970, Richardson 1971, Richardson and Gunn 1971) and Switzerland (Bruderer 1971) indicated that substantial spring migrations initiate and continue under the light variable winds and fair weather that are typical near the centers of high-pressure areas and in southerlies (spring migration tailwinds). Strong autumn migration occurs in the eastern and central parts of high-pressure areas shortly after the passage of cold fronts in North America (Richardson and Gunn 1971, Able 1972, Richardson 1972), Europe (Williamson 1969, Alerstam et al. 1973, Nilsson et al. 2019) and China (Mao 1985, Williams 1986), in light winds and strong northerlies (autumn migration tailwinds).

In some cases, departure decisions could be fatal. Historical data from weather radar and water- and land-based weather stations enabled Diehl et al. (2014) to reconstruct the circumstances leading to mass bird mortality documented along the shores of Lake Michigan in northeastern Illinois in May 1996. Storms that included strong winds, as well as heavy rain and hail, pushed birds over the lake and led to the documented death of almost 3000 migratory birds from 114 species, mostly small passerines whose carcasses were found in the lake's shores, with the actual numbers of dead birds likely much higher.

PRECIPITATION, CLOUDS AND FOG: Rain and precipitation, in general, are known to suppress migratory flight (Richardson 1978a, 1990), but one must note that radars are unable to detect birds that are flying under heavy rain. Also, fog may affect migration timing because migrating birds may postpone their departure when visibility is poor (Alerstam 1990, Richardson 1990, Panuccio et al. 2019).

TEMPERATURE AND THERMAL UPDRAFTS: There is a strong relationship between rising temperature and high migration intensity in spring (dropping temperature in autumn), as well as the likelihood of flight initiation (Richardson 1978a, 1990). Temperature is the most important predictor of spring migration timing and intensity based on data from a weather radar network deployed across North America (Van Doren and Horton 2018). The same study also discriminated the effects of wind and temperature: in similar wind conditions, more birds took flight when temperatures were warmer. Soaring birds exploit thermal updrafts forming in the boundary layer during the day and initiate their flight when thermals start developing, after dawn. Conversely, their flight terminates when no strong thermal are available, after sunset (Spaar and Bruderer 1996, 1997).

TOPOGRAPHY: Radar studies have so far not found effects of mountain barriers on initiation or termination of bird migration. Generally, birds tend to avoid high terrain elevations, as migration intensities over mountains are substantially lower (sometimes by as much as 90%) compared to those over lowlands (the Alps: Bruderer 1978, Liechti et al. 1996b, Aurbach et al. 2018; the Appalachians: Williams et al. 2001; the Galilee in Northern Israel: Liechti et al. 2019). This ‘funneling effect’ described by higher bird migration densities within the lowlands compared to low migration intensities over mountains, shows that local topography may strongly influence migration patterns and can lead to local concentration of migrants (Bruderer and Liechti 1990, Liechti et al. 1996b).

WATER-LAND INTERFACE: Land birds likely decide whether to stop, follow the coast or cross the sea by considering the possible fatal consequences of drifting over the sea (Alerstam and Pettersson 1977, Horton et al. 2016). Bird decisions are related to the geographic settings (e.g., the width of the crossing and coastline direction in relation to goal direction), as well as the specific wind conditions at the crossing point. Several radar studies found no, or only weak, coastline effects on landing decision during autumn and spring migration (Bruderer and Liechti 1998, Zehnder et al. 2001, Nilsson et al. 2014). One explanation could be a progressive change of flight heading throughout the night, with an increasing rate of migration towards land during the second part of the night, presumably due to the birds’ preference to stop-over and cease cross-country flight during the day (Alfia 1995, Bruderer and Liechti 1998, Horton et al. 2016; see also Diehl et al. 2003). Radar observations have revealed that the peak longitude of arrival at the coast for birds migrating aloft is related to the annual variability in the average wind speed and direction over the Gulf of Mexico (Gauthreaux et al. 2006). Moreover, the average wind speed and direction over the Gulf of Mexico affected also longitudinal patterns in the distribution of birds leaving stopover sites along the coast during spring (Lafleur et al. 2016). Furthermore, nocturnally-migrating birds that were found over the Great Lakes of North America at dawn were observed to gain altitude until seeing the closest shoreline in their vicinity to which they reoriented rather than continued their cross-water journeys, leading to greater densities of birds stopping-over near the shore (Archibald et al. 2017).

HUMAN AND INFRASTRUCTURE DEVELOPMENT: Although artificial light at night associated with human development has been known to influence migrating birds during flight for hundreds of years (Gauthreaux and Belser 2006), the response of birds to artificial light when initiating or terminating migratory flight is not well understood. Recent weather radar studies have revealed that migrating land birds stop-over in relatively high densities in city parks (Buler and Dawson 2014) and nearer to highly light-polluted areas (McLaren et al. 2018). This broad extent stopover pattern may be caused by young migrants orienting towards the skyglow of cities (Gauthreaux 1982) while selecting landing sites at the termination of migratory flight. Estimating fine-scale temporal differences in departure timing is possible with weather radar (Buler et al. 2018), revealing the influence of human development on migratory flight initiation at a scale beyond the individual.

2. In-flight behavior: speed, direction and altitude

Insects

WIND: The optimal response of a flapping migrant to tailwinds is airspeed reduction, to decrease the metabolic cost of flight. Higher airspeed is expected in headwind conditions (Pennycuick 1978). The response of insects to wind conditions is strongly constrained by their lower airspeeds (Schaefer 1976, Larkin 1991), which is virtually negligible in small insects. Migrating insects experiencing crosswinds show a variety of responses, including complete and partial drift, as well as complete compensation for lateral displacement in light winds (Chapman et al. 2010, 2015a,b, Reynolds et al. 2016). Preference for a specific altitude was found to relate to strong wind support (Drake 1985, Wood et al. 2006, Drake and Reynolds 2012). For instance, red admiral butterflies *Vanessa atalanta* chose cool northerly tailwinds for their southern migrations from Scandinavia. They furthermore fly at high altitudes when strong winds from the north predominate, but descend lower down when migrating in headwinds (Mikkola 2003).

Long-distance insect movements are typical in steady flows caused by the global-scale wind patterns and the synoptic weather systems embedded within them, for example, the depressions and anticyclones within the mid-latitude westerlies. Synoptic-scale winds (that are usually associated with specific air temperature and precipitation conditions) may facilitate or impede insect migration. For example, the seasonal insect invasions of higher latitudes in spring often occur during spells of warm southerlies (northerlies in the southern hemisphere) on the western flank side of an anticyclone (Drake and Reynolds 2012).

PRECIPITATION, CLOUDS AND FOG: In the case of convective rain, insect migration can continue outside the precipitating cumulonimbus cells (Leskinen et al. 2011, Browning et al. 2011, Drake and Reynolds 2012). Browning et al. (2011) found that insects entrained in layers of warm air flowing into a thunderstorm took no action until they were within a 10-min period before the arrival of the storm's precipitation. They then descended with a tumbling motion – presumably an 'emergency' reaction to avoid being taken up to great altitude (and killed) in the violent updrafts associated with the storm. On several occasions, during nocturnal migration over the Bass Strait in Australia, flying moths were seen to be unaffected by the passage of a rain shower, suggesting that rain do not have any significant effect on their migration, at least if the insects are already airborne when the rain arrives, and the rain is not very heavy (Drake et al. 1981). Heavy, widespread rainfall induces descent that may result in landing and the termination of migration (Drake and Reynolds 2012; see also above).

TEMPERATURE AND THERMAL UPDRAFTS: Unlike the effects of temperature on flight initiation (see above Section 1.), radar evidence suggests that, once aloft, some large insects may fly in surprisingly low air temperatures (~5° C) (e.g. Drake and Reynolds 2012), presumably because they generate enough internal heat through their wing-beating action. Interestingly, dragonflies, butterflies and locusts concentrate in the boundaries of convective thermal cells (Schaefer 1976, Drake and Reynolds 2012), thus exhibiting a surprisingly convergent flight behavior with that of large soaring birds (Box 3, but see Geerts and Miao 2005).

TOPOGRAPHY: Insects were found to concentrate and respond to lee waves, topographic wind eddies and rotors (Chapter 11 in Drake and Reynolds 2012). Additionally, quasi-stationary convergence lines associated with rotors may provide aerial concentrating mechanisms and lead to high-density outbreaks of, for example, the African armyworm (*Spodoptera exempta*) (Rose et al. 2000). No radar study has documented the seasonal near-ground passage of hordes of insects (such as butterflies and hoverflies, Diptera: Syrphidae) through high mountain passes in the Pyrenees and Alps (e.g. Lack and Lack 1951, Aubert et al. 1976).

WATER-LAND INTERFACE: Data from meteorological radars suggest a predisposition of insects to resist being carried over coastlines and over the sea (Russell and Wilson 1996, 2001; see also Chapman et al. 2010, 2015a, as well as Shashar et al. 2005). Nonetheless, radars have documented large-scale insect migrations across the sea (e.g. Drake et al. 1981, Feng et al. 2006, 2009).

HUMAN AND INFRASTRUCTURE DEVELOPMENT: Despite the well-known attraction of many insects towards artificial lights (the basis of the light-trap), radar detected insects engaged in steady nocturnal migration at altitude do not appear to be affected by lights on the ground (see p. 276 in Drake and Reynolds 2012). The powerful vertical-beam searchlight trap used in some Chinese radar studies (Feng et al. 2009) constitutes an exception, but lights of this sort would rarely be encountered by migrating insects.

Birds

WIND: Radar studies reveal the flight strategies of birds when facing various wind conditions. Like in insects, the optimal expected response of a bird flying in tailwinds is airspeed reduction, and airspeed increase in headwinds (Pennycuick 1978). This expectation has been empirically demonstrated in a number of radar studies involving terrestrial flapping birds (Bloch and Bruderer 1982, Williams et al. 1986, Gudmundsson et al. 1992, Hedenström et al. 2002), terrestrial soaring-gliding birds (Spaar and Bruderer 1996, 1997, Malmiga et al. 2014, Becciu et al. 2018) and seabirds employing a range of flight modes (Mateos-Rodríguez and Bruderer 2012), with the exception of flapping auks whose response is probably limited by their high wing loading.

Migrating birds in crosswinds demonstrate a wide range of strategies involving complete drift, as well as partial and complete compensation for lateral displacement (Green 2001). A radar study in the Strait of Gibraltar found that flapping seabirds (auks, puffins, gannets and small shearwaters) compensate for wind drift independently of the predominant wind direction, unlike the larger shearwater species that use a dynamic directional response to wind, allowing to be drifted in spring when westerly tailwinds are prevalent and compensating for wind drift in autumn, when both easterly and westerly winds are similarly frequent (Mateos-Rodríguez 2009).

To reduce metabolic costs of flight and increase ground speed, flying birds may adjust their flight altitude to better exploit tailwinds along their predominant migratory direction. This has been suggested for broad-front nocturnal migrants over Europe and Israel (Bruderer and Liechti 1995, Dokter et al. 2011), as well as for migrating geese over southern Sweden (Green 2004). Diurnal migrating birds that use flapping flight do not explore the entire air column of potential flight altitudes, but instead follow a rule of climbing if tailwind assistance increases (Mateos-Rodríguez and Liechti 2012, Kemp et al. 2013). On the other hand, nocturnal migrants reach higher altitude taking advantage of vertical wind shear, which arises in particular synoptic situations related to the magnitude and direction of large-scale horizontal temperature gradients (Dokter et al. 2013). Flight altitude in soaring migrants depends mainly on thermal conditions (see below).

PRECIPITATION, CLOUDS AND FOG: Fog and low clouds limit bird visibility during flight and may disrupt bird orientation (Lack 1962, Alerstam 1990, Richardson 1990). Radar-tracked Sandhill cranes (*Grus canadensis*) showed more circuitous flight on a foggy day than on days with good visibility (Kirsch et al. 2015; see also Pastorino et al. 2017). Precipitation, low clouds and fog have a strong influence on visibility and obstacle avoidance behavior over complex terrain (Emlen and Demong 1978, Rüsch and Bruderer 1981). For instance, when visibility is reduced, flight directions are more dispersed (Emlen and Demong 1978, Liechti 1986, Becciu et al. 2017).

TEMPERATURE AND THERMAL UPDRAFTS: Birds are much more flexible than insects in terms of timing and altitude of flight and may tolerate a wider temperature range. Nevertheless, radar-based studies found that migrating raptors, as well as other soaring birds, increase their ground speed and flight altitude in the hottest hours of the day – at midday and in the afternoon – probably because of the stronger thermal uplift associated with high temperatures (Spaar and Bruderer 1996, Leshem and Yom-Tov 1998). In fact, for soaring birds, flight altitude depends on the strength of thermal uplifts and on the bird's decision to leave an uplift and start gliding (Pennycuick et al. 1979, Kerlinger et al. 1985, Horvitz et al. 2014).

TOPOGRAPHY: Radar studies found that birds adjust their flight path with respect to mountain ranges (Rüsch and Bruderer 1981, Liechti 1986, but see Mabee et al. 2006), suggesting that topographic features constitute serious obstacles that animals have to cope with during migration (Bruderer 1978, Liechti et al. 1995, Liechti et al. 1996a, 1996b). Birds were observed to deviate from their regular flight direction to follow local topography through mountain passes (Williams et al. 2001). Nonetheless, Hilgerloh et al. (1992) suggest that the Pyrenees do not constitute an ecological barrier to avian migrants that commonly cross the ridge and similarly, another radar study found no effect of the Allegheny Front ridgeline on autumn nocturnal migrants in West Virginia, USA (Mabee et al. 2006).

Weather conditions, such as wind were found to modulate the tendency of low-flying birds to circumvent mountains instead of crossing them (Williams et al. 2001). For instance, circumvention behavior of a complex and rough terrain is more pronounced under headwind conditions when most birds fly at relatively low altitudes (Liechti 1986). On the other hand, under tailwinds birds are prone to cross the Pyrenees in higher numbers (Lack and Lack 1951). Soaring migrants likely exploit orographic uplifts while travelling along mountain ridges (Panuccio et al. 2016). Increasing migration intensity was observed along the Appalachian Mountains that are orientated similar to the birds' main migration direction (Mabee et al. 2006), likely indicating a funneling effect of the mountains. We note that high resolution wind flow description and simulation of movement over complex terrain could provide deeper understanding of the environmental factors faced by travelling birds (see Aurbach et al. 2018).

WATER LAND INTERFACE: Metabolic costs associated with flapping flight scale disproportionately high in relation to body mass (Hedenström 1993). Since flapping is the flight mode used by sea-crossing migrants including those which usually soar during flight, a negative relationship between bird size and its sea crossing propensity has been documented in several radar studies. While small raptors routinely cross the sea using flapping flight, likely because of their relatively low flapping flight metabolic costs, larger soaring birds avoid sea crossing as much as possible (Meyer et al. 2000, 2003, Malmiga et al. 2014). While doing so, soaring birds tend to take long detours over land (Meyer et al. 2000, Alerstam 2001), concentrating in peninsulas, isthmuses and narrow land corridors (Nilsson et al. 2014). Furthermore, the response of migrating raptors to wind conditions is modulated by the geography of their migration route in Southern Italy, with an asymmetric behavioral response of the birds to crosswinds, compensating when winds blew towards the sea and drifting when winds blew towards land (Becciu et al. 2018). Likely the route selection was dependent on wind direction as migration intensity unexpectedly decreased with increasing tailwind assistance, probably because tailwind conditions facilitate a shortcut of the birds over the sea instead of undertaking a long over-land detour (Becciu et al. 2018). A recent broader-scale radar study demonstrated a similar asymmetric response of nocturnally migrating songbirds to crosswinds near the North American Atlantic coast in which the birds drifted when flying over inland areas, but compensated for drift to avoid flying over the ocean near the coast (Horton et al. 2016). Noteworthy, when migrating passerines found themselves offshore at dawn in unfavorable winds for a long overwater flight, they reoriented toward land (Richardson 1978b).

Seabirds usually migrate across open waters without apparent barriers to their movements. Under special conditions, such as those experienced when crossing a strait, seabirds may benefit from coastal orographic features during flight, but their response may vary depending on their flight modes. Under moderate winds and whenever visual contact with the coastline is present (as in the case of the Strait of Gibraltar) seabirds changed their course, presumably to better respond to wind conditions. They approached the coast under headwinds proportionally to the magnitude of wind intensity, as a strategy to reduce the effect of headwinds and tended to fly further from the coast under tailwind conditions, to profit from increasing tailwind speed there (Mateos-Rodríguez and Arroyo 2011).

HUMAN AND INFRASTRUCTURE DEVELOPMENT: On-the-ground anthropogenic development has consequences on birds engaged in active migration, and radars have been widely used to study the effect of wind turbines and, more recently, light pollution on the movement of migrating birds. Radars provided insight of flight directions, altitudes and speeds of nocturnal migrants near wind turbine facilities (e.g. Mabee et al. 2006, Cabrera-Cruz et al. 2017), with a recent suggestion that bird mortality due to collision with wind turbines occurs regardless of the intensity of the migratory flow (Aschwanden et al. 2018). Radar also assisted assessing the reaction of diurnally migrating birds to wind farms. For example, geese and ducks migrating through the Baltic Sea (Desholm and Kahlert 2005) and raptors and other soaring birds migrating through the Isthmus of Tehuantepec in southern Mexico (Villegas-Patraca et al. 2014, Cabrera-Cruz and Villegas-Patraca 2016) seem to avoid entering newly installed wind farms and change their track accordingly. Artificial lights also disrupt the flight of migrating birds (Cabrera-Cruz et al. 2018), particularly under poor weather and low visibility conditions. For example, nocturnal migrants circled around the steady burning lights of a communication tower during nights with low cloud elevation as opposed to migrants' linear trajectories when no such conditions prevailed (Larkin and Frase 1988). However, if the source of light is bright enough, lights will affect the flight behavior of migrating birds regardless of the weather conditions. For example, Bruderer et al. (1999) demonstrated that nocturnal migrants changed their flight direction by re-orienting themselves 8±10° away from a bright light source pointed at them, and that this stimulus also made some birds to decrease their ground speed or change their flight altitude. The drastic effect of the super bright beams of light used during the 9/11 "Tribute in Light" memorial in New York city on nocturnal migrants include the massive bird attraction to the site when lights were on. The birds flew in circles around the beams of light but nonetheless their concentration dissipated and they resumed their normal migratory flight when the lights were turned off (Van Doren et al. 2017). These findings are just a few examples of the extensive research conducted with radar technology which can be used to inform conservation efforts. Hüppop et al. (2019) provide an in-depth review of radar applications to biological conservation of aerial vertebrates, including migratory birds.

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FIGURE LEGEND

Figure 1. Major behavioral responses of flying migrants caused by the interaction between atmospheric conditions and geographic features as revealed by radar studies. Behavioral responses were found in insects only (blue glow), in birds only (red glow) or in both groups (violet glow). Birds changed their altitude when crossing mountains (Lack and Lack 1951, Williams et al. 2001) and also selected to cross mountains and waterbodies or terminate their flight (in the case of insects; Feng et al. 2009, Russell and Wilson 2001) or circumvent them (in the case of birds; Williams et al. 2001) depending on wind conditions. Similarly, birds funneled in bottle-necks (valleys or peninsulas) that are usually aligned with preferred migration directions of the migrants (Mabee et al. 2006, Aurbach et al. 2018). Flying migrants compensate for wind drift close to coastlines when the wind is blowing towards the sea to avoid the risk to be displaced far offshore (insects: Russell and Wilson 1996, 2001, Chapman et al. 2015a; birds: Richardson 1978b, Horton et al. 2016). When flying close to the coast or over large waterbodies, fog and low clouds can prevent diurnal migrating insects from continue flying and terminate their flight above ground, such that their flight extends over water in the night (Feng et al. 2006). Migrating birds that fly in the vicinity of tall illuminated towers and buildings may disorient when low clouds and fog prevail (Larkin and Frase 1988), which may lead to mortality.


Atmospheric conditions
Behavioral response
Geographic features
Barrier
Compensation for drift
Termination of flight
Disorientation

TABLE LEGENDS

Table 1. Flight initiation and termination, and migration intensity of migrating insects and birds in response to different meteorological conditions and geographic features

Behavior	Flight initiation/termination and migration intensity	
Taxa / Environmental condition	Insects	Birds
Wind (micro- meso-scale)	Tailwinds induce departure and high migration intensity Likely, flight termination and risk of fatalities with extreme winds (hurricanes, tornados)	
Wind associated with other atmospheric conditions (synoptic scale)	Autumn departure associated with the passage of cold fronts and high-altitude winds	<u>Spring</u>: departure near the centers of high pressure areas and in southerlies – or northerlies for the austral hemisphere (tailwinds). <u>Autumn</u>: departure close to high pressure areas shortly after the passage of cold fronts
Precipitation, Clouds & Fog	Heavy rain may inhibit departure and induce termination of flight, but consider related effects with rainy weather: decreasing temperature, weaker or absent thermal convection and strong downdraughts. <u>Insects</u>: fog was found often in association with relatively calm	

	conditions at the surface and intensive migration aloft, but its effects are not well understood.	
Temperature & Thermal updrafts	Take-off when temperatures are above 10°C, but some large insects (e.g. moths) can fly at lower temperatures (~5°C). Falling temperatures in autumn promote migratory flight initiation	Variation in temperature promotes take-off, highest intensities in days with warmest temperature in spring
Topography	*No studies*	No studies about effects on initiation/termination. Migration intensity is lower over complex terrain than in lowlands.
Water-Land Interface	Cues which normally cause flight termination are overridden when flying over water	Stop over before and after crossing a water body
Human & Infrastructure Development	Artificial lights attract insects and may stop migratory flights.	Artificial lights attract birds and may stop migratory flights, as well as collisions with wind farms. <u>Nocturnal migrants:</u> Stop over in city parks and collision with wind farms

Table 2. Changes in flight airspeed, direction and altitude of migrating insects and birds in response to different meteorological conditions and geographic features

Behavior	In-flight behavior (speed, direction, altitude)	
Taxa / Environmental condition	Insects	Birds
Wind (micro- meso-scale)	Animal airspeed increases in headwinds. Lateral drift by crosswinds, but also partial or complete compensation. Altitudinal layering by favorable wind. Migrants try to avoid storms, but hurricanes and typhoons can trap and transport them. See Box. 3 for a classification of flying animals in relation to airflow	
Wind associated with other atmospheric conditions (synoptic scale)	Synoptic weather associated with the winds (particularly air temperature, and the likelihood of precipitation) will facilitate or impede insect migration	Magnitude and direction of large scale horizontal temperature gradients affects the relative gain in wind assistance that nocturnal migrants can obtain through ascending
Precipitation, Clouds & Fog	Light rain does not affect flight of large insects; insects can avoid heavier rain by	Fog and low clouds can disturb visibility and affect orientation. Effects of

	gaining altitude (not intentionally), and found themselves flying outside the cumulonimbus cells	precipitation on flight performance are unclear, likely negative
Temperature & Thermal updrafts	Insects and birds may disregard temperature variation. Use of strong thermals to soar or ascend and glide or actively fly downward (insects: locusts, butterflies and dragonflies; birds: soaring-gliding birds; see Box. 3 for a detailed unified characterization of flying animals in relation to airflow). Soaring-gliding birds: increase flight speed and altitude in the hottest hours of the day. Nocturnal birds: selection of travelling altitude according to a compromise between not too cold temperature and slight wind support	
Topography	*No radar studies (but see Lack and Lack 1951, and Chapter 11 in Drake and Reynolds 2012)*	Funneling effect through mountain valleys. Flapping birds: Headwinds favor circumvention of complex terrain, tailwinds favor crossing over it. Soaring migrants: exploit orographic uplifts
Water-Land Interface	Large insects: partial compensation for drifting over the sea. Small insects: subject to drift. Adaptive drift can increase migration distance by 40%. Large-scale migration over the sea is known	When flying on land along coastlines compensation for lateral drift towards the sea. Flapping birds: usually cross water bodies, better with tailwinds but also with opposite winds. Soaring migrants: usually no crossing (or cross with tailwinds), and circumvent water bodies. Seabirds: reduce the effects of headwinds by flying closer

		to the coast, and further away with tailwinds
Human & Infrastructure Development	Insects in steady nocturnal migration at high altitudes are not affected by lights on the ground, with some exceptions	Nocturnal migrants: Re-orientation towards the most intense city skyglow, with risky consequences of collision. Diurnal migrants: avoidance of wind farms, but high risk of collision

EXHIBIT

6

Indications for Protracted Groundwater Depletion after Drought over the Central Valley of California*,+

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ABSTRACT

Ongoing (2014–16) drought in the state of California has played a major role in the depletion of groundwater. Within California's Central Valley, home to one of the world's most productive agricultural regions, drought and increased groundwater depletion occurs almost hand in hand, but this relationship appears to have changed over the last decade. Data derived from 497 wells have revealed a continued depletion of groundwater lasting a full year after drought, a phenomenon that was not observed in earlier records before the twenty-first century. Possible causes include 1) lengthening of drought associated with amplification in the 4–6-yr drought and El Niño frequency since the late 1990s and 2) intensification of drought and increased pumping that enhances depletion. Altogether, the implication is that current groundwater storage in the Central Valley will likely continue to diminish even further in 2016, regardless of the drought status.

1. Introduction

California's Central Valley is undergoing a groundwater drilling boom amid one of the most severe droughts in state history, and new wells often have to be drilled deeper in order to tap into the shrinking aquifer (Howard 2014; Kennedy 2014). Drought conditions have forced the state of California to consider new methods and regulations regarding the monitoring and appropriation of groundwater resources (AghaKouchak et al. 2014b). Satellite monitoring of the Gravity Recovery and Climate Experiment (GRACE) has indicated a $31 \pm 3\,\mathrm{km}^3$ loss in groundwater storage from 2006 to 2012 (Famiglietti et al. 2011; Scanlon et al. 2012). A recent study (Howitt et al. 2014) estimated that the 2014 drought resulted in an additional groundwater loss on the order of $6.3\,\mathrm{km}^3$, and the depletion continues despite efforts to curb water use (Famiglietti 2014).

The present groundwater status in California's Central Valley is rooted in its history. For more than 50 years the Central Valley has been one of the most productive agricultural regions of the world, which is facilitated by sufficient supply of irrigation water (Bertoldi et al. 1991; Faunt 2009). Irrigation and agricultural activity have

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accounted for the vast majority of all water use: during the 1960s and 1970s, annual irrigation water was derived equally from groundwater and surface water, though in drought years the amount supplied by groundwater would increase (Bertoldi et al. 1991). In the early 1980s, the overall usage of irrigation water increased slightly, and an increased proportion came from surface water. According to USGS water use data for California, from the 1980s until 2010, the Central Valley began using less total water for irrigation, yet there has been an increase in the proportion taken from groundwater sources. The Central Valley has seen a rapid population growth from 5.7 million people in 2000 to 6.7 million people in 2010 (http://www.census.gov/2010census/), leading to increased household usage of water in addition to agricultural water use. In the meantime, groundwater storage in the Central Valley has declined by almost 60 million acre feet since the 1960s (Faunt 2009).

Climatic factors have affected groundwater in the Central Valley as well. The effects of global warming at the regional scale include a hotter and drier climate (Dai 2013) and earlier snowmelt (Westerling et al. 2006), both of which can aggravate drought conditions. A companion study that analyzed water cycle extremes in California (Yoon et al. 2015a,b) has projected that both intense drought and excessive flooding will increase by at least 50% toward the end of the twenty-first century, and such an increase is linked to strengthened impacts from the life cycle of El Niño–Southern Oscillation (ENSO) (Wang et al. 2015). Given the severe drought conditions in California, a pressing question posed is whether the state will experience continued shortfalls in groundwater in upcoming years. To better assess future water resources, this study investigated the linkage between groundwater and drought, and particularly the hypothesis that the recent and projected amplification of water cycle extremes in California (Yoon et al. 2015b) may exacerbate groundwater depletion. Using diagnostic approaches, this study represents a preliminary investigation of likely climatic factors in the drought–groundwater relationship.

2. Data and methods

a. Data

Depicting drought in the state of California can be complicated owing to its terrain and associated snow hydrology. The Palmer drought severity index (PDSI; Dai 2013) has been the most widely used metric for drought depiction and is the front-page indication of drought status in the U.S. Drought Portal (www.drought.gov). Here, we utilized the PDSI data produced by the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) with a 4-km resolution (http://prism.nacse.org/). However, the PDSI could be problematic in the western United States in that it does not account for time lags introduced by snow accumulation and, as a result, may handle California's snow cycle poorly. Thus, we adopted additional measures of drought by using the Climate Prediction Center (CPC) model-calculated monthly soil moisture water height equivalents (hereafter soil moisture) at 0.5° grid spacing (http://www.esrl.noaa.gov/psd/data/gridded/data.cpcsoil.html) and the Climatic Research Unit (CRU) Time-Series, version 3.21 (TS3.21), gridded precipitation and temperature data (http://www.cru.uea.ac.uk/data). All these gridded data were averaged in the Central Valley, defined as elevations lower than 1000 m (Fig. 1a).

For the estimation of groundwater storage, we utilized the level-3 GRACE data of monthly liquid water equivalent thickness (LWET) provided by NASA GRACE Tellus (http://grace.jpl.nasa.gov/; Landerer and Swenson 2012). The GRACE twin satellites detect gravity changes and use them to measure variations in water stored at all levels above and within the land surface; this measurement indicates terrestrial water storage change. The GRACE-derived LWET (hereafter LWET) was averaged within the Central Valley. Although the Central Valley has a smaller areal extent than the GRACE footprint, previous studies (Famiglietti et al. 2011; Scanlon et al. 2012; Anderson et al. 2015) have shown that GRACE-derived groundwater storage change is in agreement with the well data within the valley. We note that the LWET signal may not completely reflect groundwater since the signal leakage effect coming from proximity of the Sierra Mountains (i.e., snow, soil moisture, and surface water) was not removed.

Groundwater level measured by wells within the Central Valley was obtained from two sources: the U.S. Geological Survey (USGS; http://waterdata.usgs.gov/nwis) and the California Department of Water Resources (DWR; http://www.water.ca.gov/). We used 467 wells as indicated in Fig. 1a; these are wells that provide observations in any month during the September–December period with at least 15 years of data. The available data length of each well is plotted as horizontal lines in Fig. S1 of the supplemental material, and the numerous data gaps reflect the well-known problem that groundwater observations in the Central Valley are inhomogeneous and discontinuous (Kennedy 2014). To form long-term time series of groundwater level, one needs to combine these well data; to do so, groundwater level of each well was first standardized (within ±1) and then averaged across all wells to form a single time series. This procedure eliminates the difference and

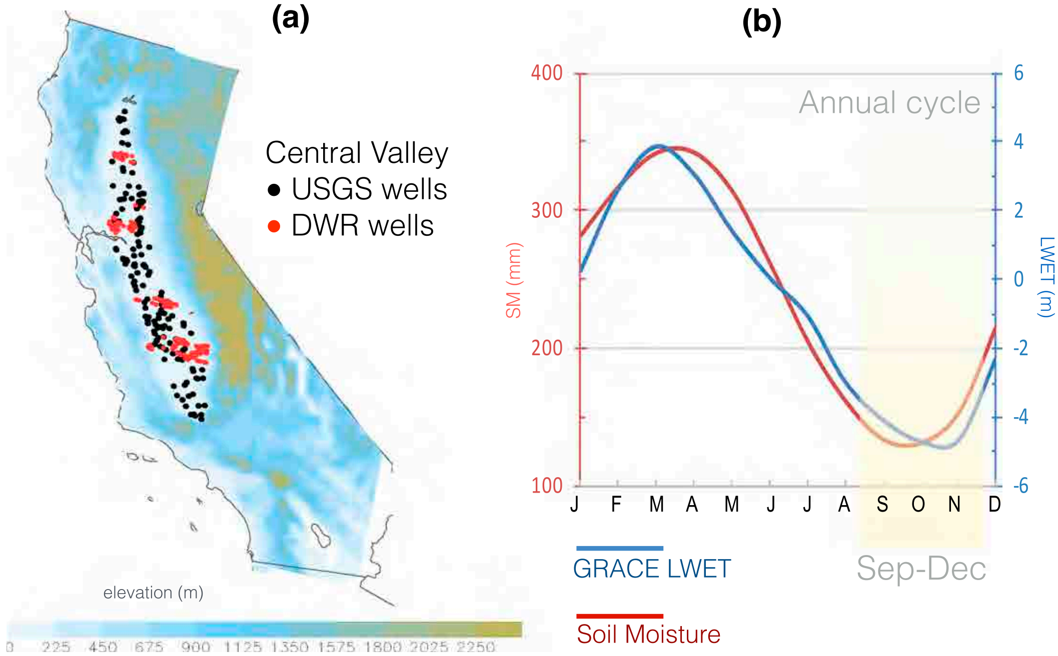

FIG. 1. (a) Topography of California that outlines the Central Valley (<300 m) overlaid with the 497 wells analyzed, obtained from USGS (black dots) and California DWR (red dots). (b) Long-term monthly distribution of LWET (blue) and soil moisture (red) averaged in the Central Valley, while the low season of September–December is highlighted.

locality of well levels. As shown in Fig. S1, we conducted a sensitivity test for different parts of the Central Valley: north, central, and south (discussed later). Groundwater level fluctuation is considered uniform throughout the valley despite the limited number of wells after the year 2000. Additional water use data referred to in the text were provided by the USGS (http://waterdata.usgs.gov/ca/nwis/water_use/).

b. *Methods*

To understand the cause and effect of the Central Valley's groundwater problem and to help visualize the temporal change and areal extent from which the problem is derived, we first used the Pearson correlation and cross correlation. Correlation is a simple and direct way to understand the relationship between two variables and associated change, while cross (lagged) correlation provides an effective measure to establish the similarity of two variables as a function of the time lag of one relative to the other. For the purpose of examining the time–frequency distribution of drought and groundwater, that is, how the variation changes over time, as well as further validation of correlation analysis, we conducted the wavelet power spectrum analysis following the derivation of Torrence and Compo (1998). The wavelet coefficients yield information about the correlation between the wavelet (spectral power) and the data array (at a particular data point). To verify lagged correlations, we utilized the wavelet transform coherence (WTC) for analyzing the coherence and phase lag between two time series as a function of both time and frequency. The WTC analysis is based on the continuous wavelet transform developed by Grinsted et al. (2004) for geophysical time series. Significance test was performed by using the Monte Carlo method (i.e., adding random noise to the two signals and repeating this 1000 times) to calculate the 95% confidence interval about the "true" phase difference.

3. Results

In the California Central Valley, groundwater undergoes a pronounced annual cycle that peaks in March and reaches minimum in November, as is displayed in Fig. 1b by the long-term LWET data. Recharge begins in November, at the start of the rainy season, and typically lasts until March. Soil moisture in the Central Valley exhibits an annual cycle similar to LWET (Fig. 1b). Based upon this annual cycle, the period of September–December appears to be the low season of groundwater level. Thus, we divided the year into three different seasons (January–April, May–August, and September–December) and computed the cross correlations between the PDSI and LWET averaged over the

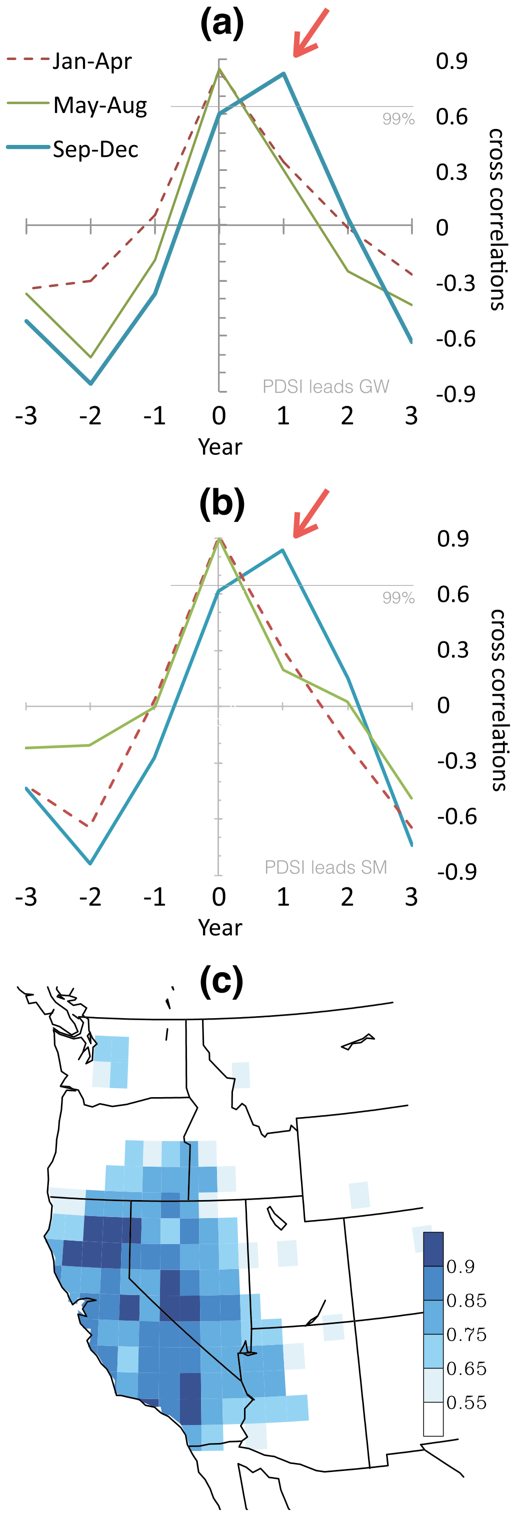

FIG. 2. (a) Cross correlations between PDSI and LWET over the Central Valley for each 4-month season as indicated in the legend. The gray line indicates the 99% confidence level; the red arrow indicates the significant lagged correlation in the September–December season. (b) As in (a), but for soil moisture and LWET. (c) Point-to-point correlations between the September–December PDSI and LWET in the following year. Only values that are above the 99% confidence level are plotted.

Central Valley during 2002–14. As shown in Fig. 2a, the September–December period is the only season whose correlations are significant both at the current year (year 0) and at a 1-yr lag (year +1), suggesting a prolonging effect of meteorological drought on groundwater. It could mean that groundwater decline in autumn is maintained over a 2-yr period that persists approximately one full year after drought has occurred (or seized). A similar pattern in the correlations is observed between soil moisture and LWET (Fig. 2b) as well as precipitation (not shown), which lends support to the prolonging effect of drought on groundwater depletion. We also computed the point-to-point correlation between the grid-scale PDSI (year 0) and LWET (year +1) to delineate the geographical distribution of this year +1 correlation, using the September–December data. As shown in Fig. 2c, significant correlations encompass the Central Valley and extend into Nevada, southeastern Oregon, and northwestern Arizona. This regional extent of year +1 correlations suggests that the occurrence of drought affecting the Central Valley is associated with a larger-scale climate pattern beyond the state of California.

Of further relevance, prior to the twenty-first century the 1-yr lag in the drought–groundwater correlation was not apparent: Fig. 3a presents evidence from wells in the Central Valley by computing correlations for a series of sliding, trailing 15-yr windows between PDSI (year 0) and groundwater level (year +1), based on September–December (hereafter "sliding correlations"). Actual time series of PDSI and groundwater level are displayed in Fig. 4a for visual inspection. The contemporaneous (year 0) correlations are rather stable and remain marginally significant throughout the analysis period, as expected. By comparison, the lagged (year +1) correlations increase drastically and become significant ($p < 0.01$) at the beginning of the twenty-first century. Prior to that, the year +1 correlations are insignificant, suggesting that the situation of protracted groundwater decline a full year after drought was not the case. A similar analysis using soil moisture (Fig. 3b) obtained the same conclusion, that the year +1 correlations have increased prominently since 2005. This strengthened effect of drought in prolonging groundwater depletion was previously undocumented. The cause of such a change in lagged correlations is manifold and we acknowledge that a lot of factors that are involved in water management could obscure the relationship between drought and groundwater; these are addressed in section 4.

We tested the significance for the difference in the sliding correlations by applying a bootstrapping scheme with 500 pairs of correlated white noise time series, following Gershunov et al. (2001); the test result

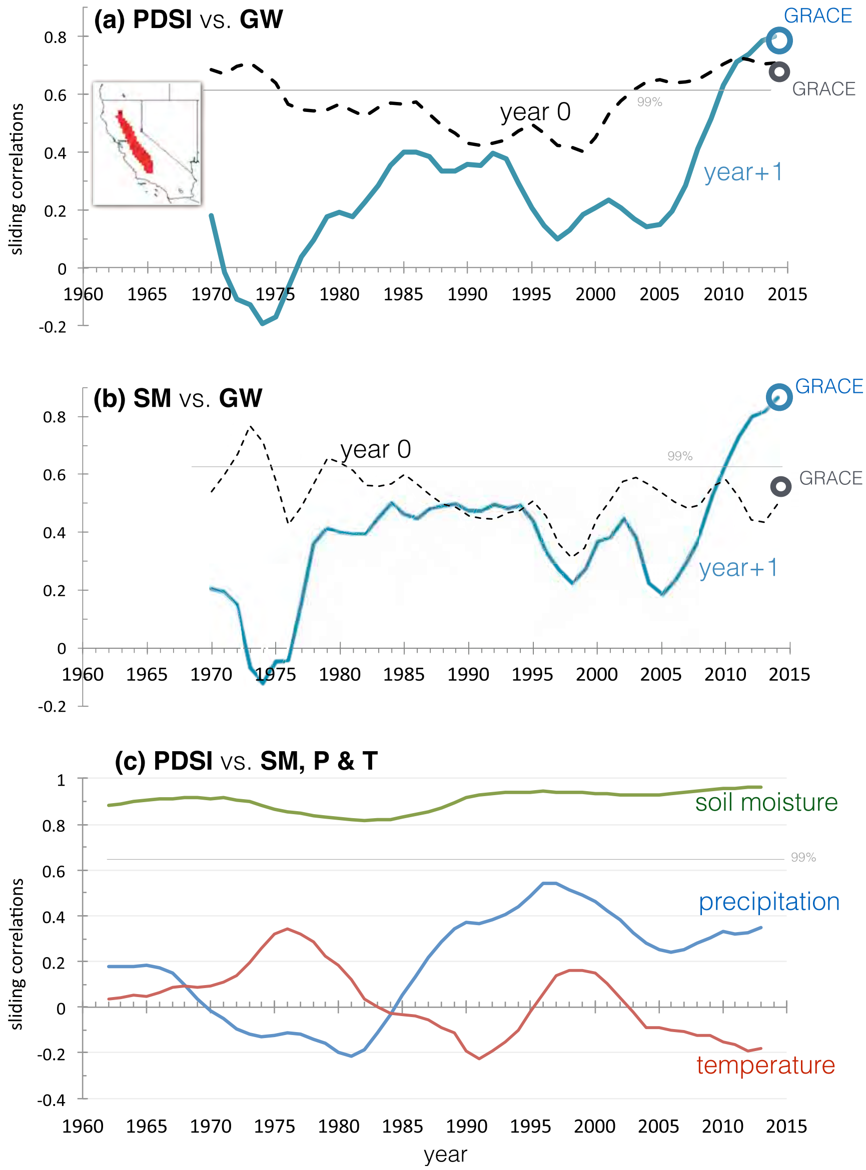

FIG. 3. (a) Sliding correlations between the Central Valley PDSI and the groundwater level (GW) in the following year (year +1; blue solid line) and in the same year (year 0; black dashed line), computed with a 15-yr running window (one sided). The LWET correlations with PDSI are indicated by thick circles for 2002–14. Gray horizontal lines indicate the 99% confidence level. (b) As in (a), but for soil moisture (SM) and GW. (c) Sliding correlations (no lag) between the PDSI and SM (green line), precipitation P (blue line), and surface air temperature T (red line) within the Central Valley using a centered, 15-yr running window.

indicates a significant post-2005 difference at $p < 0.01$. We also examined the sliding correlations using various window sizes from 10 to 20 years, and those too yielded consistent results (not shown). In terms of geographical difference, we computed these correlations from each subregion of the Central Valley as indicated in the supplemental material. The result as shown in Fig. S1 suggests that the correlations are not sensitive to the region we selected (though the southern Central Valley exhibits a lower year +1 correlation in recent years). Moreover, the LWET–PDSI correlations for the 2002–14 period (indicated by open circles in Fig. 3a) align with the well data analysis, and this agreement suggests that any potential bias that resulted from the signal leakage effect of GRACE within the Central Valley is minimal.

Since groundwater depletion in semiarid areas such as the Central Valley is largely controlled by soil moisture storage change (Rodell et al. 2007; Long et al. 2013), the

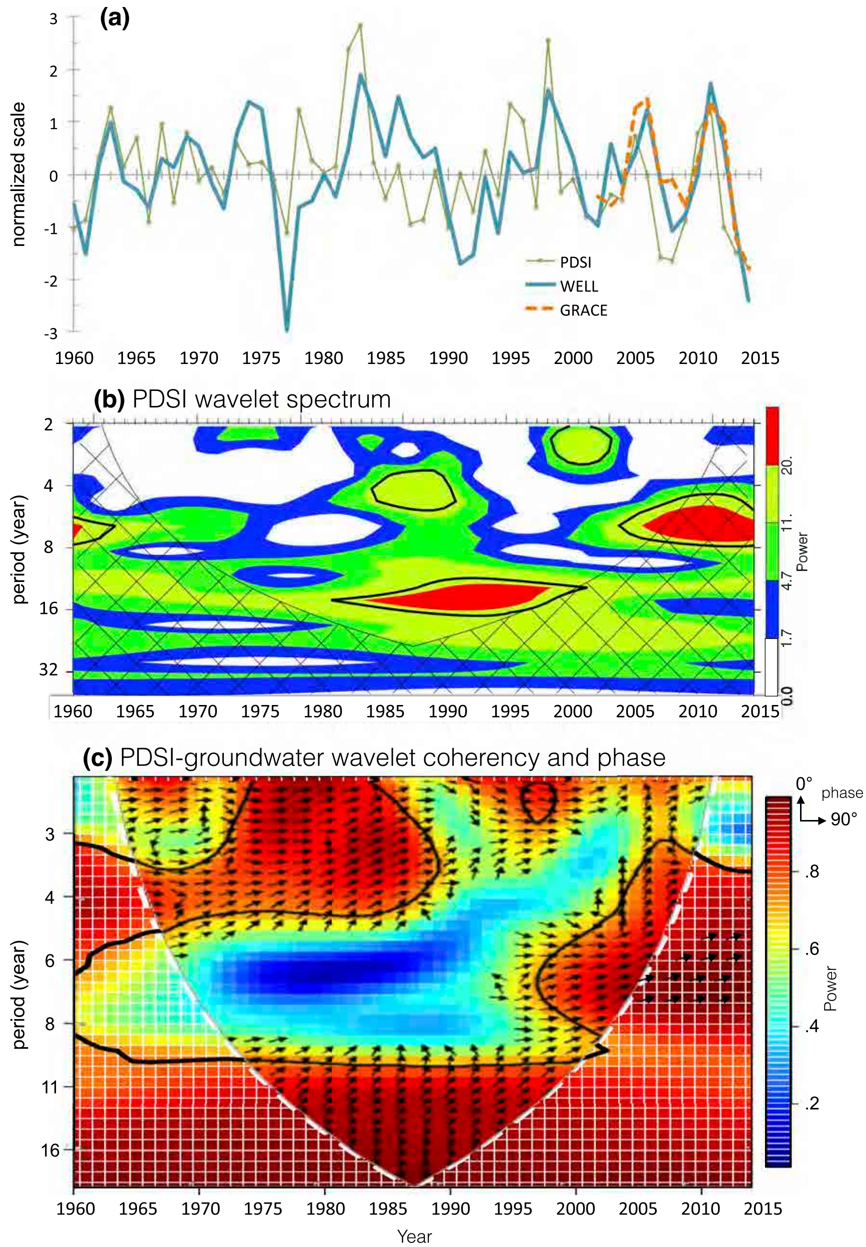

FIG. 4. (a) Time series of the September–December PDSI (green line), LWET (orange dashed line), and GW (blue line) from 1960 to 2014. (b) Wavelet spectrum of the PDSI using the Morlet parameter-6 approach, in which the contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power are above each level. (c) Wavelet coherency (shading) and phase (vectors) between the PDSI and GW. Vectors pointing to the right indicate a quarter phase. The cone of influence and the 95% confidence level based on red noise are hatched/contoured.

expectation is that groundwater storage, soil moisture, and drought occurrence would be highly correlated (Famiglietti et al. 2011; Castle et al. 2014). Figure 3c reflects such a process through the computation of sliding correlations between PDSI and soil moisture, precipitation, and surface air temperature within the Central Valley. The PDSI shows a weak association with precipitation and temperature, although the correlations with precipitation have increased after 1980 (yet insignificant). The PDSI's correlation with soil moisture has been significant and consistently high (~0.9) throughout the past 65 years. Therefore, it is possible that the prolonging effect of drought and low soil moisture on groundwater level has increased. This notion echoes recent observations (AghaKouchak et al. 2014a; Griffin and Anchukaitis 2014; Diffenbaugh et al. 2015) that long-term warming during the recent decades and the record high temperature in summer can aggravate drought severity through increased evapotranspiration (Anderson et al. 2015), which furthers the reduction in soil moisture. Enhanced high pressure anomaly over the West Coast that was linked to increased anthropogenic warming (Wang et al. 2014; Diffenbaugh et al. 2015) also contributes to the lengthening of dry/warm days, which helps increase evaporation from the soils.

To illustrate the history of drought variability experienced in the Central Valley, Fig. 4a shows the September–December PDSI alongside the groundwater well levels and LWET. The low-frequency variability in all these datasets is discernable. It appears that the tendency for any drought to last longer than 2 years has become more pronounced. The changing drought frequency was assessed using the wavelet spectral analysis (Torrence and Compo 1998) of the PDSI, and the result is shown in Fig. 4b. Since the late 1990s, spectral power within the 4–6-yr frequency undergoes considerable amplification. The effect of this amplified drought variation on groundwater was examined by computing the wavelet spectral coherency between PDSI and groundwater level using the formulation derived by Grinsted et al. (2004). As shown in Fig. 4c, significant coherency between the two variables in the 4–6-yr frequency appears after 1995 with a phase difference of (vector pointing toward) 75°; this phase difference amounts to a time lag of 1 year within a 4–6-yr ''cycle,'' lending support to the increased year +1 correlations presented in Fig. 3a.

Noteworthy is the 1980–95 period when the Central Valley experienced a lower-frequency climate fluctuation in the 10–16-yr time scale (Fig. 4b) in which the depletion of groundwater lags drought by certain years (Fig. 4a). Previous research has reported an energetic 10–20-yr (or quasi decadal) oscillation in the western United States, and its signal is especially pronounced in Northern California (Wang et al. 2009; St. George and Ault 2011). As is shown in Fig. 4c, the 50° phase difference within the significant 10–16-yr coherency indicates a time lag of about 2–3 years. Consequently, the prolonging effect of drought on groundwater depletion during this time period is not revealed as strongly from the year +1 correlations in Fig. 3a.

4. Discussion

What are the possible causes for the recent increase in the lagged correlations between the PDSI and groundwater level in the Central Valley? In terms of climatic factors, there is a tendency that drought conditions in California have become increasingly more intense and lasted longer (Cayan et al. 2010; MacDonald 2010; Diffenbaugh et al. 2015). Previous studies (Wang et al. 2009; Cayan et al. 2010; Seager and Vecchi 2010) have noted an intensification in the low-frequency drought variation across the western United States, echoing the result shown in Fig. 4. Recent studies (Wang et al. 2015; Yoon et al. 2015b) linked this intensified drought variation with strong ENSO events that modulate California's climate not only through the warm and cold phases but also their precursor patterns. Using large-member ensemble simulations, Yoon et al. (2015a) found a large increase specifically in the 4–6-yr spectral coherency shared by the El Niño–La Niña cycle and California's precipitation, vegetation index, and fire probability and attributed such a change to an increased association with the El Niño–La Niña teleconnections. To put these results into the context of this study, we adopted from Yoon et al. (2015a) the power spectrum of California's winter precipitation simulated by the Community Earth System Model, version 1 (CESM1), Large Ensemble Community Project, which is displayed in Fig. S2a. The result indicates a prominent increase in the variation of the 4–6-yr frequency. Likewise, Fig. S2b shows the spectral coherency of the precipitation with the ENSO cycle (represented by the Niño-3.4 index), and it too suggests a strengthened relationship in the same 4–6-yr frequency. This additional result is supportive of the 4–6-yr wavelet coherency between the PDSI and groundwater in the Central Valley observed in Fig. 4c, as well as their phase lag of 1 year.

In terms of local effects, the 2014 drought induced heat waves that resulted in the first half of the year being the hottest in 120 years of state record (James 2014); this subsequently exacerbated the drought situation and, according to the observations by Bertoldi et al. (1991) and Anderson et al. (2015), would prompt further withdrawal from the aquifer. Changes to surface water deliveries could very well affect the correlations discussed, yet there have been indications that they are not the leading cause for the increase in year +1 correlations. For instance, by focusing on the Colorado River basin, Famiglietti (2014) noted a disconnect between reservoir storage and groundwater level while stating that ''the steepest rate of groundwater storage decline (in the upper Basin in 2013) follows exceptional drought conditions in 2012 and record low Rocky Mountain snowpack.'' While it is expected that low snowpack affects surface water availability and thus tends to promote groundwater pumping, the notion in Famiglietti (2014) (alongside his Fig. 3) suggests that drought is the leading contributor to groundwater behavior, rather than changes in reservoir storage. If this idea is applied to California, it would imply that drought is the leading cause for the change in year +1 correlations since the 2000s rather than the change in reservoir storage. Meanwhile, it is also possible that existing water management practices in surface water resources, nonlocal water supplies, river flow control, reclamation, changes in usage, etc. could complicate the relationship between drought and groundwater level. Given that groundwater is unregulated and has been mined indiscriminately during this prolonged drought, some of the findings as presented here may be tempered.

In the context of climate change, since the CESM1 simulation of the changing association between ENSO cycle and California's precipitation as shown in Fig. S2 was derived from a higher representative concentration pathway (RCP8.5) of anthropogenic greenhouse gases, the amplification in the drought variation and the associated protraction of groundwater depletion is likely to continue. Further research is necessary to comprehensively understand the climate and hydrological linkages that manifest in the groundwater response to the changing frequencies of drought.

5. Conclusions

We present evidence that, since the beginning of the twenty-first century, groundwater levels in the Central Valley have tended to decline not only in response to drought conditions of the same year but also in the following year. In addition to the climatic factors outlined earlier, the reported long-term increase in groundwater withdrawal could play a role. Undeniably, the accelerated depletion in groundwater is linked to increased withdrawal (Famiglietti et al. 2011; Scanlon et al. 2012; Famiglietti 2014) and the drilling boom since 2014 is yet another compelling piece of evidence. However, quantifying the role of human withdrawal of groundwater is difficult because of the lack of reliable data. Performing land surface modeling with irrigation fluxes by utilizing GRACE groundwater storage estimate, as was recently done by Anderson et al. (2015), may offer a clue. Nonetheless, the present analysis for the Central Valley points to the fact that the effects of drought are becoming overarching and can be enduring. Despite changing water use habits, the water table continues to drop while drought becomes longer and more severe.

As of January 2016, an El Niño has fully developed and an alert was announced by the NOAA CPC (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/). This El Niño, if it persists through spring 2016 (as it is being predicted to), could enhance precipitation in California and bring some relief to the current drought conditions. However, the analysis presented here suggests that, even in the face of some drought recovery, groundwater depletion in the Central Valley will likely continue into late 2016, resulting in further reduction in groundwater level. The groundwater table in the Central Valley has been declining to such a degree that it requires a deeper understanding of the temporal dynamics of drought, their dependence on regional climate variability and change, and their implications for water demand and use in all forms.

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EXHIBIT 6

Journal of Animal Ecology

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Wind turbines cause functional habitat loss for migratory soaring birds

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Abstract

1. Wind energy production has expanded to meet climate change mitigation goals, but negative impacts of wind turbines have been reported on wildlife. Soaring birds are among the most affected groups with alarming fatality rates by collision with wind turbines and an escalating occupation of their migratory corridors. These birds have been described as changing their flight trajectories to avoid wind turbines, but this behaviour may lead to functional habitat loss, as suitable soaring areas in the proximity of wind turbines will likely be underused.

2. We modelled the displacement effect of wind turbines on black kites (*Milvus migrans*) tracked by GPS. We also evaluated the impact of this effect at the scale of the landscape by estimating how much suitable soaring area was lost to wind turbines.

3. We used state-of-art tracking devices to monitor the movements of 130 black kites in an area populated by wind turbines, at the migratory bottleneck of the Strait of Gibraltar. Landscape use by birds was mapped from GPS data using dynamic Brownian bridge movement models and generalized additive mixed modelling was used to estimate the effect of wind turbine proximity on bird use while accounting for orographic and thermal uplift availability.

4. We found that areas up to approximately 674 m away from the turbines were less used than expected given their uplift potential. Within that distance threshold, bird use decreased with the proximity to wind turbines. We estimated that the footprint of wind turbines affected 3-14% of the areas suitable for soaring in our study area.

5. We present evidence that the impacts of wind energy industry on soaring birds are greater than previously acknowledged. In addition to the commonly reported fatalities, the avoidance of turbines by soaring birds causes habitat losses in their movement corridors. Authorities should recognize this further impact of wind energy production and establish new regulations that protect soaring habitat. We also showed that soaring habitat for birds can be modelled at a fine scale using publicly available data. Such an approach can be used to plan low-impact placement of turbines in new wind energy developments.

Keywords

Aerial habitat; avoidance behaviour; migration; orographic uplift; raptor; thermal uplift; wind farms

Introduction

Wind energy generation has increased immensely over the last decades and this growth is expected to continue in the forthcoming years, with a predicted annual increase of 5% of the installed capacity until 2020 (GWEC, 2015; IPCC, 2011). Despite the immediate benefits for climate change mitigation, negative interactions between wind energy production and wildlife, mainly birds and bats, have been widely reported (Saidur et al., 2011). Soaring birds, including most raptors, storks and other large birds, are among the groups of highest concern, as their movement corridors have been populated by wind farms (Cabrera-Cruz, & Villegas-Patraca, 2016; Katzner et al., 2012; Martín et al., 2018) leading to high fatality rates through collisions with turbines (e.g. Barrios, & Rodriguez, 2004; Ferrer et al., 2012; Smallwood, & Thelander, 2008).

Soaring flight allows large birds to travel long distances with a reduced energetic cost (Duriez et al., 2014; Pennycuick, 1975). However, soaring depends on updrafts, which are relatively scarce and scattered across the landscape (Horvitz et al., 2014; Katzner et al., 2015). Two types of updrafts are commonly used by terrestrial soaring birds: (1) orographic uplift that results from the deflection of horizontal winds by sloping terrain and (2) thermal uplift that is formed during the day due to the heating of the land surface by solar radiation (Kerlinger, 1989). Soaring birds use orographic uplift either to gain altitude and glide downwards in a desired direction, or to travel along uplift-rich areas such as mountain ranges (Bohrer et al., 2012; Katzner et al., 2015). Orographic uplift is particularly useful when generated from mountain ranges oriented in the migration direction (Dennhardt et al., 2015; Kerlinger, 1989). In the case of thermal uplift, soaring birds typically climb in thermals using a circular trajectory from which they glide linearly towards the next thermal in the desired direction (Katzner et al., 2015; Kerlinger, 1989; Santos et al., 2017). Due to such specific requirements, soaring birds tend to move along areas with high uplift potential, often named corridors (sensu Dennhardt et al., 2015). Besides the physical requirements for soaring, the importance of different corridors may vary dramatically depending on their geographic position relative to migration routes of soaring birds. For example, areas in the vicinity of narrow sea crossings may experience higher traffic during migrations, as soaring birds avoid crossing large bodies of water (Newton, 2008).

Soaring birds and wind energy developments may compete for the same areas both at the local and regional scales. At local scales, wind turbines are frequently installed along the top of mountain ranges, in order to maximize exposure to horizontal winds, and these areas also tend to have high orographic uplift potential for birds (Katzner et al., 2012). At a broader scale, migratory bottlenecks of soaring birds often correspond to narrow sea crossings or mountain passes where the topography favours high wind speeds, thus also well suited for wind-power production (Hilgerloh, Michalik, & Raddatz, 2011; Martín et al., 2018; Villegas-Patraca, Cabrera-Cruz, & Herrera-Alsina, 2014).

Therefore, understanding how wind turbines impact movement corridors of migratory soaring birds is of utmost importance to better reconcile the production of wind power with wildlife conservation.

In general, birds tend to avoid wind turbines through evasive movements and changes in space use (May, 2015). Empirical evidence published on soaring birds has been showing they change their flight trajectories to avoid turbines (de Lucas, Janss, & Ferrer, 2004; Villegas-Patraca, Cabrera-Cruz, & Herrera-Alsina, 2014) and that their numbers decrease in the close proximity of the turbines (Barrios, & Rodriguez, 2004; Pearce-Higgins et al., 2009). Similarly, comparisons between the pre- and post-construction phases showed that soaring birds reduce their use of the areas where turbines are installed and their trajectories become more scattered in nearby areas (Cabrera-Cruz, & Villegas-Patraca, 2016; Farfan et al., 2017; Garvin et al., 2011; Johnston, Bradley, & Otter, 2014). While these avoidance behaviours suggest that soaring birds are to some extent able to cope with the presence of wind turbines (Marques et al., 2014), they may also cause functional habitat loss (i.e. loss of aerospace in movement corridors; Diehl, 2013), which is a potentially important, though largely neglected, impact of wind-power generation (Davy, Ford, & Fraser, 2017).

In this study we investigated the footprint of wind turbines on movement corridors of migratory soaring birds using high-frequency GPS tracking (1-minute temporal resolution or higher). GPS tracking is a powerful tool to investigate direct interactions between birds and wind turbines at multiple spatiotemporal scales, but it was only recently introduced in this field of study (e.g. Garthe, Markones, & Corman, 2017; Thaxter et al., 2015; Thaxter et al., 2018). We tracked 130 black kites (*Milvus migrans*) during the post-breeding migration in an area highly populated by wind turbines in the region of Tarifa, Spain. Black kites and other soaring birds concentrate in this region to cross the Strait of Gibraltar during their migration to Africa (MIGRES, 2009). Birds were captured and tracked during periods of strong crosswinds at the Strait of Gibraltar, which forced them to roam around Tarifa while waiting for conditions favouring the sea crossing. Bird movements were used to map space use intensity using Brownian bridge movement models. The influence of the wind turbines on the birds' use of the landscape was then modelled taking into account the main predictors of soaring flight, orographic and thermal uplift (Bohrer et al., 2012; Kerlinger, 1989). We hypothesised that (1) birds will use areas with greater uplift (orographic and thermal) more frequently, and (2) the area in the proximity of the wind turbines will be less frequented regardless of its uplift potential.

Materials and methods

Study area

This study was conducted in the region of Tarifa (36.0132ºN, 5.6027ºW), on the Spanish side of the Strait of Gibraltar. The Strait is a narrow sea crossing between Europe and Africa and is the main migration bottleneck for soaring birds travelling along the Western European–West African Flyway (Newton, 2008). The region of Cádiz (that includes Tarifa) is of high importance to the wind energy industry, with ca. 70 wind farms and over 1300MW of installed wind-power capacity (IECA, 2015). Our focal area had 160 operating wind turbines on seven wind farms, representing 132MW of power generation (Fig. 1, Table S1). These turbines were mainly arranged in rows from North to South (Fig. 1).

Bird captures and tracking

Our model species, the black kite, is an obligate soaring migrant, and one of the most common soaring species crossing the Strait of Gibraltar during the post-breeding migration (between 100 and 150,000 individuals are counted on an annual basis; Martín et al., 2016). These features make this species susceptible to interactions with wind turbines, and fatalities due to collision with wind turbines have been recorded in earlier studies in this region (Ferrer et al., 2012).

We captured and fitted 130 birds with GPS data loggers during the post-breeding migration (July to September) in 2012 and 2013 (Table S2). Birds were captured during periods of strong Levanter winds (5-15 m/s blowing from the east), which are frequent in the summer (Dorman, Beardsley, & Limeburner, 1995) and are known to prevent the passage of soaring birds to Africa, causing them to congregate around Tarifa for periods up to one week (Miller et al., 2016). Birds were captured in a walk-in trap (7 x 7 x 3.5 m) baited with carrion, located 3.5 km North of Tarifa (36.0426ºN, 5.6150ºW). We captured more birds than those eventually tracked, which enabled us to select similar numbers of adults and juveniles in each capture event. Overall, we tracked 72 adults and 58 juveniles. Sex ratio was also relatively balanced (69 females, 59 males and 2 unidentified, results from molecular sexing).

Birds were equipped with GPS-GSM data loggers (42g, TM-202/R9C5 module, Movetech Telemetry, UK, https://www.uea.ac.uk/movetech) attached as backpacks using Teflon ribbon. A weak-link was built in to each harness to allow the loggers to automatically detach. The weak-link was made from rubber band for the birds tagged in 2012 and from biodegradable plastic thread in those tagged in 2013. Previous tests showed that the rubber band breaks within two to four weeks when exposed to solar radiation and the biodegradable plastic thread within a year. Birds were released a few hours after capture, immediately after the tagging was completed. Loggers were set to obtain a GPS position at least once a minute. GPS mean error calculated from ca. 1500 fixes collected by two data loggers left at a fixed known position was 1.4 m in horizontal and 1.5 m in vertical, with maximum errors of 15 m and 31 m respectively. Data were uploaded to an online server via the GSM network every two hours.

The procedures involved in bird trapping and the GPS tagging were approved by the Consejería de Medio Ambiente of the Junta de Andalucía through the license to Alejandro Onrubia.

Estimation of orographic and thermal uplift

We used estimates of orographic and thermal uplift to test our first study hypothesis. The orographic and thermal uplift velocities were estimated using a modified version of the methodology employed by Bohrer et al. (2012) and Brandes and Ombalski (2004) for high resolution spatial data, described in Santos et al. (2017). The estimation of orographic uplift uses parameters from local topography (terrain aspect and slope) and wind (direction and speed). Local topography was obtained from a Digital Elevation Model of 30 m spatial resolution available at http://gdex.cr.usgs.gov/gdex/ (NASA JPL, 2009). Wind direction and speed was obtained at a weather station in Tarifa (36.0138ºN, 5.5988ºW). Measurements of wind for the whole migration season of black kites (mid-July to mid-September; MIGRES, 2009) during in 2012 and 2013 lead to the conclusion that there are two predominant wind conditions: (1) strong Levanter winds (wind direction from 80 to 120º; speed from 4 to 15 m/s) lasting for periods up to a week; and (2) western breeze (wind direction from 270 to 310º; speed from 1 to 6 m/s), typically occurring between Levanters (Fig. S1). These wind conditions match with that generically described for the summer at the Strait of Gibraltar (Dorman, Beardsley, & Limeburner, 1995). In this context, we decided to build three different orographic uplift models, the first representing uplift for average conditions of wind during the collection of our tracking dataset (direction = 97.8º, speed = 8.8m/s), and the other two models representing the average conditions of Levanter wind (direction = 100º, speed = 7.7m/s) and western breeze (direction = 290º and speed = 4.1m/s) observed during the whole migration season of black kites in 2012 and 2013. The uplift estimated from the first model was used as predictor in bird space-use models (described in the section below), while the estimates of the remaining two uplift models were used in the calculation of general scenarios of habitat loss during Levanter wind and western breeze (shown in Fig. 5).

The estimation of thermal uplift velocity according to Santos et al. (2017) uses land surface temperature derived from LANDSAT imagery. In general, satellite images obtained in the same season show high correlation in reflectance values if no major changes of land use are observed (Zhu, 2017). Consequently, high correlation is also expected for thermal uplift models built from those images. Santos et al. (2017) confirmed that uplift models built for the study area in different days during the summers of 2012 and 2013 are highly correlated (r > 0.77). Therefore, we decided to build a single thermal uplift model that used land surface temperature estimated from a LANDSAT 8 OLI/TIRS image acquired on July 17th 2013, available at http://earthexplorer.usgs.gov/ (NASA Landsat Program, 2015). The model was representative of uplift at 225 m height, which is the mean flight height of birds in our tracking dataset, and its spatial resolution was 100 m, corresponding to that of the LANDSAT 8 OLI/TIRS thermal band.

Bird movement modelling

Our modelling approach followed the concept of Resource Utilization Function (RUF) proposed by Marzluff et al. (2004). RUF uses a two-step analysis, the first that estimates the density or intensity of space use (i.e. Utilization Distribution; UD) over the geographic domain of interest and the second links the space use to a set of spatially explicit covariates in a regression model (Hooten et al., 2017).

Our modelling dataset included GPS positions of flying birds (i.e. GPS speed >1 m/s, Fig. S2) collected during daylight and in days of Levanter wind (direction: mean = 97.8º, SD = 0.22, range = 83.2-116.3º; speed: mean = 8.8m/s, SD = 2.2, range = 4.2-12.7 m/s). Very few tracking data were collected with different wind conditions than Levanter because birds cross the Strait of Gibraltar as soon as the Levanter ceases (Miller et al., 2016). These data were thus excluded from the analysis. We also concentrated the analysis in the area where the concentration of bird movement was the highest (represented in Fig. 1).

We used dynamic Brownian bridge movement models (dBBMM; Kranstauber et al., 2012) to estimate the UD of each bird in each day on a 100x100m grid. Contrasting to conventional methods of UD estimation, the Brownian bridge movement model quantifies the UD based on the movement path of animals rather than individual points (Horne et al., 2007; Kranstauber et al., 2012). A major advantage of this method is that it accounts for temporal autocorrelation in the data, which is a fundamental problem of tracking data, particularly for GPS data obtained at high frequency (Kranstauber et al., 2012). The dBBMM were implemented in R (R Core Team, 2016) with the function brownian.bridge.dyn of the package move (Kranstauber, Smolla, & Scharf, 2017), using a window size of 15 locations and a margin of 5 locations following the recommendations of Kranstauber et al. (2012). The UD calculated for each bird in each day were summed in order to produce a general UD for our study area. This UD was used as a response variable in the models described below.

In order to specifically test our study hypotheses, we fitted a generalized additive mixed model (GAMM) using distance to wind turbines and the orographic and thermal uplift velocities as predictors of bird UD. Orographic and thermal uplift are the most important drivers of soaring flight on land (Kerlinger, 1989), thus we expected bird UD to be fundamentally determined by those factors but potentially affected by the proximity of wind turbines. We selected GAMM as modelling technique because it simultaneously allowed the use of non-linear predictors and accounting for spatially correlated data (Beale et al., 2010; Zuur et al., 2009). The model was fitted with the function gamm of the R package mgcv (Wood, 2018). Bird UD and all predictors were represented by single values in the 100x100m grid generated in the dBBMM interpolation. We must emphasise that orographic and thermal uplift estimates result from static uplift models, representing the generic conditions for the period of tracking data collection (see section above). We added a Gaussian spatial correlation structure to the model to account for spatial autocorrelation (Beale et al., 2010; Dormann et al., 2007; Wood, 2017). This was done with the function corGaus of the R package mgcv

(Wood, 2018) following Zuur et al. (2009). Bird UD was log-transformed to normalize its distribution. No random factors were included in the model. In a first approach, the degree of smoothing of predictors (k) was left free to be optimized by cross-validation (the default method of the gamm function). However, we found that the effects of uplift predictors on bird UD were approximately linear in the regions well supported by data (Fig. S3). Therefore, we set these two predictors as linear in our final model. The modelling dataset was restricted to grid cells at distances up to 2 km from wind turbines (i.e. 9,136 grid cells), as the influence of wind turbines on bird UD is expected to dissipate with distance.

A second model was built for grid cells positioned far away from the influence of the wind turbines (1 to 2 km away from turbines) using only the orographic and the thermal uplift velocities as predictors. We used this model to estimate soaring suitability in the absence of wind turbines (used for the results presented in Figures 4 and 5). This model was a Generalized Least Squares (GLS) since it did not include non-linear predictors. The model was fitted with the function gls of the R package nlme (Pinheiro et al., 2018). As in the GAMM model, in this model we used function corGaus to account for spatial autocorrelation of the data, and the bird UD was log-transformed to normalize its distribution.

Both models were validated through 10-fold cross-validation. The original dataset was randomly split into a training subset with 90% of the data that was used to fit the model, and a testing subset with 10% of the data against which the model is tested. This procedure was repeated 10 times in a way that the training and testing subsets of each run were complementary and cover all the original dataset (Geisser, 1993). The precision and predictive performance of models were evaluated from their Normalized Root Mean Square Error (nRMSE), defined as the root mean square error divided by the range of the model response variable. The Root Mean Square Error (RMSE) is a commonly used metric for regression models accuracy and performance that quantifies model error in the units of the observed data (Kuhn, & Johnson, 2013). Normalizing the RMSE facilitates the comparison between models built at different spatial and temporal scales (e.g. Bocinsky, & Kohler, 2014; Feilhauer et al., 2010).

For both models, fitting assumptions were checked from diagnostic residual plots of R the packages mgcv and nlme (see Fig. S4), and spatial autocorrelation correction was validated from plots of residual autocorrelation generated with the function correlog of the R package ncf (Fig. S5, Bjornstad, 2018).

Results

We tracked 130 individual black kites for an average of 3 days each, generating ca. 220,000 GPS locations (Fig. 1 left panel). Movements were concentrated within a radius of ca. 40 km from Tarifa, with individual birds moving about 120 km on average before they crossed the strait of Gibraltar (see Fig. S6 for examples of tracks). From the original dataset, 77,228 GPS locations were used for modelling purposes (Fig. 1 left panel, Table S2; see methods for details on data selection).

The UD estimated from dBBMMs showed an uneven spatial pattern, with reasonably defined areas of concentration of movement (Fig. 1 right panel). Higher intensity of movement was observed along two central areas aligned approximately North-South and along the coastline (Fig. 1 right panel).

The estimates of uplift showed highly heterogeneous distributions (Fig. 2). The highest orographic uplift velocities during the period of data collection were estimated along the east-facing mountain slopes in the most western and eastern regions of the study area (Fig. 2 left panel). In contrast, the highest estimates of thermal uplift were concentrated in a valley located in the centre of the study area (Fig. 2 right panel). Orographic uplift was spatially more concentrated with more extreme velocities than thermal uplift, but the latter showed higher values on average (orographic uplift velocity: mean of grid cell values = 0.35m/s, SD = 0.72, range = 0-6.18m/s; thermal uplift velocity: mean of grid cell values = 1.69m/s, SD = 0.26, range = 0.10-2.19m/s).

GAMM results showed that bird UD was significantly affected by the distance to wind turbines and the two types of uplift (Table 1, Fig. 3). A negative effect of wind turbine proximity on bird UD was observed up to a distance of approximately 674 m (i.e. the maximum of the curve of Fig. 3 left panel), which dissipates beyond that. However, it should be noted that there was a slight drop of bird UD after the 674 m. Both orographic and thermal uplift velocities had a positive effect on bird UD (Table 1, Fig. 3).

The GLS model, fitted with data obtained beyond the influence of the wind turbines (i.e. 1 to 2 km from wind turbines), showed effects of orographic and thermal uplift velocities on bird UD similar to those of the GAMM (Table 1, Fig. S7). Predictions of the GLS model applied to areas up to 674 m from the wind turbines were significantly higher than the dBBMM estimates for the same areas (Fig. 4). This indicates that birds used areas close to turbines less than expected based on their soaring suitability. After extrapolating this model to the entire study area we found that between 3 and 14% of the area suitable for soaring was within the area of influence of wind turbines (i.e. within 674 m of wind turbines), these being similar during Levanter wind (4-14%) and western breeze (3-14%; Fig. 5).

Discussion

We found that wind turbines affect a large area of potentially suitable soaring-habitat around them. GPS-tracked black kites showed a reduced use of the areas up to approximately 674 m away from the wind turbines (corresponding to an area of ca. 143 ha around each turbine), this effect being stronger at shorter distances (Fig. 3), which proves our second study hypothesis. We also demonstrated that areas within 674 m of the wind turbines had suitable uplift conditions for soaring flight but they were used less than expected by the black kites (Fig. 4). Interestingly, there was a slight peak of bird use at areas near the 674 m threshold (Fig. 3) that might have been a consequence of birds changing direction to avoid entering the areas adjacent to the turbines (Cabrera-Cruz, & Villegas-Patraca, 2016; Villegas-Patraca, Cabrera-Cruz, & Herrera-Alsina, 2014). Additionally, we showed clear increasing relationships between orographic and thermal uplift and bird UD (Fig. 3 and Fig. S5), proving the first hypothesis of this study.

We must emphasise that our models include some level of error (see Table 1), likely because that were other environmental variables influencing the movement of the birds that were not included as predictors. However, that amount of error is comparable to that found in previous studies linking bird soaring behaviour to uplift proxies (Bohrer et al., 2012; Dodge et al., 2014; Hernandez-Pliego, Rodriguez, & Bustamante, 2015; Santos et al., 2017; Sapir et al., 2011). The fact that uplift predictors were estimated for a single generic circumstance in time may also have added inaccuracy to our models. Tracking data used in the models were collected in highly uniform conditions of wind direction, therefore we do not expect that the areas with orographic uplift potential to change spatially in time. However, the variation observed in wind speed may have affected overall uplift intensity of those areas. This could potentially have influenced the birds' trade-off in using orographic uplift or thermal uplift in nearby areas. Regarding the thermal uplift, a considerable temporal variation is expected within a day and between days mostly due to the amount of solar radiation heating the earth surface (Stull, 1988). As in the case of orographic uplift, we do not expect such variation to promote spatial changes in uplift but some intensity variation is expected that could represent a trade-off in the use of alternative sources of uplift.

The displacement effects of wind-power plants have been demonstrated in earlier studies for soaring birds (Barrios, & Rodriguez, 2004; Cabrera-Cruz, & Villegas-Patraca, 2016; de Lucas, Janss, & Ferrer, 2004; Garvin et al., 2011; Johnston, Bradley, & Otter, 2014; Pearce-Higgins et al., 2009; Villegas-Patraca, Cabrera-Cruz, & Herrera-Alsina, 2014). However, to the current date only a single study quantified the extent of the area affected by this phenomenon (Pearce-Higgins et al., 2009). That study reports lower densities of two species of raptors during their breeding season in areas up to 800 m from turbines, coarsely matching the estimates of our model. Our study is the first attempt to quantify the proportion of soaring habitat lost or negatively affected by the presence of wind farms. We estimated that 3-14% of the areas suitable for soaring in our study area were impacted by wind-energy production, this estimate being similar for Levanter winds and western breeze (Fig. 5). These two sorts of wind comprise most wind conditions found in Tarifa during the migration season of black kites (Fig. S1). The magnitude of this impact is likely similar in other critical areas for migratory soaring birds where new large wind-power projects are being constructed, such as the Gulf of Suez in Egypt (Hilgerloh, Michalik, & Raddatz, 2011) or the Isthmus of Tehuantepec in Mexico (Villegas-Patraca, Cabrera-Cruz, & Herrera-Alsina, 2014). It should be emphasized that soaring birds are restricted to fly in soaring corridors (e.g. Leshem, & Yom-Tov, 1998; Santos et al., 2017; Shamoun-Baranes et al., 2003), thus, small losses of suitable area may have large constraints for their vital activities. Losses in movement corridors may be particularly important during migrations, as soaring birds already experience considerable mortality while overcoming natural barriers, such as deserts and sea stretches (Bildstein et al., 2009; Klaassen et al., 2014; Strandberg et al., 2010). Suboptimal soaring conditions may force birds to delay or suspend migration or to use flapping flight, which is energetically unsustainable for most species (Newton, 2008).

The reason why migratory soaring birds avoid wind turbines is still unclear. The fact that birds are displaced far beyond the areas occupied by the physical infrastructure of wind-power plants could be a consequence of neophobia, as turbines do not belong to their natural environment (Walters, Kosciuch, & Jones, 2014), but it could also be a consequence of earlier negative experiences, such as birds being caught in the airflow around turbines, or even witnessing fatalities of conspecifics. In addition, the functioning of wind turbines disturbs local airflow regimes (e.g. Magnusson, & Smedman, 1999; Sorensen et al., 2015), which may compromise uplift generation. However, this is expected to affect only the areas downwind the turbine rotors (e.g. Magnusson, & Smedman, 1999; Sorensen et al., 2015). We should also recognize that the avoidance of turbines varies considerably among soaring species, their life stage and their annual cycle (May, 2015), thus the range of influence of wind turbines found in this study is not necessary replicable in other contexts.

Our findings indicate that the negative effects of wind-power developments on soaring birds may be far more extensive than the commonly reported mortality caused by collision (Marques et al., 2014). Avoidance behaviour may suggest that soaring birds, as well as other birds, are partly able to cope with the existence of wind turbines (Marques et al., 2014). However, our results make clear that this is a simplistic interpretation and may lead to the underestimation of the real impacts of wind-power generation. We recommend that the authorities responsible for wildlife protection and wind industry regulations recognize the loss of aerial habitat caused by wind turbines and the potential associated negative impacts on soaring birds. It becomes clear from our results that individual turbines greatly differ on their impact depending on their geographical position (Fig.5), thus it is possible to significantly reduce overall impact of wind-power production with adequate planning. The method we used to map updrafts uses only data that is publicly available (Santos et al., 2017) and can be used in environmental impact assessment studies to guide the selection of low-impact locations for new wind turbines. We are convinced that wind-energy production is necessary to face global warming, but the accelerating increase of wind-power developments needs to be accompanied by science-based solutions to minimize its impacts on wildlife.

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Authors' contributions

A.T.M., C.D.S., J.P.S., J.P., F.M. and M.W designed the study; C.D.S., A.-R.M, A.O. and J.P.S. collected the data; A.T.M., C.D.S. and F.H. analysed the data; A.T.M. and C.D.S. wrote the manuscript. All authors discussed the results and commented on the manuscript.

Data accessibility

The tracking data used in this study is available at Movebank Data Repository http://doi.org/10.5441/001/1.q23p1t84 (Marques 2019).

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Tables and figures

Table 1. Summary statistics for the two models explaining black kite UD. The first model tested the effect of wind turbines on bird UD while accounting for the effects of uplift. The model was a GAMM fitted with grid-cell data at distances up to 2 km from wind turbines, and included the distance to the wind turbines, the orographic and the thermal uplift velocities as predictors. The second model was designed to evaluate soaring suitability grid cells independently of the effect of wind turbines. The model was a GLS fitted with data obtained far from the influence of wind turbines (between 1 and 2 km distance) and used only orographic and thermal uplift velocities as predictors. Both models were corrected for spatial autocorrelation (see methods for details). Fitting and cross validation Normalized Root Mean Square Error ($nRMSE_{fit}$ and $nRMSE_{cv}$) are shown for the evaluation of precision and predictive performance of the models respectively. For $nRMSE_{cv}$ we show the range of the nRMSE calculated for the 10 models produced in the cross validation procedure (see methods for further details). SE – Standard error; t – T statistics; edf – Estimated degrees of freedom; F – F statistics.

	Estimate	SE	t	edf	F	P-value	$nRMSE_{fit}$ (%)	$nRMSE_{cv}$ (%)
Model: Effect of wind turbines							13.7	13.6 – 16.5
Intercept	-10.59	0.26	-41.33					
s(distance to turbines)				5.22	12.95	<0.001		
orographic uplift	0.11	0.01	8.03			<0.001		
thermal uplift	2.70	0.15	18.17			<0.001		
Model: Soaring suitability							14.5	14.8 - 17.9
Intercept	-10.42	0.36	-28.74					
orographic uplift	0.12	0.02	5.96			<0.001		
thermal uplift	2.62	0.21	12.68			<0.001		

Figure 1. Use of the aerospace in the study area (Tarifa, Spain) by the black kites during the post-breeding migration of 2012 and 2013, and the locations of the wind turbines. Left panel: GPS locations of 130 tracked birds. Locations are only shown for birds flying (speed >1 m/s) during daylight in periods of Levanter wind (blowing from the east), and for the region where the concentration of bird movement was the highest. Right panel: cumulative Utilization Distribution modelled from dBBMMs. Map grid with 100m spatial resolution. Black dots in each map are the locations of wind turbines.

Figure 2. Estimated orographic (left) and thermal (right) uplift velocities in the study area. Orographic uplift represents deflected Levanter winds during the period of bird tracking (wind direction: mean = 97.8º, SD = 0.22, range = 83.2-116.3º; wind speed: mean = 8.8m/s, SD = 2.2, range = 4.2-12.7 m/s). Thermal uplift velocity was modelled for 225m height (mean flight height of birds) using land surface temperature estimated from a Landsat 8 OLI/TIRS image acquired in July 17th 2013 (NASA Landsat Program, 2015) (available at the USGS archive, http://earthexplorer.usgs.gov/). Light hill shading was added to illustrate interaction between topography and uplift. Black dots represent wind turbines.

Figure 3. GAMM partial effects of distance to turbines, orographic uplift and thermal uplift on black kite UD. Shaded areas represent 95% confidence intervals. Modelling dataset includes grid cells up to 2 km from wind turbines.

Figure 4. Comparison between soaring suitability and the use by black kites of the areas close to wind turbines (up to 674 m of distance) and far from wind turbines (located at 1 to 2 km distance from the closest turbine). Bird use corresponds to the UD obtained directly from the dBBMM, and the soaring suitability is the UD predicted from a GLS fitted with orographic and thermal uplift velocities as predictors and the dBBMM UD as response variable (see methods for further details).

The GLS model was fitted with data of grid cells placed far away from the influence of wind turbines (between 1 and 2 km distance of the closest turbine). These data were randomly divided in two datasets, the first was used to fit the GLS model (with 90% of the data) and the second was used to represent bird use far from turbines in the plot (with 10% of the data). Error bars in the plot represent 95% confidence intervals.

Figure 5. Soaring habitat affected by wind turbines for average conditions of Levanter wind (blowing from the east) and western breeze observed during the migration seasons of the black kites in 2012 and 2013. Wind turbine influence is represented by circles of 674 m radius around each turbine (this distance resulted from the GAMM model shown in Table 1 and Fig. 3). Soaring suitability resulted from predictions of a GLS model (detailed in Table 1 and Fig. S7) using thermal and orographic uplift estimates for the whole study area and for the two sorts of wind observed during the migration seasons of the black kites in 2012 and 2013. The UD predictions produced from the GLS model were simplified in soaring suitability categories: very high suitability – are the 10% highest UD values; high suitability – are the following highest 15% UD values; moderate suitability – are the following highest 25% UD values; and low suitability – are the lowest 50% UD values. The inset plot shows the percentage of area under the influence of wind turbines considering different scenarios of soaring suitability. Confidence intervals in the plot result from confidence intervals of fitted values of GLS model predictions.

Figure 1

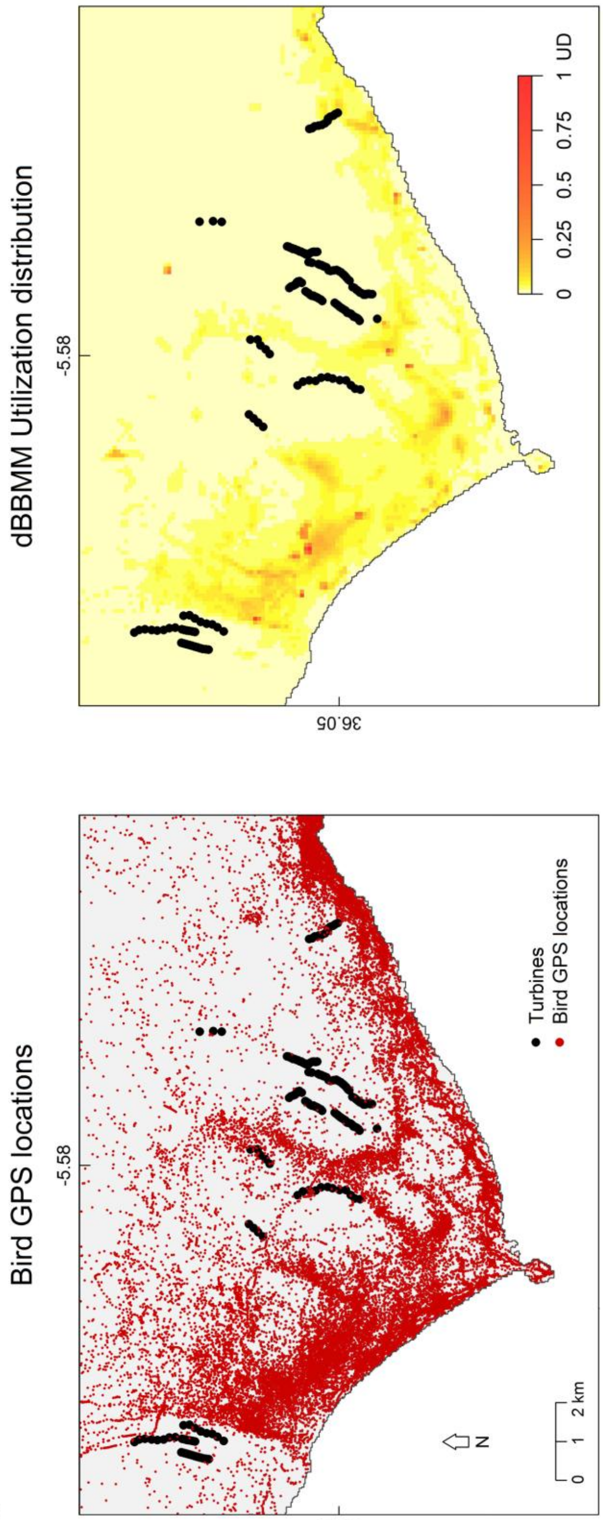
Bird GPS locations
dBBMM Utilization distribution
-5.58
-5.58
36.05
36.05
Turbines
Bird GPS locations
N
0 1 2 km
0 0.25 0.5 0.75 1 UD

Figure 2

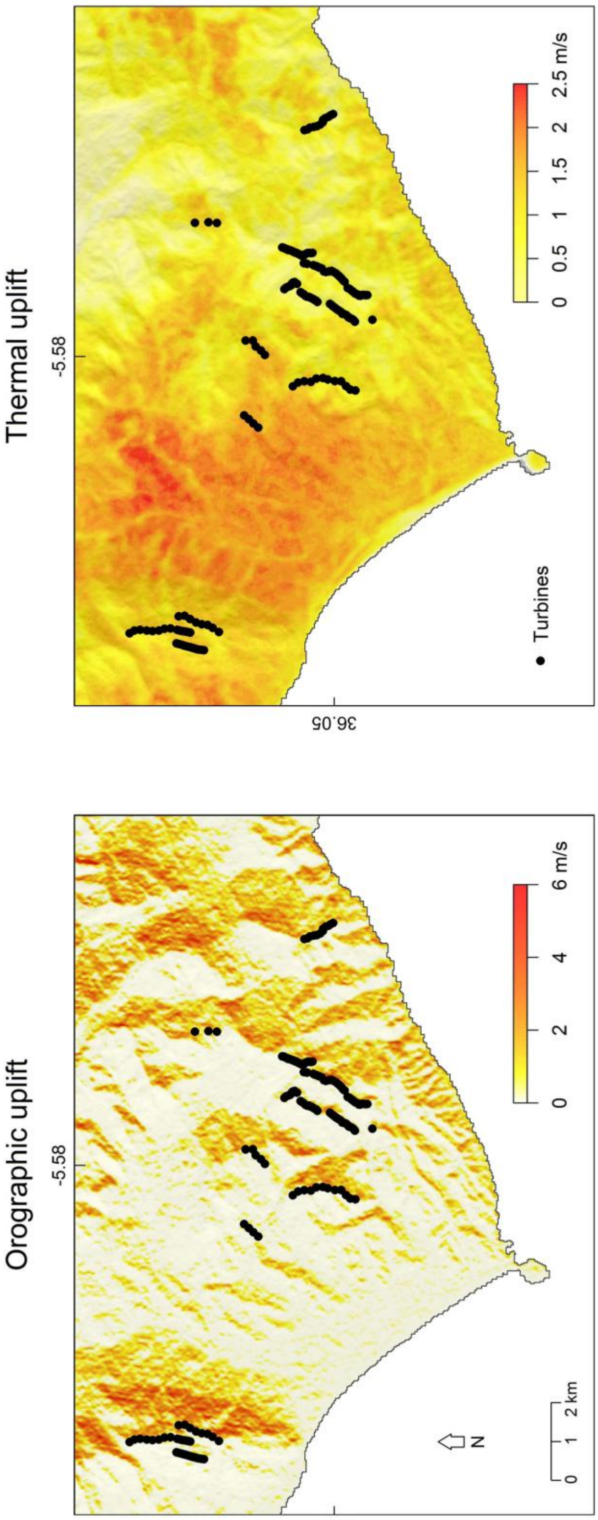
Orographic uplift
-5.58
36.05
0
2
4
6 m/s
N
0 1 2 km
Thermal uplift
-5.58
36.05
0
0.5
1
1.5
2
2.5 m/s
Turbines

Figure 3

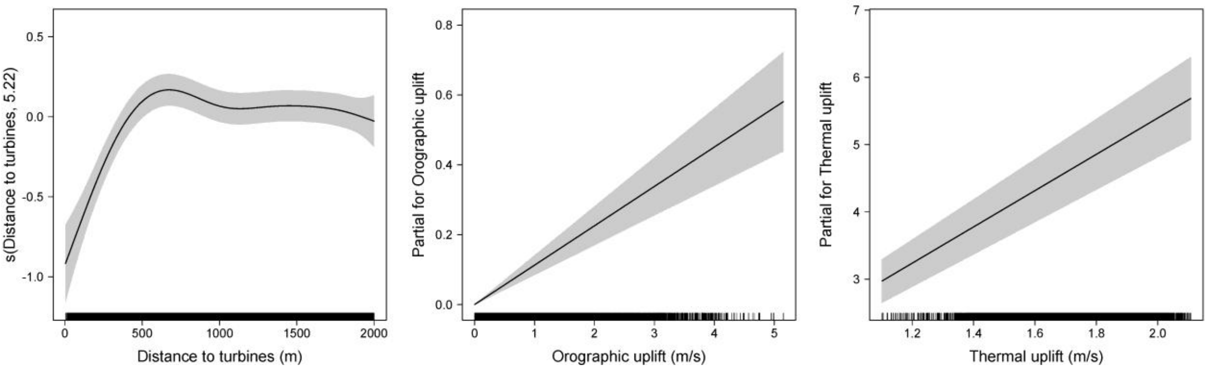

Figure 4

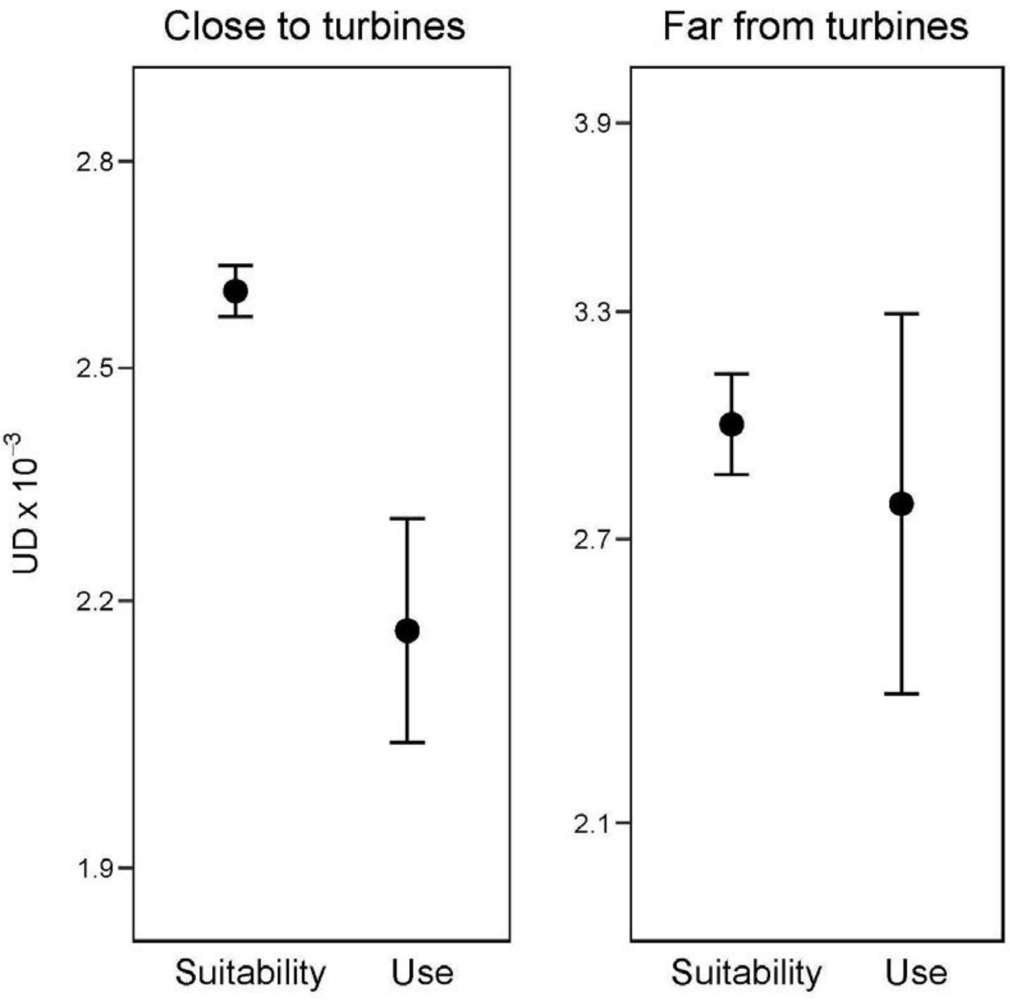

Figure 5

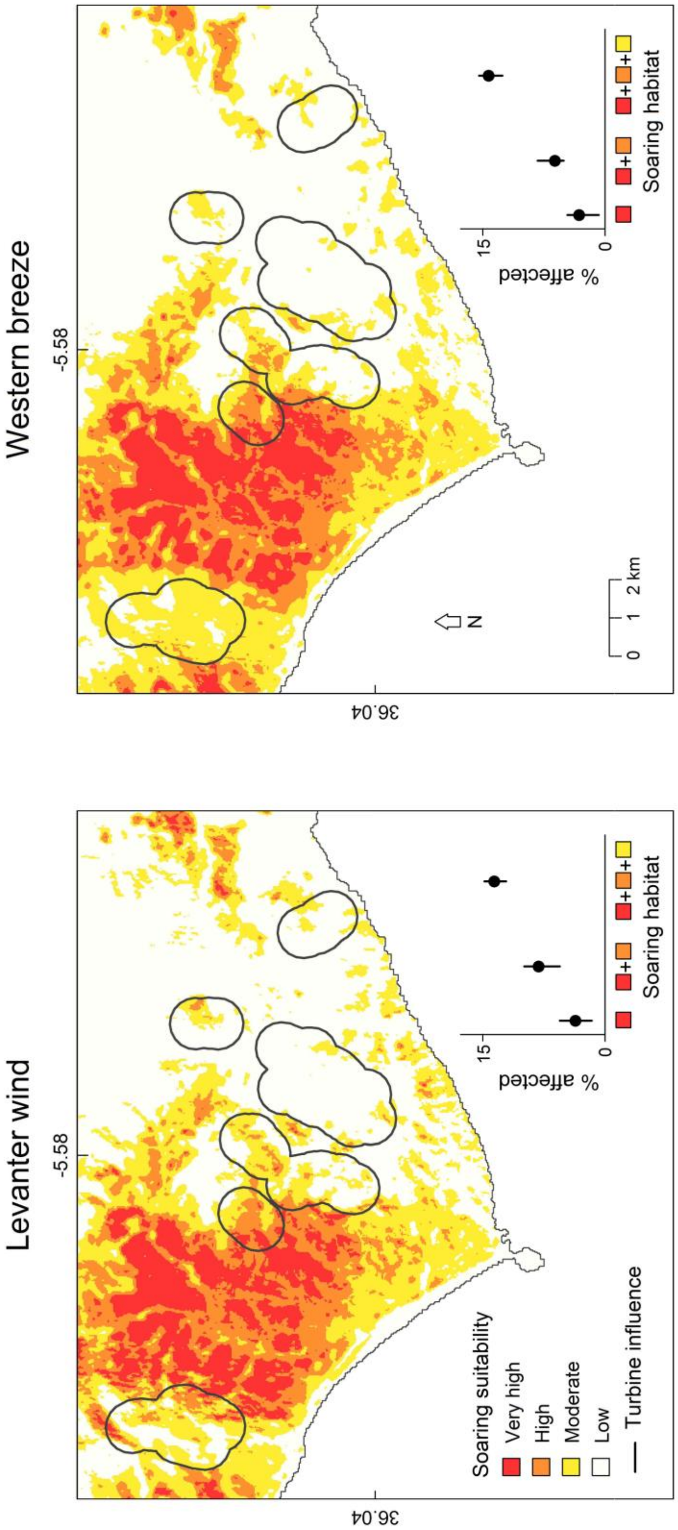
Levanter wind
Western breeze
-5.58
36.04
Soaring suitability
Very high
High
Moderate
Low
Turbine influence
% affected
15
0
Soaring habitat
N
0 1 2 km

EXHIBIT
7

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
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Groundwater depletion during drought threatens future water security of the Colorado River Basin

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Key Points:
- Groundwater depletion in the Colorado River Basin is greater than we thought
- As GW disappears, the basin will struggle to supply water to the seven basin states
- It is time to bring groundwater under the water management umbrella

Supporting Information:
- Readme
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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Abstract Streamflow of the Colorado River Basin is the most overallocated in the world. Recent assessment indicates that demand for this renewable resource will soon outstrip supply, suggesting that limited groundwater reserves will play an increasingly important role in meeting future water needs. Here we analyze 9 years (December 2004 to November 2013) of observations from the NASA Gravity Recovery and Climate Experiment mission and find that during this period of sustained drought, groundwater accounted for 50.1 km^3 of the total 64.8 km^3 of freshwater loss. The rapid rate of depletion of groundwater storage ($-5.6 \pm 0.4\ km^3\ yr^{-1}$) far exceeded the rate of depletion of Lake Powell and Lake Mead. Results indicate that groundwater may comprise a far greater fraction of Basin water use than previously recognized, in particular during drought, and that its disappearance may threaten the long-term ability to meet future allocations to the seven Basin states.

1. Introduction

Over a decade, drought in the Colorado River Basin (Basin; Figure 1) has exposed the vulnerability [*Bureau of Reclamation*, 1975; *Barnett and Pierce*, 2008] of the most overallocated river system in the world [*Christensen et al.*, 2004]. Recently, the U.S. Bureau of Reclamation acknowledged the potential challenges [*Bureau of Reclamation*, 2012] to meeting future surface water allocations to the seven Basin states (Figure 1), noting that the contribution of local supplies, including groundwater withdrawals, will be required to offset anticipated shortages. While the need to exploit groundwater resources to meet Basin water demands has long been recognized [*Bureau of Reclamation*, 1975], withdrawals required to meet current demands remain undocumented and are uncertain in the future. In particular, water management under drought conditions focuses on surface water resources [*Basin Interim Guidelines*, 2007] without a regulatory framework to manage groundwater withdrawals outside of "river aquifer" systems [*Leake et al.*, 2013]. At question is the potential impact of solely managing surface water allocations and diversions in the Basin, without regard to groundwater loss, on meeting future water demands.

The ability to observe changes in water resources at large scales has been greatly facilitated by the deployment of recent Earth-observing satellites. One such satellite mission, the NASA Gravity Recovery and Climate Experiment (GRACE) [*Tapley et al.*, 2004], has measured the temporal variations in the Earth's gravity field since March 2002. These observations are now routinely applied to estimate the monthly changes in terrestrial or total land water storage (i.e., all of the snow, surface water, soil moisture, and groundwater) in regional areas that are 200,000 km^2 or larger [*Wahr et al.*, 2004] (Figure 2). Several studies have now demonstrated that GRACE observations, when combined with coincident data sets for snow water equivalent (SWE), surface water storage, and soil water content in a mass balance, can quantify changes in groundwater storage with sufficient accuracy [e.g., *Rodell et al.*, 2009; *Famiglietti et al.*, 2011] to influence regional water management decisions [*Famiglietti and Rodell*, 2013].

Our goal in this report is to identify changes in freshwater storage, including surface reservoir and groundwater storage, to assess the influence of conjunctive surface water and groundwater use on water availability in the Colorado River Basin during the recent drought. We evaluate the terrestrial water storage anomalies (TWSA) using GRACE observations during a 9 year period (December 2004 to November 2013) that begins 4 years into a prolonged drought in the southwestern United States, after water levels in Lake Powell

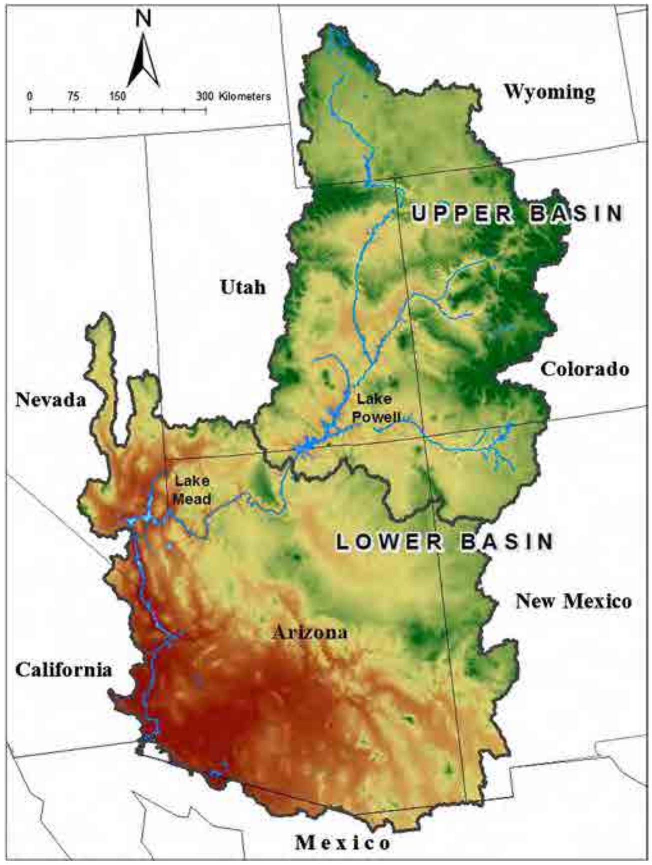

Figure 1. The Colorado River Basin of the western United States. The state and international boundaries are in light gray. The green and brown colors represent the high and low elevations, respectively [*McKay et al.*, 2012]. The upper Basin is that portion of the Basin upstream of Lake Powell. The lower Basin is the remainder of the basin downstream of Lake Powell. The basin outlines are in dark gray. The river, its main tributaries, and Lake Powell and Lake Mead are shown in blue.

and Lake Mead had declined precipitously [*Piechota et al.*, 2004] (see Methods section). In particular, we estimate the changes in groundwater storage during the 9 year drought period, when reservoir volumes were intensively managed to maintain hydropower production and to meet surface water allocations to the Basin states.

2. Methods

We used the Release 05 of the University of Texas Center for Space Research GRACE data [*Tapley et al.*, 2007] (ftp://podaac.jpl.nasa.gov/allData/grace/L2/CSR/RL05/). Average water storage changes for the Colorado River Basin were computed as anomalies of terrestrial water storage in equivalent water height (in millimeters, converted to cubic kilometers here using the area of the study basins) following *Swenson and Wahr* [2009] (Figure 2). Processing methods include filtering GRACE data to reduce noise [*Swenson and Wahr*, 2006] and later restoring the associated lost signal over a specific region by scaling the data correctively [*Velicogna and Wahr*, 2006]. This processing results in estimates of satellite measurement error and leakage error from out-of-basin signal, both of which are included in a Basin-specific time-invariant error estimate [*Wahr et al.*, 2006]. Figure 2 shows the Basin time series of terrestrial water storage changes from January 2003 to November 2013, nearly the complete available GRACE data record.

Because our focus here is on quantifying groundwater storage changes versus surface water storage changes during drought, we restrict our analyses to the 9 year period from December 2004 to November 2013. Prior to December 2004, the Basin had experienced four additional years of drought, effectively limiting surplus inflows that replenish Lake Powell and Lake Mead. This caused steep declines in reservoir storage prior to December 2004. Late 2004 also marked the beginning of a clear drought signal in the GRACE data, relative to its launch date in March 2002 (Figure 2).

To assess the accuracy of the GRACE data used here, we performed independent water budget analyses using regional precipitation (P) data from the PRISM system [*Daly et al.*, 2008] (http://prism.oregonstate.edu/recent/), satellite-based evapotranspiration (ET) from Moderate Resolution Imaging Spectroradiometer (MODIS) [*Tang et al.*, 2009], and the U.S. Bureau of Reclamation dam releases (Q) (usbr.gov; accessed December 2013) on the Colorado River. Uncertainty in the water balance estimate [*Rodell et al.*, 2004a, 2004b] was calculated assuming relative errors of 15% for P [*Jeton et al.*, 2005] and 5% in Q [*Rodell et al.*, 2004b]. A 15% bias on the daily ET was determined by *Tang et al.* [2009]; we assume the relative error increases to 25% on a monthly time scale. We computed the monthly storage changes, dS/dt, as $P - ET - Q$, and compared them to dS/dt derived from the GRACE terrestrial water storage anomalies using a discrete backward difference. Results illustrate a good agreement between dS/dt derived from the water budget and that

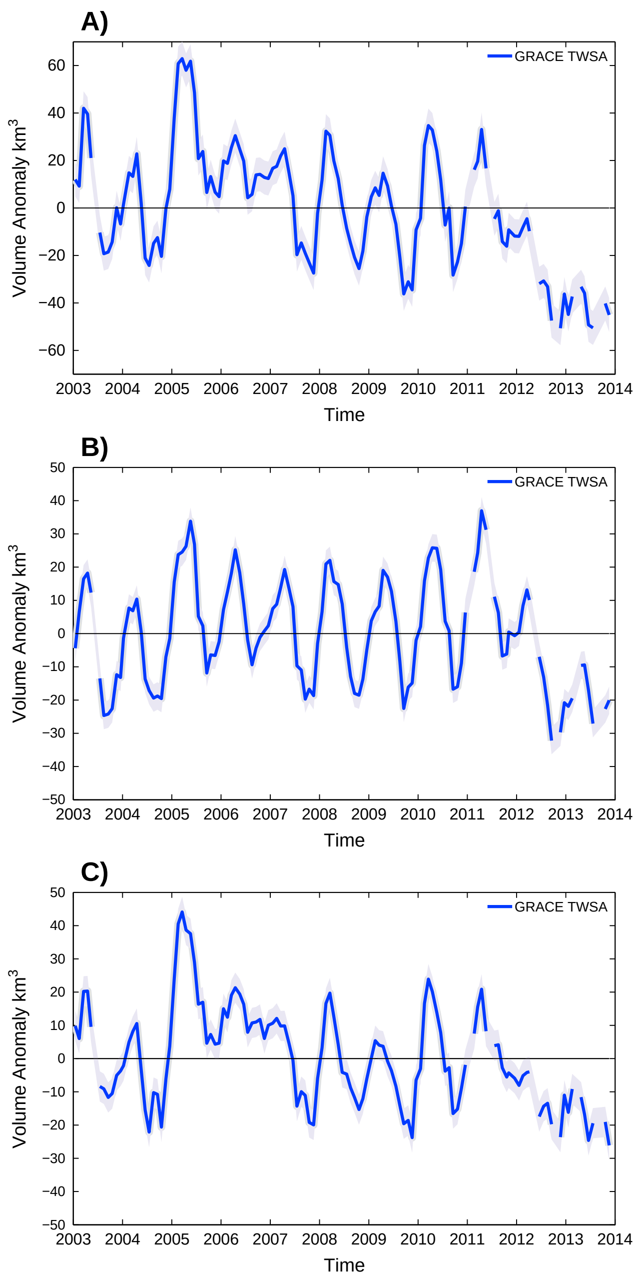

Figure 2. Monthly anomalies (deviations from the mean of the study period) of the total water storage (TWSA) for (a) the entire Basin, (b) the upper Basin, and (c) the lower Basin, from January 2003 to November 2013 (i.e., the full GRACE RL05 record available at writing). The three TWSA estimates were calculated independently using basin-specific scaling. The anomaly errors are shown in light blue shading. There are inconsecutive gaps in the GRACE data record, increasing in number toward the end of the time period due to recent declines in satellite power supply. Subsequent analyses focus on the period of prolonged drought extending from December 2004 to November 2013.

observed by the GRACE, for the entire Basin, and the upper and lower Basins (Figure S1 in the supporting information). Our comparisons were limited to March 2005 to March 2010 owing to the availability of *ET* estimates. Numerous additional studies have shown strong correspondence between GRACE water storage changes, hydrologic fluxes, and observations [see, e.g., *Swenson et al.*, 2006; *Famiglietti et al.*, 2011].

Accessible water storage changes (the combination of surface reservoir and groundwater storage changes) in the Basin are quantified using a water mass balance approach. Studies [e.g., *Rodell and Famiglietti*, 2002; *Rodell et al.*, 2009; *Famiglietti et al.*, 2011; *Scanlon et al.*, 2012] have shown that GRACE-observed water storage changes, in combination with additional data sets, can be used to isolate individual components of the terrestrial water balance. We assume that the total water storage in a region is composed of soil moisture (SM), snow water equivalent (SWE), surface water (SW), and groundwater (GW):

$$\mathrm{TWS}_t = \mathrm{SM}_t + \mathrm{SWE}_t + \mathrm{SW}_t + \mathrm{GW}_t, \quad (1)$$

where the subscript t indicates a function of time, and changes in these components balance in their sum. We apply GRACE observations of variations from the long-term mean of this total with estimates of soil moisture and SWE to quantify changes in accessible water. We simplify equation (1) by defining accessible water as the sum of groundwater and surface water storage:

$$\Delta\mathrm{AW}_t = \mathrm{TWSA}_t - \Delta\mathrm{SWE}_t - \Delta\mathrm{SM}_t, \quad (2)$$

where Δ indicates a variation from the time mean in an individual variable, and TWSA is the terrestrial water storage anomaly.

Soil moisture anomalies in equation (2) were estimated from the NASA Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004a] (http://disc.sci.gsfc.nasa.gov/) due to the lack of observational soil moisture data on large scales and for consistency with the previous studies [*Rodell et al.*, 2009; *Famiglietti et al.*, 2011]. We average the results of three land surface models from GLDAS (Variable Infiltration Capacity [*Liang et al.*, 1994], Noah [*Chen et al.*, 1996], and Community Land Model 2 [*Dai et al.*, 2003]) and apply the mean monthly standard deviation as an error estimate based on model structural biases (Figure S2 in the supporting information).

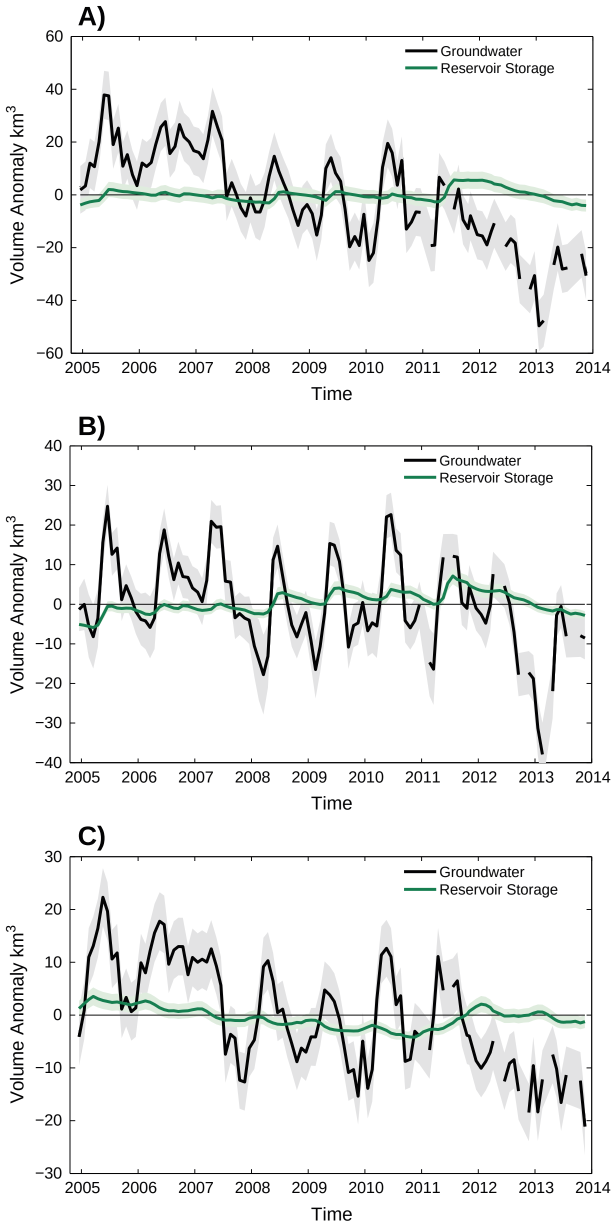

Figure 3. Monthly anomalies (km^3) of groundwater storage (black) and of surface reservoir storage (green) for (a) the entire Basin (trend: $-5.6 \pm 0.4\ km^3\ yr^{-1}$) and Lake Powell and Lake Mead combined (trend: $-0.9 \pm 0.6\ km^3\ yr^{-1}$), (b) the upper Basin (trend: $-1.7 \pm 0.4\ km^3\ yr^{-1}$) and Lake Powell (trend: $-0.6 \pm 0.6\ km^3\ yr^{-1}$), and (c) the lower Basin (trend: $-2.6 \pm 0.3\ km^3\ yr^{-1}$) and Lake Mead (trend: $-0.1 \pm 0.6\ km^3\ yr^{-1}$), from December 2004 to November 2013. The anomaly errors are shown in light gray shading for groundwater storage and in light green shading for reservoir storage. All trends are summarized in Table 1.

Data obtained from the Snow Data Assimilation System (SNODAS) [*National Operational Hydrologic Remote Sensing Center*, 2004] (http://nsidc.org/data/polaris/) were used for SWE in equation (2) (Figure S2 in the supporting information). SNODAS is the only gridded observation-based SWE product that assimilates ground, airborne, and satellite snow observations into its model structure and consequently has been used to represent SWE in other regional hydrologic studies [*Famiglietti et al.*, 2011; *Barlage et al.*, 2010]. Previous studies documented error of approximately 11% between SNODAS and snowpit observations in the Rocky Mountains [*Rutter et al.*, 2008] and 15% error for basin-wide analysis [*Famiglietti et al.*, 2011]. For this study, we assume 20% error due to the topographic and terrain heterogeneity throughout the Basin [*U.S. Geological Survey*, 2004].

We further separated the components of accessible water (Figure S3 in the supporting information) into surface water reservoir storage and groundwater storage (Figure 3). Reported reservoir storage time series from Lake Powell and Lake Mead were obtained from the U.S. Bureau of Reclamation [usbr.gov; accessed December 2013]. We assume that Lake Powell and Lake Mead account for the majority of the observed surface water change as they comprise approximately 4 times the annual flow of the river and make up 85% of surface water in the Basin [*Rajagopalan et al.*, 2009]. The U.S. Geological Survey (USGS) errors for hydrologic measurements ranging from "excellent (5%)" to "fair (15%)" [*Sauer and Meyer*, 1992] were used to provide error estimates for surface water reservoir storage. A two sample *t* test could not reject the null hypothesis that sample means were different using the USGS ranges in error, and throughout the rest of the analysis, we used a 10% error estimate for the surface water reservoir storage time series.

We rearranged equation (1) to isolate the contribution of groundwater storage changes (Figure 3) to changes in the total water storage (Figure 2). We used the reservoir storage changes in Lake Mead and Lake Powell with soil moisture and snow water equivalent data as described above:

$$\Delta GW_t = TWSA_t - \Delta SWE_t - \Delta SM_t - \Delta SW_t, \tag{3}$$

where ΔSW_t indicates the surface water anomaly from the reservoirs (Lake Powell and Lake Mead combined for the entire Basin: Lake Powell for the upper Basin and Lake Mead for the lower Basin). Equation (3) was

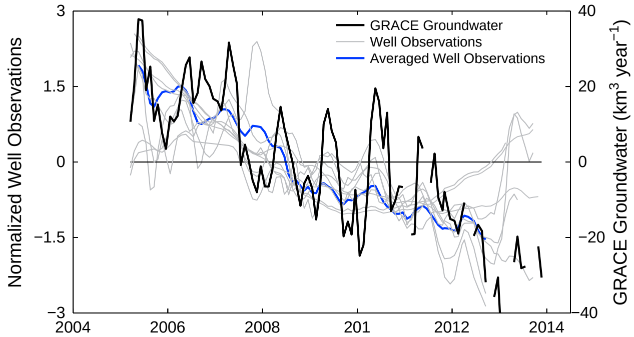

Figure 4. Entire Basin comparison between the GRACE groundwater storage anomalies (black line) in km^3 and the monthly USGS well observations. Because specific yield information is not available for all wells, we normalize each well time series by its standard deviation and then average (in blue). Selected well observations were only available from March 2005 to October 2012; thus, we calculated the average over this time period.

solved each month, and errors in the groundwater storage were estimated by propagating the errors of TWSA, SM, SWE, and SW, following *Rodell et al.* [2004b].

We compared our GRACE-based estimates of groundwater storage changes to groundwater level observations at 74 monitoring wells located throughout the Basin. These data were obtained from the USGS [*USGS Groundwater Climate Response Network*, 2014] and from the Arizona Department of Water Resources (ADWR; https://gisweb.azwater.gov/waterresourcedata/GWSI.aspx, accessed May 2014). The selection of wells for comparison was limited to the locations with observations that were concurrent with GRACE. Of these, 7 USGS and 65 ADWR were located in the lower Basin, and 2 USGS monitoring wells were identified in the upper Basin. GRACE-derived groundwater estimates generally capture the observed behavior well (see Results section and Figure 4).

The trends reported in the text and summarized in Table 1 were estimated employing a method that accounts for residual serial correlation and time series error, and subbasin trends may not sum linearly [*Johnston and DiNardo*, 1997]. We identified several significant trends over the entire 108 month time period studied, and in shorter time periods, from December 2004 to January 2010 and from February 2010 to November 2013 (Table 1).

Table 1. Trends in Water Budget Components Were Calculated Employing a Method Which Adjusts a Linear Model for Residual Serial Correlation and Time Series Error [*Johnston and DiNardo*, 1997][a]
Trends in Terrestrial Water in km^3/yr

Time	Component	Entire Colorado River Basin (CRB)	Upper CRB	Lower CRB
Entire time period	TWSA	**−7.18 ± 0.75**	**−2.34 ± 0.59**	**−3.90 ± 0.47**
December 2004 to November 2013	SWE	0.00 ± 0	0.00 ± 0	0.00 ± 0
	SM	−1.29 ± 1.8	−0.861 ± 0.85	**−0.905 ± 0.24**
	Reservoirs	−0.865 ± 0.60	−0.638 ± 0.63	−0.057 ± 0.63
	GW	**−5.56 ± 0.44**	**−1.66 ± 0.40**	**−2.63 ± 0.30**
	AW	**−5.40 ± 0.47**	**−1.13 ± 0.44**	**−3.02 ± 0.30**
Time				
Piecewise analysis 1	TWSA	**−10.6 ± 1.4**	**−3.41 ± 1.1**	**−7.49 ± 0.90**
December 2004–January 2010	SWE	0.00 ± 0	0.00 ± 0	0.00 ± 0
	SM	−2.67 ± 4.2	−1.74 ± 1.9	−1.45 ± 2.2
	Reservoirs	−0.428 ± 0.34	**1.31 ± 0.13**	**−1.20 ± 0.05**
	GW	**−6.23 ± 0.91**	**−1.91 ± 0.80**	**−4.06 ± 0.60**
	AW	**−6.29 ± 0.96**	−1.37 ± 2.2	**−5.27 ± 0.62**
Time				
Piecewise analysis 2	TWSA	**−19.2 ± 2.1**	**−11.5 ± 2.0**	**−9.14 ± 1.3**
February 2010 to November 2013	SWE	0.00 ± 0	0.00 ± 0	0.00 ± 0
	SM	**−6.82 ± 1.2**	**−2.88 ± 0.76**	**−3.64 ± 0.62**
	Reservoirs	−8.42 ± 4.7	**−3.22 ± 1.2**	−0.085 ± 2.0
	GW	**−10.9 ± 1.5**	**−6.10 ± 1.5**	**−5.83 ± 0.89**
	AW	**−11.2 ± 1.6**	**−7.48 ± 1.6**	**−4.85 ± 0.90**

[a]The approach identified several significant trends (shown in bold) in accessible water (AW) in the Basin over the entire time period from December 2004 to November 2013 and a piecewise trend analysis conducted from December 2004 to January 2010 and from February 2010 to November 2013. The Basin TWSA estimates are calculated independently, and there is no assumption that subbasin trends will sum linearly.

3. Results

We find that during the 108 month study period, the entire Colorado River Basin lost a total of 64.8 km^3 of freshwater ($-7.2 \pm 0.8\ km^3\ yr^{-1}$, where ± represents the standard error of the slope coefficient) (Figure 2a) with a more severe rate of loss since February 2010 ($-19.2 \pm 2.1\ km^3\ yr^{-1}$). The upper Basin (Figure 1) lost 21.6 km^3 of water during the entire study period, with more severe loss rates after February 2010 ($-11.5 \pm 2.0\ km^3\ yr^{-1}$) (Figure 2b). Study period losses in the lower Basin of 34.7 km^3 were greater than in the upper Basin and declined at a faster rate ($-3.9 \pm 0.5\ km^3\ yr^{-1}$) (Figure 2c). All trends are listed in Table 1. As described in the Methods section, we compared our GRACE-derived water storage estimates to independent water balances for the entire, upper, and lower Basins with good agreement (Figure S1 in the supporting information). This comparison lends additional confidence to the results reported here.

Further analysis of trends in groundwater storage (Figure S4 in the supporting information) revealed two distinct phases of depletion prior to and following 2009–2010. From December 2004 to January 2010, groundwater storage declined more rapidly in the lower Basin ($-4.1 \pm 0.6\ km^3\ yr^{-1}$) compared to the upper Basin ($-1.9 \pm 0.8\ km^3\ yr^{-1}$). Groundwater losses from February 2010 to November 2013 were found to be even greater in the upper ($-6.1 \pm 1.5\ km^3\ yr^{-1}$) and lower Basins ($-5.8 \pm 0.9\ km^3\ yr^{-1}$).

A brief recovery in groundwater storage is apparent from June 2009 to March 2010, when moderately wetter conditions provided a combination of potential groundwater recharge and temporarily alleviated the need to augment surface water supplies. The steepest rate of groundwater storage decline (in the upper Basin in 2013) follows exceptional drought conditions in 2012 and record low Rocky Mountain snowpack (U.S. Drought Monitor, 2012; see Figure S2 in the supporting information). Such behaviors highlight the close connection between surface water availability and groundwater use [*Famiglietti et al.*, 2011].

We find that water losses throughout the Basin are dominated by the depletion of groundwater storage (Figure 3). Renewable surface water storage in Lake Powell and Lake Mead showed no significant trends during the 108 month study period, more recent declines (since 2011) and currently low (<50% of capacity) storage levels notwithstanding. Groundwater storage changes however accounted for the bulk (Table 1) of the freshwater losses in the entire Basin (50.1 km^3 and $-5.6 \pm 0.4\ km^3\ yr^{-1}$), the majority of which occurred in the lower Basin (Figure 3c). As mentioned in the Methods section, we examined the USGS and ADWR monitoring wells in the Basin during the study period. The observed behavior in these wells showed a good agreement with our GRACE-based estimates. Figure 4 shows the comparisons for the USGS wells. A Sen's slope trend comparison to the ADWR wells showed that measured groundwater table changes closely matched our GRACE-based estimates. These comparisons help confirm the groundwater depletion rates reported here.

4. Discussion

Drought in the Basin has effectively limited the surplus inflows that replenish Lake Powell and Lake Mead since the beginning of the 9 year study period, while active surface water management has prevented further declines in reservoir levels. Consequently, reservoirs show insignificant trends in storage levels ($-0.9 \pm 0.6\ km^3\ yr^{-1}$), while groundwater has been significantly depleted ($-5.6 \pm 0.4\ km^3\ yr^{-1}$). The vast difference may well be attributed to the regulatory framework already in place to manage surface waters, and to the general need for more active and enforceable groundwater management throughout the Basin, in particular, during drought.

The large, net negative change in groundwater storage is a clear indication that groundwater withdrawals are not balanced by recharge and must be greater than the observed depletion rate. The additional loss of 5.6 $km^3\ yr^{-1}$ of groundwater, relative to the annual Basin surface water allocations of 18 $km^3\ yr^{-1}$, indicates further that the Basin water supply was overallocated by at least 30% during the study period. Thus, we observe that groundwater is already being used to fill the gap between Basin demands and the annual renewable surface water supply.

Groundwater is typically used to augment sparse surface water supplies in the arid, lower Basin, and across the entire Basin during drought [*Hutson et al.*, 2004; *Kenny et al.*, 2009]. More generally, water managers around the world rely on groundwater to mitigate the impacts of drought on water supply [*Leblanc et al.*, 2009; *Famiglietti et al.*, 2011; *Famiglietti and Rodell*, 2013; *Taylor et al.*, 2013]. Groundwater represents the largest supply of water for irrigation within the Basin [*Hutson et al.*, 2004; *Kenny et al.*, 2009], while irrigated acreage in the Basin has increased during our study period [*Ward and Pulido-Velazquez*, 2008; *Cohen et al.*, 2013]. Furthermore, prolonged drought across the southwestern U.S. has resulted in overreliance on groundwater to minimize impacts on public water supply [*Famiglietti and Rodell*, 2013]. Long-term observations of groundwater depletion in the lower Basin (e.g., in Arizona—despite groundwater replenishment activities regulated under the 1980 Groundwater Code—and in Las Vegas [*Konikow*, 2013]) underscore that this strategic reserve is largely unrecoverable by natural means and that the overall stock of available freshwater in the Basin is in decline.

Future water management scenarios that account for both population growth and climate change also point to the inability of reservoir storage alone to meet the Basin allocations [*Barnett and Pierce*, 2008; *Bureau of Reclamation*, 2012]. These scenarios indicate that additional stresses will be placed upon the groundwater system, beyond those described here, to meet future Basin water demands. We believe that the combination of reduced surface water availability resulting from decreasing future snowpack [*Barnett et al.*, 2008] and groundwater depletion poses a significant threat to the long-term water security of the region. As groundwater supplies reach their limits, the ability to supply freshwater during drought, or to fill the predicted, increasing gap between supply and demand [*Bureau of Reclamation*, 2012], will be severely constrained.

The challenge to policy makers and water managers in the Colorado River Basin is to reliably meet freshwater demand under these dynamic conditions. Our work suggests that a conjunctive surface water and groundwater management plan is essential for sustainable water management in the Basin. Despite commendable efforts to craft solutions to meet required surface water allocations [*Bureau of Reclamation*, 2012], consideration of the ability of groundwater withdrawals to meet current and future demands remains dormant. We hope that the heightened awareness of the rates of the Basin groundwater depletion highlighted here will foster urgent discussion on conjunctive management solutions required to ensure a sustainable water future for the Colorado River Basin and for the western United States.

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EXHIBIT
8

Impact of Renewable Energy Sources on Birds of Prey

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Contents

Chapter 13
Impact of Renewable Energy Sources on Birds of Prey

James F. Dwyer, Melissa A. Landon, and Elizabeth K. Mojica

Introduction

Renewable energy, defined as energy generated from natural processes that are replenished over time (Johnson and Stephens 2011), is increasingly important in global energy portfolios. This chapter begins by reviewing reasons for shifting from fossil fuels to renewable energy, including reasons which have nothing to do with environmental concerns but are nevertheless driving advances in the renewable sector. The chapter then focuses on birds of prey, describing actual and potential direct and indirect mortality, habitat loss, avoidance, and displacement resulting from the development and operation of renewable energy facilities. The chapter considers renewable energy facilities themselves, including wind, biofuel, solar, hydro, geothermal, and oceanic energy sources. Transmission connections linking renewable facilities to the existing electric transmission grid are considered, as are potential offsite impacts where the materials used to construct renewable infrastructure are mined and manufactured. The chapter closes with a discussion of mitigation strategies designed to reduce or compensate for negative impacts for birds of prey and a discussion of potential benefits of renewable energy facilities for birds of prey. The latter are important to understand when evaluating the overall balance of costs and benefits of renewable energies on birds of prey.

Knowledge of the connections between global conflicts and international dependencies on fossil fuels is important in understanding how macroeconomic forces independent of environmental concerns drive the advancement of renewable energy technologies. Because "green" initiatives may not in fact be grounded in environmental concerns, but be grounded instead in economics and national interests, potential negative environmental impacts of renewables and their high initial investment costs may carry little weight in the overall discussion, a paradox not readily apparent without consideration of the context of global competition over traditional energy reserves.

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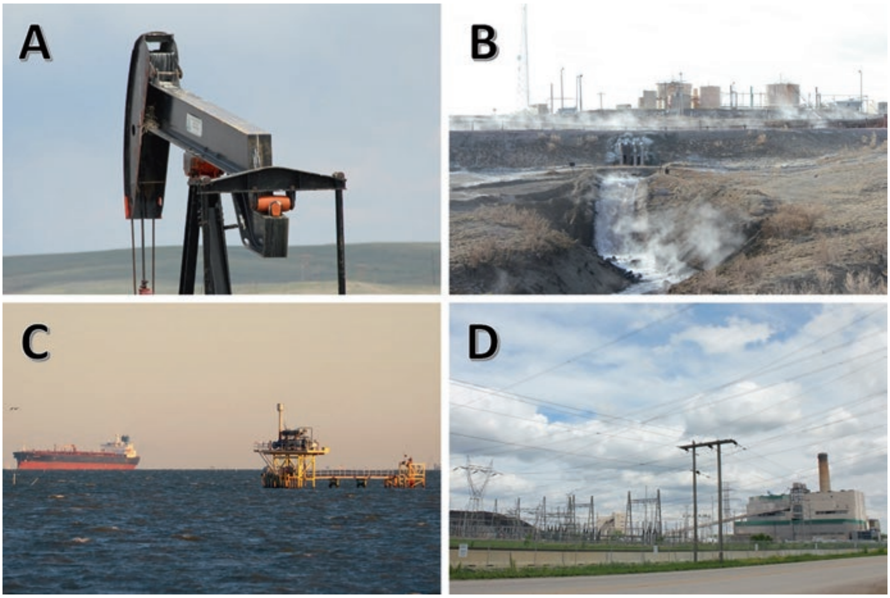

Fig. 13.1 (**a**) A pump designed to extract liquid and gas fossil fuels from terrestrial deposits; note great horned owl (*Bubo virginianus*) nest and whitewash. (**b**) Collection facility for traditional liquid and gas fossil fuels from terrestrial deposits. (**c**) Transport (left) and collection (right) of traditional fossil fuels, (**d**) Traditional coal-burning electricity generation station

Fossil fuels have been the primary energy source for developing and developed nations since the Industrial Revolution of the early 1800s when coal began to be used to power steam-driven machines and energy-intensive metallurgic and chemical processes. Emissions from these machines and processes were recognized almost immediately as harmful, triggering early environmental responses to protect urban air and water. From the late 1800s through the early twenty-first century, fossil fuels remained the primary solution to global energy needs as petroleum and natural gas products made the storage and use of chemical energy more efficient and economical (Fig. 13.1).

The resulting dependence of national and international economies on fossil fuels has created two fundamental problems. The first is a globally ubiquitous reliance on fossil fuels often derived from outside national boundaries. This reliance can place less developed nations with large reserves at the center of conflicts for control of those reserves and can place more developed nations without large reserves at the mercy of nations with reserves. Shifting energy sources from fossil fuels to renewables offers nations the ability to achieve energy independence.

The second fundamental problem created by the global reliance on fossil fuels is the impact of combustion products on the global climate. Greenhouse gases released during combustion of fossil fuels are contributing to global climate changes. Shifting energy sources from fossil fuels to renewables offers nations the ability to achieve energy independence and offers potential environmental benefits. These benefits are not without their own potential costs however, and it is those potential costs, as exerted on birds of prey populations, that are discussed here.

Effects at Renewable Facilities

Potential effects to birds of prey at renewable facilities include direct mortality and indirect effects resulting from habitat loss, avoidance, and displacement. Direct mortality is defined as death occurring as an immediate consequence of an interaction between a bird of prey and a component of renewable infrastructure. For example, a golden eagle (*Aquila chrysaetos*) killed when struck by a rotating wind turbine blade or killed when colliding with the suspended high-voltage wires of a transmission power line connecting a renewable facility to the electric grid. Habitat loss is defined as occurring when the landscape occupied by birds of prey is converted to non-habitat, for example, the displacement of prey species resulting from conversion of hunting habitat to a mirror field for a solar plant or the removal of a nest tree when creating an agricultural monoculture for biofuel production. Avoidance and displacement are similar processes occurring at different scales. Both occur when habitat persists, but is no longer used. Avoidance is defined as a shift in use of specific portions of a renewable facility, not the entire site (Band et al. 2007). Displacement occurs when an entire site is abandoned (Band et al. 2007).

These effects rarely occur in isolation but are instead likely additive, co-occurring with one another and with other anthropogenic and natural agents of mortality. Additive effects can be problematic, even at low rates, because most birds of prey are k-selected species with relatively little annual reproduction and breeding often delayed during multiple years of maturation. Population persistence for many bird of prey species requires individual breeding adults to produce young over an entire lifetime. Mortality of breeding adults can have substantial effects on the population (Bellebaum et al. 2013). For example, at some sites, griffon vultures (*Gyps fulvus*) and red kites (*Milvus milvus*) cannot maintain stable local populations with additive mortality from wind farms (Carrete et al. 2009; Bellebaum et al. 2013).

Wind Resource Areas

Direct effects of wind energy facilities (Fig. 13.2) on birds of prey involve mortality occurring when rotating turbine blades strike birds in flight. Impacts are largely species-specific. Directly affected species are characterized by low-altitude flight when gliding on local winds and on thermal and orographic lifts (Katzner et al. 2012; de Lucas et al. 2008). Because wind turbines are designed and specifically placed to harvest the kinetic energy in some of these same winds, low-altitude flight behaviors largely dictate risk by placing birds of prey and rotating turbine blades

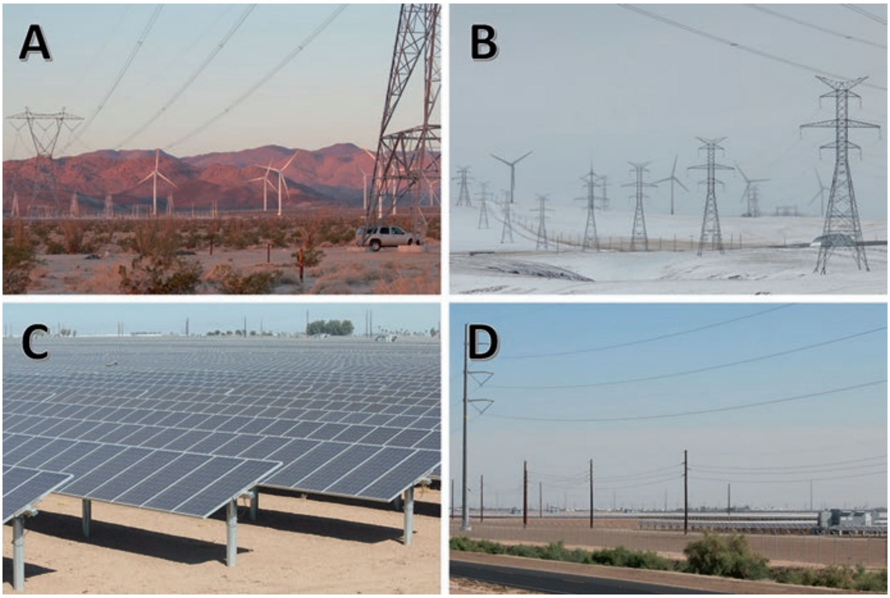

Fig. 13.2 (**a**) A wind resource area in desert habitat; note substation under construction in the background will provide a connection from the wind resource facility to the existing transmission power line network. (**b**) A wind resource area above agricultural fields, potentially facilitating both wind energy and biofuel production. (**c**) Close view of a solar field illustrating the bare and leveled earth (non-habitat) typical of such facilities. (**d**) Wide view of a solar field, illustrating fencing and bare earth designed to limit attractiveness as habitat and illustrating associated distribution and transmission lines

together in the same airspace. Hunting in these airspaces has been hypothesized to hinder the ability of a bird of prey to recognize turbines as a flight hazard (Orloff and Flannery 1992; Smallwood et al. 2009), so species habituated to hunting within wind resource areas can be at higher risk of collision. Collision risk can also increase along flight corridors where large numbers of migrating birds of prey funnel along narrow ridges and coastlines supporting wind energy facilities (Barrios and Rodriguez 2004; Katzner et al. 2012; de Lucas et al. 2012) or where communal roosts occur near wind resource areas (Carrete et al. 2012). Intraspecific and interspecific interactions during flight also increase risk for collision because birds of prey can be distracted and less likely to recognize flight hazards (Dahl et al. 2013; Smallwood et al. 2009).

Though at least 34 bird of prey species have been documented in collisions with wind turbines, population-level impacts from direct effects are unknown for most species (Beston et al. 2016); only griffon vultures (Carrete et al. 2009), red kites (Bellebaum et al. 2013) and golden eagles (USFWS 2013) are currently known to be at risk of population-level effects from these collisions.

Species-specific behaviors also drive indirect effects of wind resource areas. Species avoiding or displaced by wind resource areas tend not to be affected by direct mortality but may abandon breeding territories (Dahl et al. 2013), shift local space use (Walker et al. 2005), or decrease in local abundance (Garvin et al. 2011; de Lucas et al. 2004). Some species show avoidance behaviors for individual turbine structures by adjusting flight paths to fly between or around turbines (Cabrera-Cruz and Villegas-Patraca 2016; Hull and Muir 2013; de Lucas et al. 2004) or adjust altitude to fly over turbines in their path (Johnston et al. 2014; de Lucas et al. 2004). There is limited evidence of net population loss in birds of prey from avoidance or displacement attributable to wind resource areas, but effects could be important for threatened species when considered with direct effects (Martínez et al. 2010).

Biofuels

Biofuels primarily describe energy resources developed from agriculture and most often describe production by industrial farms focused on extracting the greatest possible crop yields per acre. Yields are maximized by eliminating as many non-producing inclusions as possible and by promoting maximum growth through regular inputs of synthetic chemicals. Eliminating inclusions requires conversion of potential nest groves and bird of prey hunting habitat to cropland. Chemical inputs regularly consist of fertilizers to maximize crop yields, and pesticides, rodenticides, and herbicides, to protect monoculture crops from competing organisms in the environment. Collectively, these processes contribute to agricultural intensification which has been at least partly responsible for declines in farmland bird populations (Campbell et al. 1997; Uden et al. 2015).

Meeting increasing demand for ethanol requires increasing cropland in production, and consequently, the development footprint of biofuels is expected to be one of the fastest growing of all renewable energy sources in the next two decades (Johnson and Stephens 2011). Impacts of biofuel energy production on birds of prey occur primarily due to indirect effects triggered by the loss of breeding and foraging habitats when stands of trees used for nesting and open spaces used for hunting are converted to biofuel monocultures. Indirect effects include habitat loss, decreases in prey abundance, and potential biochemical effects from exposure to toxic chemicals. Direct effects are generally limited to rare occurrences of nestling mortality when nest trees are removed during breeding seasons, though exposure to bioaccumulating chemicals may also have effects that have not yet been identified.

Solar Facilities

Solar energy facilities also have the potential to impact birds of prey. Direct effects most often include electrocution on collection power lines, collisions with mirrors, and thermal trauma in solar flux fields (Kagan et al. 2014; McCrary et al. 1986). Electrocution can occur when a bird of prey simultaneously contacts two differently energized conductors or an energized conductor and a path to ground (APLIC 2006, in this book Chap. 12). Collisions occur when birds apparently mistake reflections of the sky in mirrors as the sky itself and attempt to fly through a mirror, perhaps in pursuit of prey.

Solar flux fields are the areas of concentrated light surrounding the collection tower(s) at thermal solar plants. Mirrors are used at these facilities to concentrate solar energy on a single area where water within a container is heated to produce steam which powers a generator. The air around the collection tower can reach 500–800 °C (McCrary et al. 1986; Diehl et al. 2016). Damage to feathers occurs at 160 °C (Wendelin et al. 2016), so flight through a solar flux field can result in burns to feathers and tissues, causing immediate mortality or limiting or eliminating the ability to fly, depending on individual exposure. Unlike other renewable energy technologies like wind turbines, which are relatively benign when not operational, solar flux fields can be dangerous to birds even when solar flux fields are not focused on collection towers (Wendelin et al. 2016). This can occur because mirrors in standby positions often focus solar energy just above collection towers. Heat in these standby positions can be intense enough to harm birds.

Morbidity and mortality of birds of prey in solar flux fields appear relatively rare, but when cases do occur, taxonomic patterns are emerging. Specifically, falcon (Falconiformes) species may be more susceptible, apparently because falcons are attracted to hunt aerial prey concentrated near collection towers (WEST 2016). Alternatively, in both active and standby positions, warm air rising above collection towers may attract buteos and vultures seeking thermal air currents to power flight, and these birds may inadvertently enter solar flux zones regardless of the presence or absence of potential prey.

Indirect effects of solar energy facilities include habitat loss, displacement, and avoidance (Hernandez et al. 2014). Unlike wind energy facilities where some of these effects might be temporary, with birds returning after construction, solar facilities eliminate habitat from within the facility, creating a flat bare earth-scape unattractive for hunting or nesting by birds of prey. Habitat loss at solar energy facilities is generally greater per megawatt generated than at wind facilities because wind resource areas retain most of the habitat below turbines, whereas solar facilities cover much of the facility in mirror arrays. Birds of prey and other wildlife species also may avoid habitats in and around solar facilities as a result of increased human activity and habitat alteration (DeVault et al. 2014).

Other Renewable Facilities

Other renewable energy sources include geothermal, hydroelectric, and oceanic. There are no substantial direct mortality effects to birds of prey documented for these energy sources. Geothermal power stations use heat energy from within the earth's crust to generate electrical energy. Facility footprints are similar to those of liquid and gas fossil fuel extraction facilities, with impacts to birds of prey limited to indirect effects resulting from disturbance during construction and operation. Roads to extraction wells increase habitat fragmentation (Jones and Pejchar 2013), impacting edge-sensitive species. Geothermal emissions often contain vaporized toxins which, while less than coal burning plants, release toxins into the air including hydrogen sulfide, carbon dioxide, ammonia, methane, and boron, mercury, and other heavy metals (Kagel et al. 2007), so indirect effects could also include reactions to toxic emissions.

Hydroelectric and oceanic renewable energy facilities use the energy of flowing rivers or tides to turn turbines and generate electricity. Hypothetically, aquatic hunters like osprey (*Pandion haliaetus*) could become entrapped in the machinery of hydroelectric or oceanic renewable energy infrastructure, but neither of these potential agents of mortality has yet been documented. This indicates that even if mortality occurs, levels are sufficiently low to preclude population impacts. Indirect effects likely do occur, though are not necessarily negative. Construction of reservoirs to store water for a hydroelectric dam floods and destroys bottomland habitats used as nest sites by some bird of prey species, but this habitat loss may be offset by creation of new reservoirs with far more shoreline hunting and nesting habitat than existed previously.

Effects of Transmission Linkages

Renewable facilities are connected to the existing electric system through construction of new transmission lines (Fig. 13.3), termed connections, interconnections, links, or linkages (hereafter interconnections). These interconnections have the potential to create avian collision and habitat fragmentation concerns well away from, but directly attributable to, renewable energy facilities. Post-construction environmental impacts of renewable energy infrastructure are generally considered only within the footprint of renewable energy facilities, but may not include the associated interconnections even though transmission lines are associated with avian collision mortalities (Bevanger 1998; Loss et al. 2014; Rogers et al. 2014). Because renewable interconnections have not yet been thoroughly studied with respect to potential impact to birds of prey, this section summarizes knowledge of potential impacts of transmission lines in general.

Direct effects of power lines on birds occur through mortality caused by electrocution and collision (Bevanger 1998; Loss et al. 2014). Electrocution is limited mostly to distribution lines (<69 kV) where clearances are minimal and birds can simultaneously contact multiple energized components or energized and grounded components (APLIC 2006, in this book Chap. 12). Transmission clearances designed to prevent electrical energy from arcing across conductors generally include separations greater than birds can bridge with extended wings, though there are exceptions on certain configurations used for lower transmission voltages (69–138 kV). Because electrocution is generally of little concern at the transmission voltages used in renewable energy interconnections, and because detailed

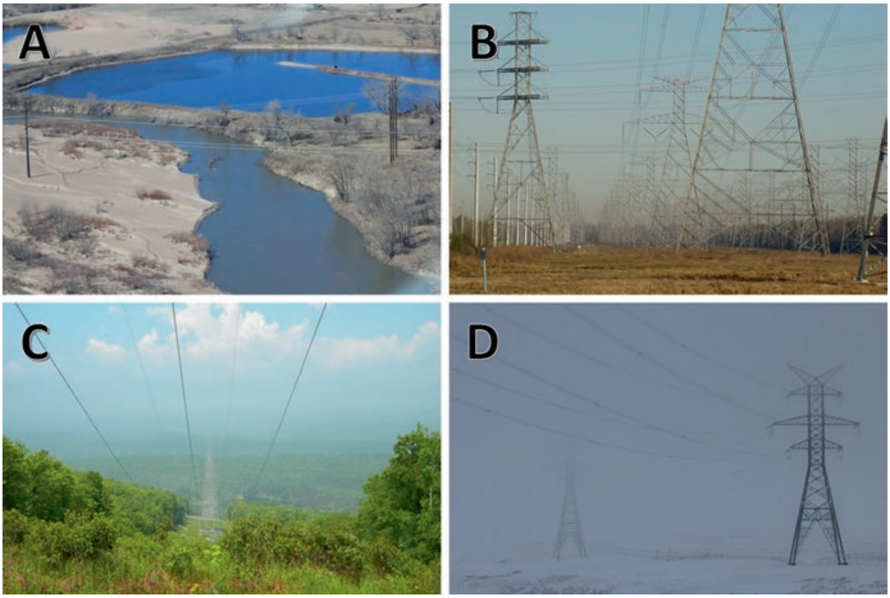

Fig. 13.3 Transmission line issues: (**a**) Transmission line bisecting a water source used by birds as a movement corridor. (**b**) Numerous transmission lines within a transmission corridor. (**c**) Overhead shield wires are less visible than conductors. (**d**) Transmission line partially obscured by fog

discussion of avian electrocution is available elsewhere in this book (in this book Chap. 12), this chapter does not address avian electrocutions.

Avian collision mortality is an ongoing global concern (Sporer et al. 2013; Rioux et al. 2013; Loss et al. 2014), though most research on the topic is not bird-of-prey-specific. Collisions involving transmission lines occur when a flying bird hits suspended wires, most often at night. Transmission lines are typically constructed with relatively thin overhead shield wires at the top and thicker energized conductors below. Birds appear to adjust flight altitudes upward to avoid large-diameter energized wires and then collide with smaller, less visible overhead shield wires (Murphy et al. 2016; Ventana Wildlife Society 2009; Martin and Shaw 2010). Transmission lines do not pose consistent risk. Rather, collision risk varies as a function of avian species and populations in the area of a given line, the surrounding habitat, and the line design (Bevanger and Brøseth 2004; Mojica et al. 2009; Rollan et al. 2010). Among birds, factors affecting collision risk include size, maneuverability, and flocking behavior (Jenkins et al. 2011; APLIC 2012). Transmission lines bisecting daily movement corridors, such as those located between roosting and foraging sites, also have been most associated with avian collisions (Bevanger and Brøseth 2004; APLIC 2012), with risk exacerbated during low-light, fog, and other inclement weather conditions (APLIC 2012; Hüppop and Hilgerloh 2012).

Birds of prey are at relatively low risk for power line collisions in general (SAIC 2000; Rioux et al. 2013), though large raptors with high wing loading and poor in-flight maneuverability like bustard species and condor species are collision prone.

In part, collision risk is low for birds of prey because they tend to fly diurnally during good weather (Ligouri 2005) and appear to detect and avoid transmission lines (Pope et al. 2006; Luzenski et al. 2016). Though risk for birds of prey is low compared to some other avian groups, collisions involving birds of prey do occur (Olendorff and Lehman 1986; Rollan et al. 2010, in this book Chap. 12). For example, California condors (*Gymnogyps californianus*) have collided with power lines (Snyder 2007), the Ventana Wildlife Society (2009) documented collisions by a northern harrier (*Circus cyaneus*) and a white-tailed kite (*Elanus leucurus*), and Mojica et al. (2009) documented multiple carcasses of bird of prey species (bald eagle (*Haliaeetus leucocephalus*), osprey, and owls) under distribution lines. Studies have shown certain African birds of prey are vulnerable to colliding with lines in foraging habitats (Boshoff et al. 2011; Rollan et al. 2010). Peregrine falcons can be at risk because they attain high speeds when pursuing prey near the ground (Olendorff and Lehman 1986). Mañosa and Real (2001) documented both collisions of breeding Bonelli's eagle (*Hieraaetus fasciatus*) and high turnover rates of pairs nesting within 1 km of power lines in Catalonia, Spain. González et al. (2007) documented infrequent collision as a cause of mortality in a study examining 267 records of nonnatural mortality of the Spanish imperial eagle (*Aquila adalberti*).

Indirect effects of transmission lines on birds of prey are not well studied but are likely low following initial disturbance and acclimation during and following construction given the fact that many birds of prey readily nest on or near transmission lines. Transmission lines can create corridors for human incursion into otherwise natural landscapes because maintenance access roads and rights-of-way may be used for recreational activities (hiking, running, mountain biking, cross-country skiing, all-terrain vehicles, etc.). Some bird of prey species respond negatively to recreational human traffic (Steidl and Anthony 1996), but no firm connection has yet been established to confirm widespread impacts with respect to power lines.

Power lines generate strong electromagnetic fields, UV discharges, and acoustic signatures which can affect animal health and behavior (Phernie et al. 2000; Tyler et al. 2014). Recent research suggests that avoidance by reindeer (*Rangifer tarandus*) may be linked to their ability to detect ultraviolet light emitted by transmission lines (Tyler et al. 2014). At least some birds also see in the ultraviolet spectrum (Lind et al. 2014), but the potential implications of this for indirect effects have not been investigated in birds of prey (in this book Chap. 12).

Offsite Effects

Offsite effects are indirect by definition. The natural resources used in constructing renewable infrastructure are typically harvested from areas well beyond the boundaries of renewable project sites. This has the potential to shift some of the environmental costs of renewable energy away from project sites where resources are used, to mine and factory sites where resources are extracted and processed. Consequently, offsite mining should be considered when developing a comprehensive understanding of potential impacts of renewable energy sources on birds of prey.

Effects of mines on birds of prey are site-specific and species-specific. For example, peregrine falcons and gyrfalcons (*Falco rusticolus*) breeding near two diamond mines in Northwest Territories, Canada, showed no difference in nest occupancy or breeding success as a function of distance from mine footprints, despite those footprints expanding during the study (Coulton et al. 2013). In contrast, prairie falcons (*Falco mexicanus*) in New Mexico appeared to avoid an entire mountain range where mining and blasting for various minerals was common but did nest in two adjacent ranges with similar habitats but less mining activity (Bednarz 1984). Mild responses to the vibration and noise associated with mining may derive from the occurrence of such natural events as thunder and landslides (Holthuijzen et al. 1990), with which birds of prey are presumably familiar both individually and over evolutionary time. Across studies, with few exceptions, evidence of disturbance by mining activity seems isolated and in some cases can be offset by relocating birds of prey nests prior to the advance of mine operations (McKee 2007). However, at least some mine sites likely included nesting territories prior to initiation of mining activities. In these cases, productivity from directly affected territories likely was reduced at least while affected individuals sought alternate nest sites. Even these impacts may be minimized, however, with measures specifically designed to support birds of prey populations, for example, through installation during reclamation of permanent structures designed to serve as nest substrates (Harshbarger 1997) and through the use of unreclaimed anthropogenic cliffs used for nesting (Moore et al. 1997). Mines also are associated with environmental pollution. Mining and smelting can lead to increased levels of lead in ospreys and American kestrels (*Falco sparverius*) nesting downstream (Henny et al. 1991, 1994) and in Eurasian eagle owls (*Bubo bubo*; Espin et al. 2014), though to our knowledge, definitive links to survival or productivity specifically related to mine sites have not been established. Though reductions in nesting attempts or productivity appear minimal overall, spills, pollution, and sedimentation from mine sites may have effects that are difficult to link conclusively to evidence of impacts specifically affecting birds of prey.

Though mining does have deleterious ecological consequences, and some examples involving birds of prey can be identified, overall it appears that offsite indirect impacts are either small or difficult to quantify and isolate (Anderson et al. 2008). Regardless of potential effects associated with renewable infrastructure, mined materials would also be necessary for fossil fuel extraction, which renewable energy facilities are designed to replace. That being so, it appears that indirect effects of extractive industries on birds of prey are minimal and offset by equivalent needs across energy sources.

Mitigation

Renewable energy facilities have the potential to bring together ecologically novel combinations of juxtaposed land covers like water bodies in deserts, prominent features like tall perches where none existed naturally, potential risks to wildlife like electrocution and mirror collisions, and potentially, unique combinations of species drawn to these features from their respective native habitats. Consequently, the removal and addition of biotic and abiotic materials at renewable energy facilities may require novel mitigation strategies applied to microclimates and biological communities which may not occur naturally. The rotor-swept zones of wind resource areas and the heated-air zones of solar tower collection areas have no natural analogues and thus no evolutionary context preparing wildlife for the risks encountered in these areas.

It should be incumbent on those creating these new landscapes, to also provide new and effective mitigation. With regard to mitigation of bird of prey mortalities at wind resource areas, innovative techniques are being developed to compensate for mortality at the renewable sites by mitigating the electrocution of birds of prey elsewhere (Fig. 13.4), creating a net benefit overall (USFWS 2013).

Wind energy facilities can also adjust turbine operations to prevent collisions by curtailing operations when birds of prey are flying within the wind resource area, and by increasing minimum operational wind speeds to wind speeds above those within which birds of prey generally choose to fly (USFWS 2013). At solar facilities with collection towers, successful mitigation involves spreading the aim points of mirrors apart to reduce the peak flux value to <4 kW/m^2 when the facility is in standby mode and not actively producing power (Multiagency Avian-Solar Collaborative Working Group 2016). For both wind resource areas and solar facilities, direct and indirect effects may be minimized by siting facilities away from

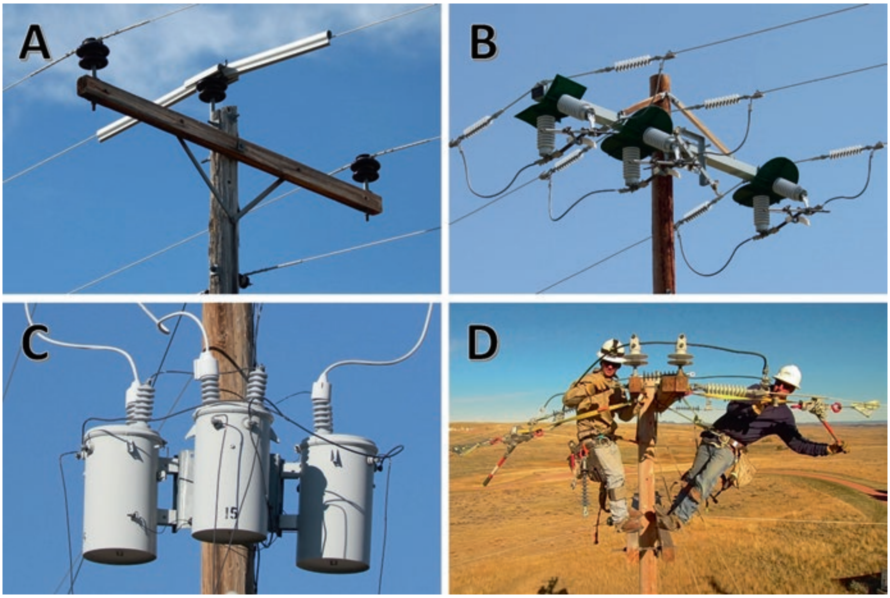

Fig. 13.4 Retrofitted power poles: (**a**) Insulation on center wire. (**b**) Insulation on connecting wires and on switches. (**c**) Insulation on connecting wires and on energized components of equipment. (**d**) Installation of insulation on equipment. (See in this book Chap. 12 for additional technical details on electrocution of birds of prey)

concentrated populations of birds of prey at migration, foraging, or roosting sites. Collisions involving birds of prey and transmission interconnections can be mitigated by marking transmission lines to increase their prominence to approaching birds of prey so lines can be avoided (in this book Chap. 12).

Unlike compensation programs for wind and solar energy, which are still in their infancy, compensation programs for biofuel monocultures are well established within a general framework of minimizing agricultural impacts to natural systems to the extent practical. Mitigation for biofuel monocultures may be achieved through existing mitigation programs, such as the US Department of Agriculture's Conservation Reserve Program which enables farmers to remove environmentally sensitive land from agricultural production in exchange for an annual payment. These types of programs tend to be successful if three obstacles can be overcome. First, because participation is voluntary, individual decisions may be influenced by the value of the payment compared to the value of potential crop yields. This mitigation strategy may lose effectiveness if demands for biofuels, and other crops competing in the market place for the same land, result in crop profits per acre that are greater than payments (Johnson and Stephens 2011). Second, compensation may undermine an individual's sense of responsibility for the land (Ramsdell et al. 2016), potentially resulting in a reduced sense of stewardship over the long term and enabling landowners to justify conversion of natural habitats if compensation programs terminate. Third, compensation programs may not be practical in developing countries lacking the necessary financial or political resources. Despite the potential obstacles involved in compensation-based mitigation programs, these solutions are nevertheless the best currently available, at least in areas like the USA where most arable farmland is privately owned and decisions affecting land use are primarily market driven. Though not necessarily focused on bird of prey concerns, these approaches often result in habitat patches that can contain hunting habitat or potential nest sites, creating focal locations which allow bird of prey populations to persist within areas dominated by agriculture.

Siting new facilities in previously disturbed habitat like nonproductive agricultural fields also can reduce impacts to birds from loss of breeding and foraging habitat (Pearce et al. 2016). Birds of prey can be intentionally displaced from solar projects when nesting sites are destroyed during construction. Burrowing owls (*Athene cunicularia*) have been successfully translocated to new breeding sites away from solar facilities (Multiagency Avian-Solar Collaborative Working Group 2016).

Benefits to Birds of Prey

Birds of prey also can benefit from renewable energy facilities and transmission linkages, primarily through provision of new nesting opportunities (Fig. 13.5) since birds of prey routinely nest on transmission structures. For example, bald eagles and osprey regularly nest on utility structures (Buehler 2000; Poole et al. 2002).

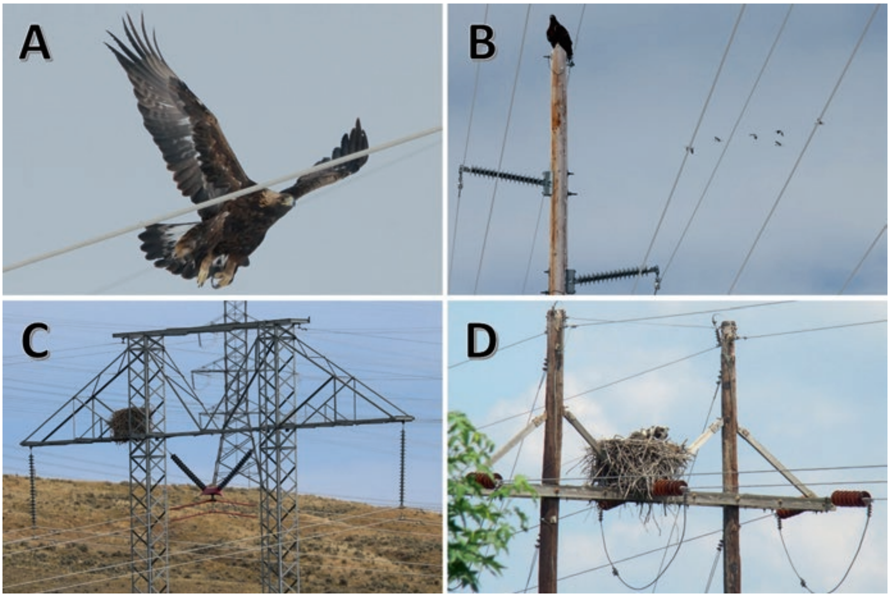

Fig. 13.5 (**a**) A golden eagle (*Aquila chrysaetos*) departing a transmission tower, potentially benefitting through hunting opportunities and, simultaneously, potentially at risk of collision with transmission wires. (**b**) A golden eagle roosting atop a transmission pole. (**c**) A golden eagle nest on a transmission tower. (**d**) An osprey (*Pandion haliaetus*) nest on a transmission H-frame structure

Other species nesting on utility structures include ferruginous hawks (*Buteo regalis*; Gilmer and Wiehe 1977), hobbies (*Falco subbuteo*; Puzović 2008), common kestrels (*Falco tinnunculus*; Krueger 1998), greater kestrels (*Falco rupicoloidesa*; Ledger and Hobbs 1999), martial eagles (*Polemaetus bellicosus*; Jenkins et al. 2013), prairie falcons (Roppe et al. 1989), lanner Falcons (*Falco biarmicus*; Ledger and Hobbs 1999), upland buzzards (*Buteo hemilasius*; Ellis et al. 2009), Swainson's hawks (*Buteo swainsoni*; James 1992), tawny eagles (*Aquila rapax*; Jenkins et al. 2013), black eagles (*Aquila verreauxii*; Jenkins et al. 2013), African hawk eagles (*Hieraaetus fasciatus*; Ledger and Hobbs 1999), and white-backed vultures (*Gyps africanus*, Ledger and Hobbs 1999). Though none of these were on renewable interconnections, the consistency between transmission structures in general and transmission structures supporting renewable interconnections specifically indicates that nesting is likely. Nesting habitat can also be created from mines providing new nest substrates for cliff-nesting birds of prey like peregrine falcons (Moore et al. 1997). Habitat conversion for dams and agriculture can also increase food availability for birds of prey because dams and reservoirs create aquatic habitat and provide abundant year-round food resources for birds of prey including water snakes (Tingay et al. 2010), waterbirds (Mukherjee and Wilske 2006; Mwaura et al. 2002), and stunned or dead fish flowing through dam spillways or turbines (Sánchez-Zapata et al. 2016).

Integrated vegetation management techniques employed in rights-of-way management for renewable energy interconnections can also play an important role in maintaining and improving habitat for wildlife (Ball 2012; Rogers 2016). These activities could create hunting habitat for birds of prey or be used as migration corridors (Denoncour and Olson 1982).

Other indirect benefits may also be important. The fundamental motivators of shifting global economies from fossil fuels to renewable energies are national energy independence and reduction of greenhouse gas emissions. Energy independence is perhaps irrelevant to birds of prey, but reduction of greenhouse gas emissions and global climate change do have substantial potential benefits for birds of prey. Global climate change is associated with increased frequency and intensity of weather events. Late spring and high-intensity weather events can directly impact the productivity and survival of birds of prey. For example, breeding success is negatively correlated with precipitation during nesting in peregrine falcons (Anctil et al. 2014; Burke et al. 2015). Survival of peregrines migrating south from the Artic is negatively correlated with climatic events suggesting the species is vulnerable to weather events along the migration route (Franke et al. 2011). Reduced impacts of climate change in general will likely reduce weather-related impacts on nesting birds of prey.

Conclusions

Ultimately, the large, widely dispersed territories of most birds of prey minimize the population impacts of either direct or indirect effects at most renewable energy facilities, transmission interconnections, or mines. This is because even if a specific territory is affected by a renewable energy facility, through habitat loss, for example, the effect is unlikely to have a population-level effect. There are exceptions however. For example, collisions involving migrating or wintering birds of prey with wind turbines can result in impacts dispersed throughout breeding ranges, and large-scale biofuel monocultures can result in elimination of habitat patches far larger than a single territory. These two areas of renewable energy advancement in particular warrant ongoing consideration, mitigation, and monitoring as renewable energy facilities expand into the habitats of birds of prey.

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EXHIBIT
9

Management and Conservation Article

Avian and Bat Fatality Rates at Old-Generation and Repowered Wind Turbines in California

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ABSTRACT Wind turbines in the Altamont Pass Wind Resource Area (APWRA), California, USA, have caused annual fatalities of thousands of raptors and other birds. Alameda County implemented an Avian Protection Program requiring mitigation measures and eventual repowering to modern wind turbines, all intended to reduce raptor fatality rates 50% from levels estimated for 1998–2003. Two years into the 3-year program, we compared estimates of fatality rates between 1998–2003 and 2005–2007 and between a repowered wind project (Diablo Winds) and the APWRA's old-generation wind turbines. The APWRA-wide fatality rates increased significantly for multiple bird species, including 85% for all raptors and 51% for all birds. Fatality rates caused by the Diablo Winds repowering project were not lower than replaced turbines, but they were 54% and 66% lower for raptors and all birds, respectively, than those of concurrently operating old-generation turbines in 2005–2007. Because new-generation turbines can generate nearly 3 times the energy per megawatt of rated capacity compared to the APWRA's old turbines, repowering the APWRA could reduce mean annual fatality rates by 54% for raptors and 65% for all birds, while more than doubling annual wind-energy generation. Alternatively, the nameplate capacity of a repowered APWRA could be restricted to 209 megawatts to meet current energy generation (about 700 gigawatt-hr), thereby reducing mean annual fatalities by 83% for raptors and 87% for all birds. In lieu of repowering, bird fatalities could be reduced by enforcing operating permits and environmental laws and by the County requiring implementation of the Alameda County Scientific Review Committee's recommendations. (JOURNAL OF WILDLIFE MANAGEMENT 73(7):1062–1071; 2009)

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KEY WORDS Altamont Pass, bird fatalities, mitigation, raptor mortality, repowering, wind energy, wind turbine.

The Altamont Pass Wind Resource Area (APWRA) began operations during the 1980s and was until recently the world's largest wind farm, with a permitted generating capacity of 580 megawatts (MW). It supplies emission-free electric power to thousands of homes, but many of the thousands of dead birds found by the wind turbines are protected by the Migratory Bird Treaty Act (MBTA) and some are protected by other state and federal laws (Appendix). Smallwood and Thelander (2008) estimated bird fatality rates in the APWRA during 1998–2003, but those estimates preceded some repowering and implementation of mitigation measures to reduce wind turbine–caused fatalities.

In 1998 the APWRA included about 5,400 wind turbines of various models, ranging in capacity from 40 kilowatts (kW) to 400 kW but most were 100 kW to 150 kW. In February 2005 the Diablo Winds Energy Project repowered 21 MW of rated capacity by replacing 126 Flowind (FloWind Corp., San Rafael, CA) vertical-axis wind turbines with 31 Vestas (Vestas Wind Systems A/S, Randers, Denmark) horizontal axis wind turbines (Table 1). The new turbines were more widely spaced and operated at lower rotor speed (rotations/min), which were traits thought by some to be safer for birds (Erickson et al. 2001, Tucker 1996). Hunt (2002) concluded repowering with larger turbines would be safer for golden eagles (*Aquila chrysaetos*), but Orloff and Flannery (1992) and Smallwood and Thelander (2004, 2005) found that turbines with larger rotor-swept areas killed more of some raptor species.

In August 2005, Alameda County renewed the conditional use permits held by most APWRA wind companies, requiring new, more stringent mitigation measures to reduce wind turbine–caused fatality rates. This Avian Protection Program was to be assessed through November 2009 by an avian monitoring team and Scientific Review Committee (SRC). The program was modified in January 2007 following a settlement agreement to litigation brought by environmental groups, including a goal to reduce wind-turbine–caused raptor fatalities by 50% since the 1998–2003 study (Smallwood and Thelander 2008), where raptors were represented by 4 target species: golden eagle, red-tailed hawk (*Bueo jamaicensis*), American kestrel (*Falco sparverius*), and burrowing owl (*Athene cunicularia*).

By November 2007, wind companies implemented some mitigation measures required by County use permits and recommended by the SRC (Table 2). Our objectives were to compare estimates of APWRA fatality rates between 1) the periods 1998–2003 and 2005–2007, and 2) a repowered wind project and the concurrently operating old-generation wind turbines.

STUDY AREA

The APWRA encompassed about 165 km^2 of ridges and hills generally extending northwest to southeast and bisected by intermittent streams and ravines in eastern Alameda and southeastern Contra Costa counties, California, USA. Elevations ranged 78 m to 470 m above mean sea level. Slopes were covered mostly by nonnative, annual grasses, which grew during the rainy months of January through March and were dead or dormant by early June. Cattle grazers held most of the land, leasing out wind-energy rights to wind-power companies.

Wind turbines were arranged in rows of up to 62 turbines, typically along ridge crests (i.e., peaks of the ridge features)

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Table 1. Attributes of wind turbines involved in the Diablo Winds Energy Project, which repowered 21 megawatts (MW) of rated capacity in the Altamont Pass Wind Resource Area, California, USA, in February 2005.

Attribute	Repowered Flowind[a] vertical-axis turbines		New Vestas[b] horizontal axis turbines	
Model	F-17	F-19	V47	V47
No. turbines	105	21	24	7
Rated output/turbine (MW)	0.15	0.25	0.66	0.66
No. of blades	2	2	3	3
Rotor diam (m)	17.2	19.1	47	47
Rotor speed (revolutions/min)	66.3	59.7	28.5	28.5
Hub ht above ground (m)			50	55
Highest blade reach above ground (m)	29.5	32.3	73.5	78.5
Lowest blade reach above ground (m)	4	4	26.5	31.5
Inter-turbine spacing within rows (m)	51	51	104	104

[a] FloWind Corp., San Rafael, California, USA.
[b] Vestas Wind Systems A/S, Randers, Denmark.

and ridgelines extending down toward ephemeral streams. Wind turbine rows also occupied slopes, valleys, and hill peaks, and all operated in winds from any direction, although most winds originated from the southwest or northwest. Old-generation wind turbine models were listed in Smallwood and Thelander (2008).

METHODS

We performed fatality searches at 2 sets of wind turbines during 1998–2003 (Table 3). We searched all set 1 turbines, because they were the only turbines to which the companies granted access until 2002, when all other turbines became available for fatality monitoring. We systematically selected set 2 turbines from the remaining pool of turbines to ensure homogenous interspersion of searched and unsearched turbines across the north to south and east to west extents of the APWRA (Smallwood and Thelander 2008). Altogether, we searched 4,074 (75%) of the 5,400 turbines in the APWRA during 1998–2003. Within set 1, we also searched all 126 Flowind vertical-axis turbines (21 MW) in 25 rows with an average interval of 45 days. These turbines ceased operations in 2000–2001 and were replaced in 2005 by 31 modern Vestas V47 turbines (20.46 MW) as part of the Diablo Winds Energy Project repowering (Table 3). Also within set 1, we searched 899 turbines (81.63 MW) that we selected randomly for the 2005–2007 fatality monitoring and so were directly comparable between monitoring periods.

We performed fatality searches since 2005 at 2,650 (53%) of the APWRA's old-generation wind turbines (Table 3). Fatality searches were within 84 randomly selected plots stratified by north and south aspects of the APWRA and by turbine size (i.e., very small: 40–65 kW; small: 100–150 kW; and medium: 250 kW). Each plot included 10–60 turbines in 1–7 rows. To estimate APWRA-wide fatality rates during 2005–2007, we extrapolated estimates from turbines in randomly selected plots to the 547.02 MW of rated capacity from which we drew our old-generation

Table 2. Implementation of Alameda County Avian Protection Program to reduce avian fatality rates in the Altamont Pass Wind Resource Area, California, USA, 22 September 2005 through 31 October 2007.

Mitigation measure (required by permit or recommended by Alameda County Scientific Review Committee [SRC])	Action taken
Convene SRC by 31 Oct 2005 (Permit).	SRC convened on 11 Sep 2006.
Remove or relocate turbines classified (K. S. Smallwood and L. Spiegel, California Energy Commission, unpublished data) as Tier 1 (most hazardous) by 31 Oct 2005 and as Tier 2 by 9 Feb 2007 (Permit).	Most operated in Apr 2007 and some operated in Sep 2007. No confirmed determination of removals or relocations through Nov 2007.
Remove vacant towers and towers supporting broken turbines, 50% by 22 Mar 2006 and 100% by 22 Sep 2006 (Permit).	Vacant towers and towers with broken turbines were not removed.
Subject to approval by United States Fish and Wildlife Service, remove all artificially created rock piles away from turbines by 20 Mar 2006 (Permit).	Rock piles were not removed.
Implement other on-site measures recommended by Smallwood and Thelander (2004) and SRC by 20 Mar 2006 (Permit).	None were implemented (see below).
Cease rodent control activities on all sites.	Wind companies stopped funding rodent control, but some land owners likely continued control efforts.
Pending SRC approval of an experimental design, paint turbine blades using Hodos (2003) scheme on a trial or larger basis (Permit). The intent was to lessen motion smear caused by moving wind turbine blades.	One company painted one blade black on 42 turbines, but without using the correct paint or obtaining SRC approval due to experimental design concerns.
Winter-time shut-down of turbines in a cross-over design, so northern turbines were to shut down during 2 months of winter and the southern turbines operated, and vice versa during winter's second half; the shut-down order was to switch between the winters of 2005–2006 and 2006–2007 (Permit).	Shut-downs were completed, but the permit requirement deviated from the original recommendation for a 4-month winter shut-down (K. S. Smallwood and L. Spiegel, unpublished data).
Remove vacant lattice towers used as end-of-row flight diverters (SRC).	Vacant towers were not removed.
Provide turbine power output data so the SRC can test hypotheses of causal mechanisms and more effectively recommend turbine removals (SRC).	No power output data were provided during our study.
Repowering should be pursued to reduce avian fatality rates (SRC).	No repowering was pursued during our study.

Table 3. Attributes of wind turbines and avian and bat fatality searches compared between 1998–2003 and 2005–2007 and within land held by East Bay Regional Park District (EBRPD), Altamont Pass Wind Resource Area, California, USA.

Attributes	Monitoring period 1998–2003 Smallwood and Thelander (2008)		Monitoring period 2005–2007 Consultants to Alameda County (Avian Protection Program)			Monitoring period 2005–2007 Smallwood et al. (2009)
Sample	Set 1	Set 2	Group 1	Group 2	Diablo Winds	EBRPD
Start and end dates	Mar 1998–Sep 2002	Nov 2002–May 2003	Oct 2005–Oct 2007	Mar 2007–Oct 2007	Apr 2005–Nov 2007	Jun 2006–Sep 2007
Duration (yr)	1.5–4.5	0.5	2	0.6	2.7	1.3
Sample selection	Census	Systematic	Random	Random	Census	Census
Turbine models	All available	All available	Old-generation	Old-generation	Vestas V47	Nordtank, Howden
Turbine sizes (kilowatts)	40–400	65–400	40–400	100–120	660	65 & 330
No. turbines	1,526	2,548	2,114	536	31	62
Rated capacity (megawatts)	153.25	267.09	212.62	54.34	20.46	12.52
Search radius (m)	50	50	50	50	75	60
Mean search interval (days)	53	>90	41	41	33	17

turbine sample. Three complications emerged from this sampled pool. In 2005, the Buena Vista Wind Energy project replaced 179 small wind turbines in Contra Costa County with 38 1-MW Mitsubishi turbines. It began operations in January 2007, but fatality monitoring by other investigators did not begin there until January 2008. We assumed fatality rates were similar between the Buena Vista project and the rest of the sampled pool of turbines, but we cannot validate the accuracy of our assumption. A second complication was an infrastructure problem that resulted in shutting down all 200 Vestas 100-kW turbines owned by the City of Santa Clara from November 2005 through February 2007, except for January 2006. We searched for fatalities at 12.8 MW (128 turbines) of this 20 MW of capacity, despite nonoperation. The third complication was refused access to 186 turbines (12.1 MW capacity) owned by Northwind Inc. in Contra Costa County. However, East Bay Regional Park District (EBRPD) allowed us to use estimates of fatality rates from EBRPD property (Smallwood et al. 2009), which included about 12% of the Northwind Inc. turbines. To the estimates of fatality rates extrapolated to 547.02 MW of capacity, we added estimates from 12.52 MW of capacity on the EBRPD property and 20.46 MW in the Diablo Winds project.

Searches were performed by biologists walking parallel transects about 4–8 m apart, viewing all ground out to 50 m at most old-generation wind turbines, 60 m at the 330 kW Howden turbines, and 75 m at the 660 kW Diablo Winds turbines. We documented as fatalities all carcasses or body parts found, such as groups of flight feathers, head, wings, tarsi, and tail feathers. When possible, we identified carcasses to species, age class, and sex. We assessed carcass condition to estimate number of days since death. Generally we assumed carcasses were older than 90 days if the enamel on culmen and talons had separated from the bone, flesh was gone, and bones and feathers were bleached, but we used judgment because carcass decomposition rates vary according to environmental conditions. Presence of blood generally indicated <4 days since death, but onset of rigor mortis, odor, and maggots or other insect larvae varied greatly with temperature, so we had to use these signs as guides in the context of current environmental conditions to estimate number of days since death. We photographed nearly all carcasses.

We considered each fatality record as unlikely, possibly, probably, or certainly caused by wind turbines. Fatalities unlikely caused by turbines were unfledged birds or those determined to have been caused by electrocution, vehicle collision, or predation. They were possible if within the fatality search radius but nearby an electric distribution pole or lines, implicating electrocution or line strike as causes of death, or if they were burrowing owls next to burrows, implicating predation. They were probable if found near wind turbines and another cause of death was not determined. They were certain if evidence suggested a turbine was involved, such as oil or grease on the bird, paint on the bird, or the bird was split in two or dismembered due to impact. We considered most of the fatalities found probably caused by wind turbines, 71% during 1998–2003 and 91% during 2005–2007. To estimate turbine-caused fatality rates we used fatalities considered possibly, probably, or certainly caused by wind turbines, or 98.6% of fatalities reported in 1998–2003 and 97.3% in 2005–2007.

Within each turbine row we expressed unadjusted fatality rate (F_U) as number of fatalities per MW per year, where we summed MW across all turbines in the row. Although individual turbines killed birds, we used the wind turbine row as our study unit because 1) we believed birds often sensed and reacted to the wind turbine row as a barrier or threat, and 2) we often could not determine which turbine in the row killed the bird. We used the MW of rated capacity of all turbine addresses initially searched within the row, regardless of whether the address later supported a functional or broken turbine or a vacant tower. We took this approach because we were not regularly updated on turbine functionality, which varied, and we were often unable to determine functionality while wind speeds were too low for power generation. To number of years in the fatality-rate calculation, we added average search interval (in days converted to yr) to represent the time period when carcasses could have accumulated before our first search. We derived fatality-rate estimates from fatalities estimated to have occurred $\leq$90 days before discovery. We discovered most excluded fatalities during start-up searches at newly visited turbines. Out to 125 m, we included carcasses found outside the search radius because we assumed likelihood of seeing carcasses outside the search radius would not vary significantly among turbine rows in the APWRA's short-stature grassland.

We adjusted our fatality-rate estimate, F_A, for carcasses not found due to searcher-detection error and scavenger removals as

$$F_A = \frac{F_U}{p \times R_C} \quad (1)$$

where F_U was unadjusted fatality rate, p was proportion of fatalities found by searchers during searcher-detection trials in grasslands across the United States and reported in Smallwood (2007), and R_C was estimated cumulative proportion of carcasses remaining since the last fatality search, assuming wind turbines will deposit carcasses at a steady rate through the search interval. We estimated R_C by scavenger-removal rates estimated from trials throughout the United States and averaged by Smallwood (2007):

$$R_C = \frac{\sum_{i=1}^{I} R_i}{I} \quad (2)$$

where R_i was proportion of carcasses remaining by the ith day following initiation of a scavenger-removal trial (intended to correspond with no. of days since the last fatality search during monitoring), and I was average search interval (days). We looked up R_C values in Smallwood (2007; Appendix) according to species group and search interval. We calculated standard error of the adjusted fatality rate, SE[F_A], using the delta method (Goodman 1960):

$$\mathrm{SE}[F_A] = \sqrt{\left(\frac{1}{p \times R_C} \times \mathrm{SE}[F_U]\right)^2 \times \left(\frac{F_U}{p} \times \frac{-1}{{R_C}^2} \times \mathrm{SE}[R_C]\right)^2 \times \left(\frac{F_U}{R_C} \times \frac{-1}{p^2} \times \mathrm{SE}[p]\right)^2} \quad (3)$$

We did not adjust estimates for background mortality, crippling bias, or search radius bias. Background mortality is the fatality rate caused by factors other than wind turbines and supporting infrastructure. Crippling bias refers to the rate of mortally wounded animals dying undetected outside the search radius or moving from unsearched turbines to searched turbines. Search-radius bias refers to the rate of wind turbine–killed birds thrown beyond the search radius and not found. Birds thrown 50 m laterally from turbines atop steep slopes can land farther down the hill than the 50 m measured from the searcher to the turbine base.

Differing from Smallwood and Thelander (2008), we included carcasses removed by companies as part of the Wildlife Response and Reporting System (WRRS), which was the industry's system of reporting carcasses found incidentally by turbine maintenance personnel. As a result, our 1998–2003 estimates reported herein will sometimes differ from Smallwood and Thelander (2008). Including WRRS data undoubtedly introduced some small error in our fatality-rate estimates because we applied the same scavenger-removal adjustments to these few fatalities as to the carcasses detected during our standard fatality searches.

We estimated bat fatality rates by applying scavenger-removal and searcher-detection rates estimated for small-bodied bird species (Smallwood 2007). However, numerous unpublished reports found that searchers miss more bats than small birds, and scavengers quickly remove many bats. Therefore, our estimates of bat fatality rates were likely biased low, but at least they were consistent between estimates reported herein, enabling preliminary comparisons between time periods and turbine fields.

Due to complexity of the APWRA-wide estimates of fatality rates, including 2 sampling approaches during 1998–2003 and multiple separate estimates added together in 2005–2007, we did not test for APWRA-wide differences in fatality rates. Instead, we simply compared estimated means and standard errors between monitoring periods. We used the t-test to test whether mean fatality rates differed between 1998–2002 and 2005–2007 within the 81.63 MW of turbines that were directly comparable (reference turbines) and within the 21 MW of the repowered Diablo Winds turbines.

RESULTS

APWRA-Wide Fatality Rates

Between 1998–2003 and 2005–2007, estimated mean adjusted fatality rate decreased 40% for American kestrel and increased 121% for red-tailed hawk, 17% for golden eagle, 30% for burrowing owl, 10% for all 4 target species combined, and 23% for all birds combined (Appendix). However, we did not test these mean differences for significance due to differences in sampling designs leading to the APWRA-wide fatality-rate estimates.

Comparing adjusted fatality rates only from old-generation turbines mutually monitored during both 1998–2003 and 2005–2007, fatality rates increased 110% for burrowing owl, 247% for barn owl (*Tyto alba*), 163% for rock pigeon (*Columba livia*), and 94% for western meadowlark (*Sturnella neglecta*), but not significantly for any other species (Table 4). Fatality rates increased 81% for the 4 target species together, 85% for all raptors, and 51% for all birds. Estimated mean fatality rate of red-tailed hawk increased 79%, but this increase was not significant.

Diablo Winds Fatality Rates

The first repowering project in the APWRA did not change fatality rates for any species or group of species, because fatality rates did not differ between the old vertical-axis turbines and the new horizontal axis turbines (Table 5). Though not significant, mean adjusted fatality rate increased for golden eagle from zero at the vertical-axis turbines in 1998–2001 to one eagle in 3 years during 2005–2007. Mean adjusted fatality rate increased 124% for red-tailed hawk, but decreased 13% for American kestrel, 21% for burrowing owl, 12% for all 4 target species together, and 25% for all

Table 4. Comparison of mean fatality-rate estimates at wind turbines mutually searched during both the 1998–2002 and in 2005–2007 monitoring programs, using 2-tailed paired-sample *t*-tests (df = 109). We searched turbines 1.5–4.5 years (most >2 yr) in 1998–2002 and 2 years in 2005–2007. Turbines totaled 81.63 megawatts (MW) of rated capacity in 110 rows, mostly in the central, eastern, and southern aspects of the Altamont Pass Wind Resource Area, California, USA.

	Adjusted fatality-rate (deaths/MW/yr)					
	1998–2003		2005–2007			
Species[a]	$\bar{x}$	SE	$\bar{x}$	SE	Paired-sample *t*-value	*P*-value
Turkey vulture	0.009	0.009	0.003	0.003	0.676	0.500
Golden eagle	0.070	0.024	0.091	0.035	0.499	0.619
Red-tailed hawk	0.437	0.121	0.782	0.148	1.756	0.082
Buteo spp.	0.000	0.000	0.016	0.015	1.083	0.281
Northern harrier	0.006	0.003	0.015	0.011	0.864	0.389
Prairie falcon	0.003	0.003	0.006	0.004	0.608	0.545
American kestrel	0.496	0.147	0.532	0.146	0.172	0.864
Burrowing owl	1.442	0.345	3.025	0.524	2.690	0.008
Great horned owl	0.043	0.023	0.048	0.026	0.149	0.882
Barn owl	0.077	0.027	0.268	0.065	2.663	0.009
Double-crested cormorant	0.017	0.017	0.000	0.000	1.000	0.320
Great blue heron	0.000	0.000	0.004	0.004	1.000	0.320
Great egret	0.000	0.000	0.156	0.156	1.000	0.320
Killdeer	0.000	0.000	0.012	0.012	1.000	0.320
Black-necked stilt	0.000	0.000	0.130	0.130	1.000	0.320
American avocet	0.059	0.049	0.000	0.000	1.186	0.238
Gull spp.	0.030	0.019	0.122	0.049	1.987	0.049
Ring-billed gull	0.029	0.024	0.000	0.000	1.229	0.222
California gull	0.028	0.016	0.035	0.035	0.173	0.863
Duck spp.	0.000	0.000	0.017	0.017	1.000	0.320
Mallard	0.187	0.065	0.137	0.090	0.824	0.412
Northern flicker	0.247	0.157	0.087	0.090	0.888	0.377
Wild turkey	0.013	0.013	0.000	0.000	1.000	0.320
Dove spp.	0.000	0.000	0.101	0.052	1.952	0.054
Rock pigeon	1.339	0.340	3.520	0.642	3.846	0.000
Mourning dove	2.538	0.943	1.054	0.305	1.488	0.140
White-throated swift	0.000	0.000	0.027	0.027	1.000	0.320
American crow	0.068	0.044	0.049	0.031	0.345	0.731
Common raven	0.088	0.068	0.145	0.053	0.668	0.506
Pacific-slope flycatcher	0.058	0.058	0.000	0.000	1.000	0.320
Western kingbird	0.021	0.021	0.000	0.000	1.000	0.320
Horned lark	0.455	0.171	0.456	0.364	0.003	0.998
Tree swallow	0.000	0.000	0.013	0.013	1.000	0.320
Cliff swallow	0.063	0.063	0.046	0.036	0.226	0.821
Mountain bluebird	0.000	0.000	0.081	0.051	1.578	0.117
Northern mockingbird	0.082	0.082	0.000	0.000	1.000	0.320
Loggerhead shrike	0.066	0.052	0.438	0.185	1.918	0.058
European starling	1.704	0.466	3.235	0.770	1.713	0.090
Sparrow spp.	0.000	0.000	0.044	0.044	1.000	0.320
Savanna sparrow	0.073	0.073	0.000	0.000	1.000	0.320
Western meadowlark	1.964	0.526	3.817	0.693	2.070	0.041
Blackbird spp.	0.000	0.000	0.713	0.488	1.460	0.147
Red-winged blackbird	0.505	0.223	0.330	0.148	0.686	0.494
Tricolored blackbird	0.030	0.030	0.000	0.000	1.000	0.320
Brewer's blackbird	0.246	0.142	0.226	0.120	1.000	0.320
Brown-headed cowbird	0.058	0.058	0.000	0.000	1.000	0.320
House finch	0.693	0.331	0.000	0.000	2.090	0.039
Cockatiel	0.000	0.000	0.068	0.068	1.000	0.320
Unidentified bird spp.	0.450	0.170	0.269	0.127	2.109	0.037
Songbird spp.	0.526	0.233	1.184	0.372	1.560	0.122
Medium nonraptor spp.	0.000	0.000	0.199	0.090	2.214	0.029
Large nonraptor spp.	0.000	0.000	0.125	0.073	1.708	0.090
Bats	0.115	0.073	0.263	0.172	0.79	0.433
Target raptor species	2.445	0.381	4.430	0.538	3.13	0.002
Total raptors	2.583	0.380	4.786	0.537	3.48	0.001
Total birds	14.220	1.542	21.627	2.079	3.00	0.003

[a] See Appendix for scientific names.

birds (Table 5). Adjusted fatality rate of bats increased from zero at the old vertical-axis turbines to 16.4/year at the new, repowered turbines, but this difference was not significant, probably due to small sample sizes.

Compared to concurrently operating old-generation turbines during 2005–2007, adjusted fatality rates in the repowered Diablo Winds turbines were lower by 64% for red-tailed hawks, 92% for American kestrel, 92% for rock

Table 5. Fatality rates caused by Diablo Winds Energy Project in the Altamont Pass Wind Resource Area, California, USA, 1) before (1998–2001) and after (2005–2007) repowering from Flowind 150-kilowatt (kW) and 250-kW vertical-axis turbines to Vestas 660-kW turbines, using 2-tailed paired-sample t-tests (df = 35), and 2) between repowered wind turbines in the Diablo Winds Energy Project and old-generation wind turbines operating concurrently in 2005–2007, using 2-tailed independent samples t-tests (df = 344).

	Adjusted fatality-rates (deaths/megawatt/yr)						*P*-value	
	Before repowering 1998–2002		After repowering 2005–2007		Old generation turbines 2005–2007		Before to after repowering at Diablo Winds	Diablo Winds to old turbines after repowering
Species[a]	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE		
Turkey vulture	0.000	0.000	0.016	0.016	0.018	0.013	0.337[c]	0.970[b]
Golden eagle	0.000	0.000	0.016	0.016	0.118	0.029	0.337[c]	0.489[b]
Red-tailed hawk	0.111	0.066	0.247	0.096	0.692	0.081	0.238[b]	0.001[c]
American kestrel	0.076	0.076	0.066	0.066	0.779	0.131	0.934[b]	0.000[c]
Burrowing owl	1.809	0.730	1.429	0.431	1.873	0.261	0.719	0.737[b]
Barn owl	0.208	0.186	0.012	0.012	0.257	0.048	0.444[b]	0.314[b]
Pied-billed grebe	0.000	0.000	0.268	0.268	0.000	0.000	0.337[c]	0.337[c]
Gull spp.	0.157	0.157	0.100	0.053	0.113	0.035	0.795[b]	0.940[b]
Mallard	0.519	0.426	0.033	0.033	0.122	0.063	0.410[b]	0.781[b]
Cliff swallow	0.487	0.403	0.000	0.000	0.036	0.024	0.383[b]	0.766[b]
Loggerhead shrike	0.000	0.000	0.179	0.121	0.321	0.110	0.165[c]	0.799[b]
European starling	0.628	0.319	0.604	0.361	3.317	0.453	0.963[b]	0.238[b]
Horned lark	0.085	0.085	0.090	0.090	0.515	0.178	0.971[b]	0.637[b]
Rock pigeon	0.089	0.071	0.114	0.072	1.468	0.235	0.820[b]	0.000[c]
Mourning dove	0.000	0.000	0.157	0.107	0.574	0.131	0.147[c]	0.532[b]
Hammond's flycatcher	0.000	0.000	0.090	0.090	0.005	0.005	0.337[c]	0.366[c]
Western meadowlark	2.249	0.945	1.747	0.597	3.135	0.338	0.715[b]	0.409[b]
Blackbird spp.	0.325	0.325	0.000	0.000	0.381	0.174	0.470[b]	0.666[b]
Brewer's blackbird	0.330	0.330	0.000	0.000	0.357	0.119	0.470[b]	0.554[b]
House finch	0.450	0.346	0.090	0.090	0.000	0.000	0.455[b]	0.337[c]
Unidentified bird	0.000	0.000	0.411	0.275	0.299	0.108	0.161[c]	0.839[b]
Bats	0.000	0.000	0.783	0.548	0.087	0.057	0.179[c]	0.231[c]
Target species	1.996	0.763	1.758	0.393	3.462	0.309	0.784[c]	0.002[c]
Total raptors	2.204	0.762	1.786	0.388	3.737	0.316	0.628[c]	0.000[c]
Total birds	7.523	1.564	5.669	1.291	14.380	1.054	0.432[b]	0.000[c]

[a] See Appendix for scientific names.
[b] Assumed equal variances, because $P > 0.05$ in Levene's Test for Equality of Variances.
[c] Assumed unequal variances, because $P \leq 0.05$ in Levene's Test for Equality of Variances.

pigeon, 49% for all target raptors, 54% for all raptors, and 66% for all birds (Table 5). Though not significant, mean adjusted fatality estimates were lower by 87% for golden eagles, 24% for burrowing owls, 95% for barn owl, 83% for horned lark (*Eremophila alpestris actia*), 73% for mourning dove (*Zenaida macroura*), 44% for loggerhead shrike (*Lanius ludovicianus*), and 44% for western meadowlark. Adjusted fatality rate of bats was nearly 800% greater at repowered turbines compared to concurrently operated old-generation turbines, but this large difference was not significant, probably due to sample sizes.

DISCUSSION

The APWRA-wide estimates of adjusted fatality rates did not lessen since 1998–2003, even though 200 100-kW Vestas turbines did not operate over 16 months of the 2005–2007 monitoring period and most APWRA turbines were shut down for 2 months of each winter. Among the mutually surveyed old-generation wind turbines, adjusted fatality rates increased significantly for the target raptors, all raptors, and all birds. We propose 4 alternative hypotheses for why the Avian Protection Program has not yet reduced fatality rates.

First, our data suggest that fatality rates might have increased if wind power generation increased within the APWRA. However, wind-power generation data from 1999 and 2006 did not support this hypothesis, assuming power generation during these years represented the corresponding fatality monitoring periods. We related monthly power-generation data maintained by the California Energy Commission to our estimated annual adjusted fatality rates for the subset of old-generation wind turbines that we searched during both monitoring periods. The capacity factor (annual MW-hr/MW of rated capacity, expressed as %) of the APWRA's old generation turbines actually decreased between 1999 and 2006 from 16.7% to 13.3%. Thus, annual deaths per gigawatt (GW)-hour increased for most species, and it increased from 1.71 raptors/GW-hour to 3.98 raptors/GW-hour (133%) and from 9.42 birds to 17.92 birds/GW-hour (90%). Fatality rates increased although power generation from old-generation turbines decreased.

Second, we suggest that increases in fatality rates may have tracked increases in avian abundance in the APWRA. We were unable to test whether relative abundance increased because utilization data remained unprepared to account for methodological differences between monitoring periods, especially the maximum distance from the observer at which birds were recorded.

Third, we suggest that fatality rates increased due to methodological bias. Our adjustments for scavenger removal were intended to account for the difference in average search interval between the 1998–2002 and 2005–2007 monitoring periods, but we lack an independent check on whether the adjustment was sufficient. It is possible that fatality rates only appeared to increase due to the shorter search interval in 2005–2007.

Fourth, we suggest that fatality rates might have increased due to inadequate or even counterproductive implementation of the Avian Protection Program (Table 2). The wind companies delayed relocating hazardous turbines until late 2007. Wind companies left vacant lattice towers at ends of rows as flight diverters, but this practice may have caused more raptor fatalities because raptors readily perched on vacant towers, which were adjacent to operating turbines. We often observed perched raptors flush as other territorial or predatory birds approached, and perched raptors often altered flight patterns of smaller raptors. Increases in these types of interactions could have led to increased collisions. Vacant towers and broken turbines were also left within turbine rows, which created gaps amongst functional turbines, and these gaps might have encouraged raptors to attempt row crossings where other raptors were perched. Alameda County required a winter shut-down that reactivated half the turbines when red-tailed hawks peaked in number and were likely habituated to shut-down turbines. For a company with 20% of the APWRA's turbines, the County waived the required increase in the duration of its winter shut-down. The blade-painting experiment of Altamont Winds, Inc. (Oakland, CA) was too small in scope to be noticed in APWRA-wide estimates of fatality rates. Finally, the year-long delay in forming the SRC also delayed scientific input on these measures.

The Diablo Winds repowering project did not reduce fatality rates compared to replaced turbines, but probably because the replaced turbines were largely defunct by the time we monitored them for fatalities in 1998–2001. We lack sufficient resolution in the wind-energy generation data at the California Energy Commission to test whether the Flowind vertical-axis turbines were declining in power output before replacement, but we recall that they rarely operated during our fatality searches. We suspect that starting with Diablo Winds, the least productive wind turbines are those selected for repowering, resulting in small if any reductions in fatality rates within the repowering project. Perhaps more relevant than comparing to fatality rates caused by a group of turbines already phased out of existence, we found substantially lower fatality rates caused by the new Diablo Winds turbines compared to concurrently operating old-generation turbines during 2005–2007. Fatality rates seemed lower yet after factoring in the improved capacity factor of the repowered turbines, which was 36.9% at Diablo Winds in 2006 compared with 13.3% at concurrently operating old-generation turbines. Fatalities per GW-hour at the repowered Diablo Winds project were lower than at the concurrently operating old-generation turbines by 94% for golden eagle, 84% for red-tailed hawk, 96% for American kestrel, 67% for burrowing owl, 78% for target raptors, 80% for all raptors, and 85% for all birds. Repowering the entire APWRA would likely reduce fatality rates a great deal, especially if considered on a power generation basis and if carefully done by locating new turbines where they pose the least hazard (Smallwood and Neher 2005, Smallwood et al. 2009). The improved capacity factor of new-generation turbines could also offset much of the nameplate capacity in the APWRA, so assuming the 36.9% capacity factor would apply throughout the APWRA, the same power generation could be achieved by 209 MW of nameplate capacity instead of the permitted 580 MW operating in the APWRA today. This capacity would include 209–317 wind turbines, assuming the turbines would range in size from 660 kW to 1 MW or 4% to 6% of the approximately 5,000 turbines that operated in 2005–2007. Turbine operations could also be restricted to times of day, seasons, or specific wind conditions to further reduce fatality rates.

A possible downside to repowering, however, may be increased bat fatalities caused by wind turbines. Extrapolating the mean adjusted bat fatality rate from Diablo Winds to a completely repowered APWRA, about 454 bat fatalities/year might result, but using more realistic scavenger-removal and searcher-detection rates could increase this number to thousands of bats. Bat fatalities in the APWRA need additional, focused research.

MANAGEMENT IMPLICATIONS

To reduce avian fatality rates caused by wind turbines in the Altamont Pass, the old-generation wind turbines should be carefully repowered as soon as possible because estimated mean annual fatalities could be reduced 54% for all raptors and 65% for all birds, while adding about 1,000 GW-hours of wind energy annually due to the nearly 3-fold increase in the capacity factor of new-generation turbines. Alternatively, the nameplate capacity of the repowered APWRA could be restricted to 209 MW to meet current energy generation levels, thereby reducing estimated mean annual fatalities 83% for all raptors and 87% for all birds. To lessen fatality rates before repowering, Alameda County would need to enforce permit conditions and require implementation of SRC recommendations, including a 4-month winter shut-down of all wind turbines, removal or careful relocation of the most hazardous turbines, and removal of vacant towers and broken turbines. Finally, State and Federal regulatory agencies could help reduce fatality rates by enforcing the MBTA and other environmental laws.

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Appendix. Avian and bat species recorded as fatalities or mortally wounded at wind turbines of the Altamont Pass Wind Resource Area (APWRA), California, USA, from January 1989 through October 2007, including estimates of wind turbine–caused fatality rates from 2 time periods of scientific monitoring. We denote status as FE = Federal Endangered, FT = Federal Threatened, CE = California Endangered, CT = California Threatened, CFP = California Fully Protected, CSC = California Department of Fish and Game listing of California Species of Concern. California Fish and Game Code 3503.5 protected all raptors, and the Migratory Bird Treaty Act protected all species in the table except exotic species and bats. We revised fatality estimates for 1998–2003 from those of Smallwood and Thelander (2008) by including the wind companies' Wildlife Response and Reporting System (WRRS) data and using similar assumptions to those of the 2005–2007 monitoring period. The 2005–2007 annual fatality estimates were sums of estimated annual fatalities from separate monitoring efforts, including from East Bay Regional Park District, Diablo Winds Energy Project, and a stratified random sample of turbines. LCL and UCL denote lower and upper confidence limits, respectively.

Species or taxonomic group	Species name	Status	Recorded deaths 1989–2007	Estimated APWRA-wide annual fatalities (80% CI)					
				1998–2003			2005–2007		
				Total	LCL	UCL	Total	LCL	UCL
Turkey vulture	*Cathartes aura*		32	2.5	0.6	4.5	10.2	0.8	19.6
Golden eagle	*Aquila chrysaetos*	CSC, CFP	495	55.3	24.3	86.3	64.7	42.3	87.0
Cooper's hawk	*Accipiter cooperii*	CSC	1						
Red-tailed hawk	*Buteo jamaicensis*		1250	177.3	114.5	240.2	391.7	302.8	480.6
Ferruginous hawk	*Buteo regalis*	CSC	13	0.0	0.0	0.0	4.0	−1.0	8.9
Swainson's hawk	*Buteo swainsoni*	CT	2	0.0	0.0	0.0	0.5	−0.2	1.2
Rough-legged hawk	*Buteo lagopus*		1						
Red-shouldered hawk	*Buteo lineatus*		1	0.0	0.0	0.0	0.3	−0.1	0.7
Buteo spp.	*Buteo* spp.		45	0.0	0.0	0.0	16.6	6.4	26.9
Northern harrier	*Circus cyaeneus*	CSC	10	0.7	0.1	1.2	3.3	0.7	5.9
White-tailed kite	*Elanus leucurus*	CFP	3	0.0	0.0	0.0	0.4	−0.1	0.8
Hawk spp.			8	0.0	0.0	0.0	1.0	−0.3	2.2
Peregrine falcon	*Falco peregrinus*	CE, CFP	2						
Prairie falcon	*Falco mexicanus*	CSC	8	1.1	0.2	2.0	1.3	0.3	2.4
American kestrel	*Falco sparverius*		217	731.2	286.0	1,176.3	439.9	285.3	594.5
Falcon spp.	*Falco* spp.		2						
Burrowing owl	*Athene cunicularia*	CSC	287	858.3	241.2	1,475.4	1,112.4	736.8	1,487.9
Great horned owl	*Bubo virginianus*		91	7.3	3.3	11.2	31.8	18.6	45.0
Long-eared owl	*Asio otus wilsonianus*	CSC	2						
Barn owl	*Tyto alba*		286	46.0	19.2	72.7	150.2	103.6	196.8
Owl spp.			3	0.0	0.0	0.0	0.1	0.0	0.3
Large raptor spp.			4	0.0	0.0	0.0	1.3	0.1	2.6
Raptor spp.			66	0.2	−0.1	0.5	2.3	0.2	4.4
Common poorwill	*Phalaenoptilus nuttallii*		1						
Brown pelican	*Pelicanus occidentalis*	FE, CE	1						
Double-crested cormorant	*Phalacrocorax auritus*	CSC	2	2.1	−0.7	4.8	0.0	0.0	0.0
Pied-billed grebe	*Podilymbus podiceps*		1	0.0	0.0	0.0	5.4	−2.3	13.2
Black-crowned night heron	*Nycticorax nycticorax*	CSA	3	1.1	0.0	2.2	0.0	0.0	0.0
Great blue heron	*Ardea herodius*		9	0.0	0.0	0.0	0.7	−0.2	1.7
Great egret	*Ardea alba*		2	0.0	0.0	0.0	28.1	−9.1	65.3

Appendix. Continued.

Species or taxonomic group	Species name	Status	Recorded deaths 1989–2007	Estimated APWRA-wide annual fatalities (80% CI)					
				1998–2003			2005–2007		
				Total	LCL	UCL	Total	LCL	UCL
Cattle egret	*Bubulcus ibis*	Exotic	1	3.1	−1.1	7.3	0.0	0.0	0.0
Sandhill crane	*Grus canadensis*	CT	1	0.0	0.0	0.0	1.5	−0.5	3.5
Long-billed curlew[a]	*Numenius americanus*	CSC	3						
Black-necked stilt	*Himantopus mexicanus*		1	0.0	0.0	0.0	23.0	−11.2	57.1
American avocet	*Recurvirostra americana*		4	6.7	−0.9	14.3	0.0	0.0	0.0
Lesser yellowlegs	*Tringa flavipes*		1	1.9	−1.1	4.9	0.0	0.0	0.0
Killdeer	*Charadrius vociverus*		4	0.0	0.0	0.0	6.3	−1.3	13.9
Ring-billed gull	*Larus delawarensis*		6	8.6	1.2	16.0	0.0	0.0	0.0
California gull	*Larus californicus*	CSC	21	8.8	2.8	14.8	6.4	−2.1	14.8
Herring gull	*Larus argentatus*		2						
Thayer's gull	*Larus thayeri*		1						
Mew gull	*Larus canus*		1						
Gull spp.	*Larus* spp.		85	109.2	38.0	180.4	65.0	31.0	98.9
Mallard	*Anas platyrhynchos*		67	55.6	13.0	98.2	67.5	17.3	117.7
Ring-necked duck	*Aythya collaris*		1	4.2	−1.5	9.9	0.0	0.0	0.0
Duck spp.			5	0.0	0.0	0.0	9.8	1.8	17.7
Wild turkey	*Melleagris gallopavo*	exotic	3	1.5	−0.5	3.6	0.9	−0.3	2.1
Mourning dove	*Zenaida macroura*		77	468.0	−112.0	1047.9	313.2	59.3	567.1
Rock pigeon	*Columba livia*	exotic	731	324.9	197.8	452.1	2,292.5	1,266.6	3,318.3
Band-tailed pigeon	*Columba fasciata*		1						
Dove spp.			11	0.0	0.0	0.0	35.6	1.4	69.9
Northern flicker	*Colaptes auratus*		9	147.3	−116.9	411.5	15.3	−7.5	38.1
White-throated swift	*Aeronautes saxatalis*		3	0.0	0.0	0.0	40.9	−10.1	91.9
Vaux's swift	*Chaetura vauxi vauxi*		1						
Tree swallow	*Tachycineta bicolor*		1	0.0	0.0	0.0	2.3	−1.1	5.8
Violet-green swallow	*Tachycineta thalassina*		2	2.4	−1.4	6.2	0.0	0.0	0.0
Cliff swallow	*Hirundo pyrrhonota*		10	29.8	−4.6	64.3	27.0	−4.9	59.0
Loggerhead shrike	*Lanius ludovicianus*	CSC	29	122.8	−97.7	343.4	181.4	21.6	341.2
Northern shrike	*Lanius excubitor*		1						
European starling	*Sturnus vulgaris*	exotic	315	1,319.0	−712.7	3,350.7	1,882.9	421.5	3,344.4
Northern mockingbird	*Mimus polyglottos*		3	9.3	−5.5	24.0	9.3	−4.5	23.2
Swainson's thrush	*Catharus ustulatus*		1	0.0	0.0	0.0	8.4	−4.1	20.9
American robin	*Turdus migratorius*		1						
Horned lark	*Eremophila alpestris actia*	CSC	56	114.0	−24.9	252.9	292.5	34.5	550.5
American crow	*Corvus brachyrhynchos*		24	15.8	2.5	29.0	30.5	12.1	48.9
Common raven	*Corvus corax*		86	40.8	1.0	80.6	88.8	40.1	137.6
Scrub jay	*Aphelocoma californica*		3	0.0	0.0	0.0	0.9	−0.4	2.2
Corvid spp.			14						
Pacific-slope flycatcher	*Empidonax difficilis*		1	6.4	−3.8	16.6	0.0	0.0	0.0
Western kingbird	*Tyrannus verticalis*		1	2.5	−1.5	6.5	0.0	0.0	0.0
Hammond's flycatcher	*Empidonax hammondii*		2	0.0	0.0	0.0	4.7	−2.2	11.7
Say's phoebe	*Sayornis saya*		4	0.0	0.0	0.0	11.3	−5.5	28.0
Western tanager	*Piranga ludoviciana*		1	0.0	0.0	0.0	2.2	−1.1	5.5
American pipit	*Anthus rubescens*		2	0.0	0.0	0.0	3.3	−1.6	8.1
Bluebird spp.			3	0.0	0.0	0.0	51.0	−6.1	108.1
Mountain bluebird	*Sialia currucoides*		22	146.5	−117.7	410.8	33.8	2.6	65.1
Western bluebird	*Sialia mexicana*		5						
House wren	*Troglodytes aedon*		1	0.0	0.0	0.0	4.7	−2.3	11.7
Rock wren	*Salpinctes obsoletus*		2	0.0	0.0	0.0	8.9	−4.3	22.2
Yellow warbler	*Dendroica petechia*	CSC	1	3.6	−2.1	9.3	0.0	0.0	0.0
Sparrow spp.			3	0.0	0.0	0.0	7.8	−3.8	19.4
Townsend's warbler	*Dendroica townsendi*		1						
Orange-crowned warbler	*Vermivora celata*		1						
Fox sparrow	*Passerella iliaca*		1						
Savanna sparrow	*Passerculus sandwichensis*		2	33.0	−31.1	97.1	0.0	0.0	0.0
Lincoln sparrow	*Melospiza lincolnii*		1	0.0	0.0	0.0	2.9	−1.4	7.3
Western meadowlark	*Sturnella neglecta*		344	1,594.2	−796.5	3,984.9	1,761.7	411.2	3,112.3
Brewer's blackbird	*Euphagus cyanocephalus*		39	340.5	−249.7	930.7	193.8	26.1	361.4
Brown-headed cowbird	*Molothrus ater*		3	145.9	−151.8	443.6	28.8	−14.0	71.6
Red-winged blackbird	*Agelaius phoeniceus*		35	77.3	−3.1	157.7	139.6	20.2	259.1
Tricolored blackbird	*Agelaius tricolor*	CSC	1	3.9	−2.3	10.1	0.0	0.0	0.0

Appendix. Continued.

Species or taxonomic group	Species name	Status	Recorded deaths 1989–2007	Estimated APWRA-wide annual fatalities (80% CI)					
				1998–2003			2005–2007		
				Total	LCL	UCL	Total	LCL	UCL
Blackbird spp.			16	9.5	−5.7	24.8	210.5	10.4	410.6
House finch	*Carpodacus mexicanus*		23	99.9	−6.5	206.3	1.8	−0.8	4.4
House sparrow	*Passer domesticus*	exotic	1	46.5	−49.3	142.3	0.0	0.0	0.0
Cockatiel	*Leptolophus hollandicus*	exotic	2	3.0	−1.8	7.7	12.2	−5.9	30.4
Small nonraptors			120	74.7	−4.4	153.7	339.9	65.8	614.0
Medium, large nonraptors			91	0.0	0.0	0.0	122.6	47.0	198.3
Bird spp.			120	285.9	−168.8	740.6	169.5	18.0	321.0
Target raptor species			2,249	1,822.1	666.0	2,978.2	2,008.6	1,367.1	2,650.0
Total raptors			2,289	1,879.8	689.3	3,070.3	2,232.0	1,496.1	2,967.9
Total birds			5,283	7,549.9	−1,731.9	16,831.8	9,297.1	3,217.8	1,5376.4
Mexican free-tail bat	*Tadarida brasiliensis*		3						
Western red bat	*Lasiurus borealis teleotis*		2						
Hoary bat	*Lasiurus cinereus*		11						
Bat spp.			3						
Total bats			19	14.4	−3.5	32.3	68.4	−5.4	142.1

[a] Reportedly found by Orloff and Flannery (1992) but did not appear in WRRS data base.

EXHIBIT
10

Conservation Biology

Contributed Paper

Effects of development of wind energy and associated changes in land use on bird densities in upland areas

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Abstract: *Wind energy development is the most recent of many pressures on upland bird communities and their habitats. Studies of birds in relation to wind energy development have focused on effects of direct mortality, but the importance of indirect effects (e.g., displacement, habitat loss) on avian community diversity and stability is increasingly being recognized. We used a control-impact study in combination with a gradient design to assess the effects of wind farms on upland bird densities and on bird species grouped by habitat association (forest and open-habitat species). We conducted 506 point count surveys at 12 wind-farm and 12 control sites in Ireland during 2 breeding seasons (2012 and 2013). Total bird densities were lower at wind farms than at control sites, and the greatest differences occurred close to turbines. Densities of forest species were significantly lower within 100 m of turbines than at greater distances, and this difference was mediated by habitat modifications associated with wind-farm development. In particular, reductions in forest cover adjacent to turbines was linked to the observed decrease in densities of forest species. Open-habitat species' densities were lower at wind farms but were not related to distance from turbines and were negatively related to size of the wind farm. This suggests that, for these species, wind-farm effects may occur at a landscape scale. Our findings indicate that the scale and intensity of the displacement effects of wind farms on upland birds depends on bird species' habitat associations and that the observed effects are mediated by changes in land use associated with wind-farm construction. This highlights the importance of construction effects and siting of turbines, tracks, and other infrastructure in understanding the impacts of wind farms on biodiversity.*

Keywords: bird guilds, displacement, habitat modification, land-use change, uplands, wind farms, wind turbines

Efectos del Desarrollo de la Energía Eólica y los Cambios Asociados al Uso de Suelo sobre las Densidades de Aves en Tierras Altas

Resumen: *El desarrollo de la energía eólica es la más reciente de muchas presiones ejercidas sobre las comunidades de aves de tierras altas y sus hábitats. Los estudios sobre aves en relación con el desarrollo de la energía eólica se han enfocado en los efectos de la mortalidad directa, pero la importancia de los efectos indirectos (p. ej.: desplazamiento, pérdida de hábitat) sobre la diversidad y estabilidad de las comunidades aviares cada vez se reconoce más. Usamos un estudio de control-impacto combinado con un diseño de gradiente para evaluar los efectos de los campos eólicos sobre las densidades de aves de tierras altas y sobre las especies de aves agrupadas por asociación de hábitat (especies de bosque y de hábitat abierto). Realizamos 506 censos de conteo por puntos en 12 sitios de campos eólicos y 12 sitios control en Irlanda durante dos temporadas de reproducción (2012 y 2013). Las densidades de aves totales fueron más bajas en los campos eólicos que en los sitios control, con las diferencias más importantes ocurriendo cerca de las turbinas. Las densidades de las especies de bosque fueron significativamente más bajas a 100 m de las turbinas que a distancias mayores y esta diferencia estuvo mediada por modificaciones asociadas con el desarrollo de campos eólicos. De manera particular, las reducciones en la cobertura de bosque adyacente a las turbinas estuvieron vinculadas con la disminución observada en las densidades de las especies de bosque.*

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Article impact statement: *Wind farm effects on birds in upland areas are guild specific and mediated by changes in land use associated with wind farm construction.*

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Las densidades de las especies de hábitat abierto fueron más bajas en los campos eólicos pero no estuvieron relacionadas con la distancia a las turbinas y tuvieron una relación negativa con el tamaño del campo eólico. Lo anterior sugiere que, para estas especies, los efectos del campo eólico pueden ocurrir a la escala de paisaje. Nuestros hallazgos indican que la escala y la intensidad de los efectos de desplazamiento de los campos eólicos sobre las aves de tierras altas dependen de las asociaciones de hábitat de las especies de aves y que los efectos observados están mediados por cambios en el uso de suelo asociados con la construcción de campos eólicos. Esto remarca la importancia de los efectos de construcción y el sitiado de las turbinas, pistas y demás infraestructura en el entendimiento de los impactos que tienen los campos eólicos sobre la biodiversidad.

Palabras Clave: cambio de uso de suelo, campos eólicos, desplazamiento, gremios de aves, modificación de hábitat, tierras altas, turbinas de viento

摘要: 风能的开发是山地鸟类群落面临的许多压力中最近出现的一种。关于鸟类与风能开发有关的研究主要集中于其直接导致鸟类死亡的影响, 但人们也逐渐认识到其对鸟类群落多样性和稳定性的间接影响 (如被迫迁徙、生境丧失) 的重要性。我们用控制-影响研究, 结合梯度设计, 来评估风电场对山地鸟类密度和按生境相关性分类的鸟类物种 (森林和开放生境的物种) 的影响。我们在 *2012* 年和 *2013* 年的两个繁殖季对爱尔兰 *12* 个风电场和 *12* 个对照位点对 *506* 个样点进行计数调查。结果显示, 风电场的鸟类总密度比对照位点低, 且差异最大的位置在涡轮机附近。在涡轮机附近 *100* 米内森林鸟类的密度显著低于离涡轮机更远的位置, 这一差异受到风电场建设相关生境改造的调控。特别是与观察到的森林鸟类密度下降与涡轮机附近森林覆盖的减少有关。风电场开放生境的物种密度也较低, 但这与距离涡轮机的远近无关, 而与风电场的大小呈负相关。这说明风电场对这些物种的影响可能发生在景观尺度上。我们的结果表明, 风电场导致山地鸟类被迫迁徙的影响尺度和强度取决于物种的生境相关性, 观察到的影响是由风电场建设相关的土地利用变化介导的。这强调了涡轮机、轨道和其它基础设施的施工效应及选址对于理解风电场对生物多样性影响的重要性。 **【翻译: 胡怡思; 审校: 聂永刚】**

关键词: 鸟类同资源种团, 被迫迁徙, 生境改造, 土地利用变化, 山地, 风电场, 风力涡轮机

Introduction

In recent decades, development of wind energy has played a key role in efforts to mitigate climate change by reducing carbon emissions while meeting increasing energy demands. It is expected that by 2050, wind energy will provide 20% of global energy requirements (IPCC 2015). Although widely perceived as one of the most environmentally responsible and affordable energy sources, ongoing increases in development of wind energy have led to concerns about its potential environmental impacts (Leung & Yang 2012; Tabassum et al. 2014; Zwart et al. 2016). Large-scale installations can result in habitat loss and degradation, displacement of wildlife, and direct mortality of birds and bats (Kuvlesky et al. 2007; Pearce-Higgins et al. 2009; Northrup & Wittemyer 2013).

In many parts of the world, onshore wind farms are commonly built in areas with high elevation, sparse human populations, and relatively low levels of management and economic productivity. These areas are attractive for wind-energy development because they typically combine high wind yield with few economically competing land uses (Bright et al. 2008; Schuster et al. 2015). However, these upland areas are often also priority conservation areas with important bird assemblages, including generalists, upland specialists, and migratory birds. In Europe many of these bird species are of conservation concern; thus, their populations are sensitive to wind-farm development and expansion (e.g., Bright et al. 2008; Bonn et al. 2009; Wilson et al. 2017). Upland bird communities have been shaped by human activity, in particular habitat loss and degradation related to agricultural improvement, peat extraction, recreation, air pollution, and climate (Fielding & Haworth 1999; Pearce-Higgins et al. 2008). Because development of wind energy has been incentivized by policies aiming to reduce carbon emissions from energy production, its effects on upland birds can be regarded as an indirect consequence of climate change (Evans & Douglas 2014). The scale of wind-farm development in many upland areas has led to a growing demand for information on its potential impacts on birds to guide sustainable development of the wind energy sector (Katzner et al. 2013; Zwart et al. 2016).

Early studies of the effects of wind farms on birds most commonly assessed direct mortality associated with wind turbines (Leung & Yang 2012; Erickson et al. 2014; Smith & Dwyer 2016). Recently, the scope of studies has broadened to include assessments of secondary effects, such as disturbance and displacement, either through habitat loss or species avoidance of habitat (e.g., Pearce-Higgins et al. 2009; Astiaso Garcia et al. 2015; Shaffer & Buhl 2016). Research has also evaluated the impact of wind farms on a variety of bird breeding indices (e.g., Pearce-Higgins et al. 2012; Sansom et al. 2016; Rasran & Mammen 2017). Reviews on the displacement effect of wind farms on birds indicate that the existence and extent of impacts varies considerably across species, land cover, seasons, and geographic regions (e.g., Pearce-Higgins et al. 2009; Shaffer & Buhl 2016; Smith & Dwyer 2016). Despite this variability, the majority of studies have focused on a small number of endangered or charismatic species with already low abundances (e.g., De Lucas et al. 2008; Smith & Dwyer 2016). Although the displacement of key species can ultimately result in a shift in the structure of avian communities (Tabassum et al. 2014), there have been few publications on the impacts of wind farms at a multispecies scale. Furthermore, few studies take into account the interdependent effects of the presence of wind turbines and habitat modification or address ecosystem-level impacts of wind-energy development. Understanding whether, and to what extent, wind turbines affect bird communities as a whole is an essential step toward understanding the effects of wind farms at an ecosystem scale.

We designed an impact-control study to assess bird densities and changes in land use due to construction at a range of large, modern wind farms and paired control sites. By surveying points at a range of distances from turbines, we simultaneously assessed impact-gradient effects. We sought to compare bird densities between areas with and without a wind farm; determine the effects of distance from wind turbines and age and size of a wind farm on total bird densities; assess whether, and how, observed effects are related to changes to species groups with different habitat associations; and assess potential effects of changes in land use due to wind-farm development on total bird densities. Our study is one of the first to combine surveys of multiple wind farms and control sites with an impact-gradient approach to assess the effects of wind-energy development on upland birds in a multispecies context (review of studies in Shaffer and Buhl [2016]).

Methods

Survey Design

We surveyed 6 wind farms and 6 control sites in 2012 and a further 6 of each in 2013, all in upland habitats across Ireland. Irish uplands are characterized by a mosaic of open habitats (e.g., heath, bog, rough and improved grassland, scrub) and closed habitats (commercial forestry plantation and natural forests). To maximize the detection of effects, we selected large, modern wind farms with at least 8 turbines of similar design covering a broad geographical range (2–8 years since construction; 8–35 turbines with individual outputs of 850–2500 kW [Supporting Information]). For each wind-farm site, a control site was selected within 12 km in an area of similar size, habitat composition, and topography but without wind-farm development. The similarity between wind-farm and control-site habitat composition (preconstruction) was assessed by visual inspection of satellite images and topographical maps. To avoid confounding effects of yearly variations in bird densities, each wind farm and its corresponding control site were surveyed during the same breeding season.

At each wind farm, 27 survey points were selected at increasing distances from the nearest turbine (9 survey points within 100 m of turbines, 6 at 100–400 m, 6 at 400–700 m, and 6 at 700–1000 m). To avoid any confounding effects of multiple turbines, points farther than 100 m from individual turbines were selected only outside of the minimum polygon containing all turbine 100-m buffers. Within each distance band, survey points were selected to represent the range of habitats and human-made structures present within that band. All points were at least 200 m from the nearest neighboring point to avoid multiple detections of individual birds.

For each survey point at a wind farm, a matching survey point with similar habitat characteristics and elevation was selected at the corresponding control site. Our aim was to assess the overall effect of wind-farm development, including the presence of turbines and the effect of changes in land use associated with wind-farm construction. For this reason, habitat composition (percent cover, based on aerial photographs) at control points was matched with that of the survey point at the wind farm prior to construction (habitat types: pre-thicket forest, closed canopy, clearfell, grassland, scrub, peatland, or human altered). This was done with the aid of aerial photographs taken prior to wind-farm construction. All pairs of wind farm and control points were selected to contain the same habitat types in as similar percentage cover as possible (±5%). By matching control-point habitats with those of wind-farm points prior to construction we ensured that land-use and habitat changes due to wind-farm development could be assessed. As a result, we expected that habitat differences would be greatest for points located closest to wind farms, where habitats would be most affected by construction. To account for variation in bird densities due to elevation, control survey points were also selected to match the elevation of their corresponding wind-farm point.

Many upland bird species in Ireland are rare and occur at relatively low abundances. Because this could affect the observed trends in total bird densities, we also carried out an analysis of densities of the most common bird species. Because of the configuration of upland habitats in Ireland, the most common bird species are associated with either forest or open habitats. By analyzing densities of forest birds and open-habitat birds, we were able to study the effects of land-use changes associated with wind farms on bird groups linked to specific habitats.

Bird and Habitat Surveys

Breeding birds were surveyed using the point-count method following Bibby et al. (2000). Surveys were conducted on days without persistent rain or strong wind (<20 km/hour) during the breeding seasons (April to

June) and in the mornings (from 1 hour after dawn until noon). Each point was visited once for 5 minutes, during which time all birds detected by sight or sound within a 100-m radius were recorded and their distance from the observer noted. All data collection was carried out under license issued by the National Parks & Wildlife Service in Ireland in accordance with the Wildlife Act 1976. Flying birds were excluded from the data analysis unless they were actively foraging or singing. Distance estimates were made by experienced observers aided by scaled aerial photos. Because time of day or season can affect bird densities, point-count pairs (wind farm and control) were surveyed in succession. If this was not possible, they were visited within the next 2 days at the same time of day and under similar weather conditions. Distance software version 5.0 (Thomas et al. 2010) was used to derive species densities from field observations. For further details on survey methods and density estimate calculations, see Supporting Information.

Survey-point bird densities were calculated for individual species and summed to calculate total bird densities. Using information on avian ecology and habitat associations in Ireland (Nairn & O'Halloran 2012), we also classified the most commonly occurring species in our study as either forest species or open-habitat species. Forest species included Great Tit (*Parus major*), Coal Tit (*Periparus ater*), Chaffinch (*Fringilla coelebs*), and Goldcrest (*Regulus regulus*). Open-habitat species included Meadow Pipit (*Anthus pratensis*), Skylark (*Alauda arvensis*), and Wheatear (*Oenanthe oenanthe*).

Once the bird survey at each point was completed, habitats within the 100-m survey radius were categorized as pre-thicket forest, closed canopy, clearfell, grassland, scrub, peatland, or human altered (e.g., bare ground, buildings, tracks providing access for forestry operations or wind farms). Percent cover of habitats, point-count elevation, and distance from nearest wind turbine were calculated using ArcGIS 10 software (Environmental Science Research Institute, Redlands, California).

Of the 648 designated point counts, it was not possible to carry out surveys at 71 points due to land-access constraints. To maintain the paired design, their corresponding survey-point pairs were also excluded from analysis. This resulted in analysis of 506 survey points (253 points at wind farms, 253 points at control sites). The final distribution of wind-farm points was 68 within 100 m of the nearest turbine; 70 from 100 to 400 m; 56 from 400 to 700 m; and 59 from 700 to 1000 m.

Data Analyses

To assess how different factors affected bird densities, we used generalized linear mixed models (GLMMs) with a Gaussian distribution and identity link functions (Zuur et al. 2013). We followed a 3-step process to test the effects of wind-energy development on bird densities. First, we built a base model explaining total bird densities (i.e., density of all species combined) based on environmental factors (percent cover of each habitat type and elevation in meters) and retaining only significant variables (model A). We then added a categorical variable with 2 levels (wind farm or control) to this model to test the effect of wind-farm development on total bird densities (model B). Finally, we used a subset of data from wind-farm sites only to test the effects of distance to turbine (meters), age of wind farm (years), and size (number of turbines as a proxy for size) on total bird densities, on forest bird densities, and on open-habitat bird densities (models C). Thus, models A and B included data from all survey points ($n = 506$), whereas model C included data from wind-farm survey points only ($n = 253$). To control for site-specific patterns, we included site as a random factor in all models (factor with 12 levels, 1 for each wind-farm and control-site pair). To control for non-independence of survey-point pairs, pair was included as a random effect nested within site for models A and B. Spearman correlation coefficients were calculated for all variable pairs. All variables included in analyses had values of $|r| < 0.5$.

Preliminary analysis revealed that the effects of wind farms on habitat were greatest closest to wind turbines. Therefore, to further analyze the spatial nature of any effects, we calculated total, forest, and open-habitat bird densities at wind-farm points at increasing distance bands from turbines (0–100 m, 100–400 m, 400–700 m, and 700–1000 m) and compared them with the densities of their matching control points with Wilcoxon signed-rank tests. To detect differences in habitats between matched points that could be attributed to wind-farm development (habitats at control points were matched to those at wind-farm points prior to construction), we performed similar analyses comparing percentage of each habitat type between wind-farm points and their matched control points for each of the distance bands. All statistical analyses were performed using R version 3.4.3 (www.r-project.org). The GLMM analyses were performed with R packages lme4 and nlme.

Results

Fifty-six bird species and 3715 individual birds were recorded. Thirty-six percent of the species recorded ($n = 20$) are of conservation concern in Ireland at present (Colhoun & Cummins 2013). Mean densities across all sites were 2.99 birds/ha, with 0.99 forest birds/ha and 0.47 open-habitat birds/ha. At wind farms, mean densities were 2.80 birds/ha, 0.93 forest birds/ha, and 0.41 open-habitat birds/ha. At control sites, mean densities were 3.19 birds/ha, 1.04 forest birds/ha, and 0.52 open-habitat birds/ha. For a list of species recorded, their conservation statuses, and densities see Supporting Information.

Table 1. Summary of environmental effects on total bird densities at wind-farm and control sites (model A).*

Factor	*Estimate (SE)*	t	p
Intercept	5.677 (0.552)	10.29	<0.001
Closed canopy	0.024 (0.003)	7.08	<0.001
Pre-thicket	0.009 (0.004)	2.46	0.012
Peatland	−0.012 (0.003)	−4.01	<0.001
Elevation	−0.010 (0.001)	−5.74	<0.001

**Predicted total bird densities (birds/ha) at individual point counts (n= 506) at 12 wind farm and 12 control sites modeled as a function of environmental factors (land-cover type and elevation). Point-count pair nested within site was included as a random factor.*

Table 2. Summary of effects of wind-farm development on total bird densities at wind farm and control sites (model B).*

Factor	*Estimate (SE)*	t	p
Intercept	5.822 (0.555)	10.50	<0.001
Closed canopy	0.024 (0.003)	6.84	<0.001
Pre-thicket	0.008 (0.004)	2.25	0.024
Peatland	−0.012 (0.003)	−4.20	<0.001
Elevation	−0.010 (0.002)	−5.62	<0.001
Wind farm present	−0.313 (0.148)	−2.11	0.035

**Predicted bird densities (birds/ha) at individual point counts (n = 506) at 12 wind farm and 12 control sites modeled as a function of different land-cover types (percent), elevation (meters), and presence or absence of wind farms. Point-count pair nested within site was included as a random factor.*

Bird densities at all survey points (wind farm and matching control) were influenced by different habitat covers and elevation (model A, Table 1). However, point counts at wind farm sites showed significantly lower bird densities than point counts at control sites (model B, Table 2).

Tests of characteristics specific to wind farms revealed different effects on total, forest, and open-habitat bird densities (C models, Table 3). Distance to turbine was significantly and positively related to total bird densities, indicating an increase in densities at increasing distances from turbines. Densities of forest birds showed a similar significant positive effect of distance to turbine. However, for open-habitat birds, only size of the wind farm was significant; large wind farms held lower densities of open-habitat birds.

Differences in total bird densities were greatest for paired wind-farm and control points that were closest to wind turbines (Fig. 1a). When assessed by distance bands, these differences were significant between wind-farm points within 100 m of turbines and their paired control points ($z = 1043.5, p < 0.001$) (Fig. 1b) but not for other distance bands. Densities of forest birds were significantly lower at wind-farm points within 100 m of wind turbines than at matching control points ($z = 553.5$, $p = 0.009$) (Fig. 1c) but not for other distance bands. Densities of open-habitat bird species were significantly lower at wind-farm sites than control sites ($z = 2910.0$, $p = 0.008$), but this difference was not significant for any specific distance band (Fig. 1d).

Comparison of habitat composition at wind-farm and control points highlighted significant differences for 3 habitat types attributed to construction effects: human-altered (bare ground, tracks, and buildings), clearfelled forest, and closed canopy forest (Fig. 2). Human-altered habitats occurred more frequently at wind-farm points ($z = 4126.0$, $p < 0.001$) (Fig. 2a); differences were significant up to 700 m from turbines. Likewise, clearfelled forest occurred more frequently at wind-farm points ($z = 492.0$, $p = 0.039$) (Fig. 2b); differences were significant within 100 m from turbines. Closed canopy forest was less abundant at wind-farm points within 100 m of turbines than at their corresponding control points ($z = 636.5, p = 0.020$) (Fig. 2c).

Discussion

Total bird densities were lower at wind-farm sites than at control sites without wind-farm development. Because wind farms were generally located at high elevations, elevation decreased and bird densities increased at points farther from turbines and at matched control points (positive slope of both lines in Fig. 1a). However, bird densities close to wind turbines were lower than at matching control points, and we recorded a higher rate of elevation-related increase at wind-farm than at control sites (lower y-intercept and steeper slope of wind-farm average density represented by the dark grey line in Fig. 1a). This indicates a gradient effect of wind farms on bird densities. Maximum differences in bird densities were recorded between wind-farm points within 100 m of turbines and their corresponding control point pairs (Fig. 1b). These findings are consistent with other studies showing the displacement of birds in areas within a few hundred meters of turbines (Pearce-Higgins et al. 2009; Stevens et al. 2013; Sansom et al. 2016; Shaffer & Buhl 2016). The magnitude of these displacement effects are shown by model estimate values indicating that total bird densities were 0.313 birds/ha (SE 0.148) lower at wind farms than control sites (Table 2). At wind-farm sites, total densities increased by 0.001 birds/ha/m (SE 0.000) (or 1.3 birds/ha/km [SE 0.4]) from a wind turbine (Table 3). Although these values may seem low, in the context of upland bird densities (e.g., mean of 2.99 birds/ha in our study) changes of 0.3–1.3 birds/ha can have important effects at both bird species population and community scales.

Densities of forest species were lower at wind farms than at control sites; distance to turbine significantly explained this observed difference. Specifically, points within 100 m of wind turbines had significantly lower densities of forest species than paired control points. In contrast, densities of open-habitat species were lower

Table 3. Summary of effects of wind-farm development on total, forest, and open-habitat bird densities at wind-farm sites (models C).*

Response variable	*Factor*	*Estimate (SE)*	z	p
Total species density (birds/ha)	intercept	4.966 (0.988)	5.03	0.002
	closed canopy	0.022 (0.004)	5.31	<0.001
	peatland	−0.015 (0.003)	−4.73	<0.001
	elevation	−0.007 (0.003)	−2.72	0.006
	distance	0.001 (0.000)	3.26	0.001
	age	−0.035 (0.084)	−0.41	0.681
	size	−0.014 (0.012)	−1.14	0.254
Forest species density (birds/ha)	intercept	0.770 (0.201)	3.83	<0.001
	closed canopy	0.018 (0.003)	7.00	<0.001
	peatland	−0.006 (0.002)	−2.94	0.003
	distance	0.001 (0.000)	3.33	0.001
	age	−0.030 (0.030)	−1.01	0.315
	size	−0.005 (0.004)	−1.25	0.213
Open-habitat species density (birds/ha)	intercept	−0.324 (0.272)	−1.19	0.234
	closed canopy	−0.003 (0.002)	−2.03	0.043
	grassland	0.005 (0.001)	3.78	<0.001
	peatland	0.007 (0.001)	5.51	<0.001
	elevation	0.002 (0.001)	2.61	0.009
	distance	0.001 (0.000)	0.91	0.365
	age	0.010 (0.016)	0.55	0.581
	size	−0.007 (0.002)	−3.11	0.002

Predicted total, forest, and open-habitat bird densities (birds/ha) at individual point counts (n = 253) at 12 wind farms modeled as a function of different land-cover types (percent), elevation (meters), distance to turbine (meters), and age (years) and size of wind farm (number of turbines). Site was included as a random factor.

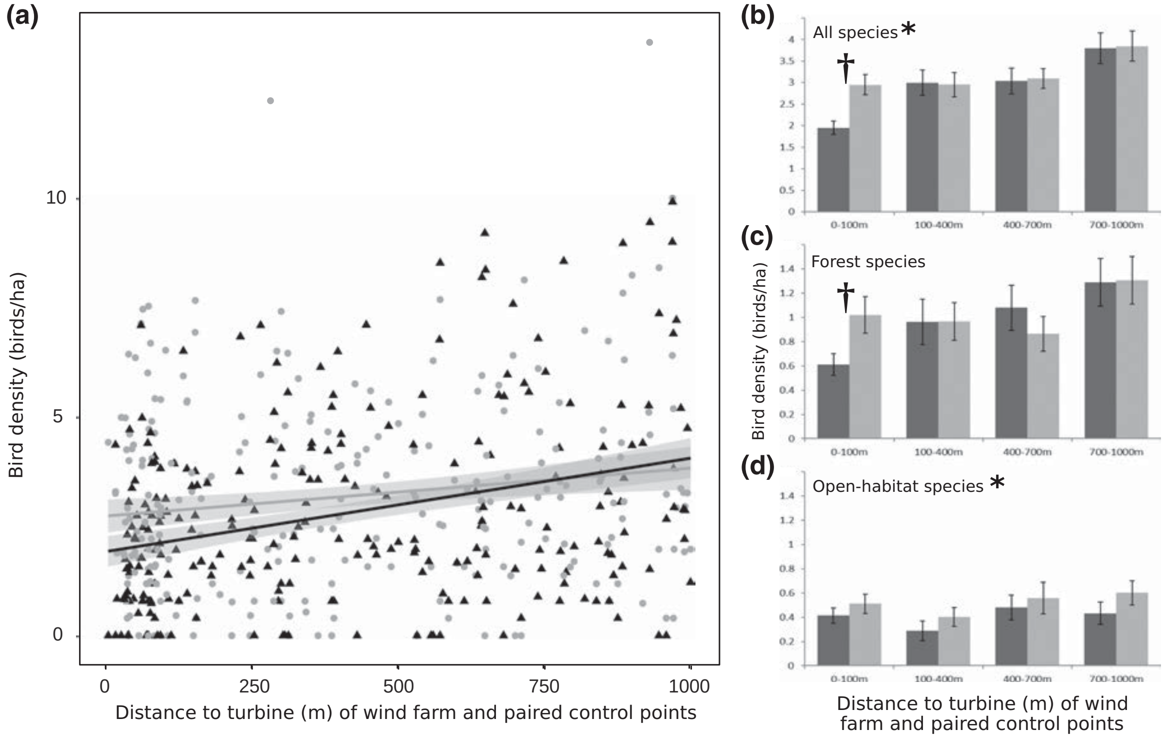

Figure 1. Bird densities recorded at 506 point counts at 12 wind farms (black) and 12 control sites (grey) in 2012 and 2013: (a) total bird densities at wind-farm point counts (triangles) and control point counts (circles) (lines, means; shading, 95% CI); (b) mean (SE) total bird densities in each distance band; (c) mean (SE) densities of forest bird species in each distance band; (d) mean (SE) density of open-habitat bird species in each distance band. Control point values are represented at the distance of their corresponding wind farm point pair (, statistical significance for that group independent of distance; †, statistical significance for that distance band).*

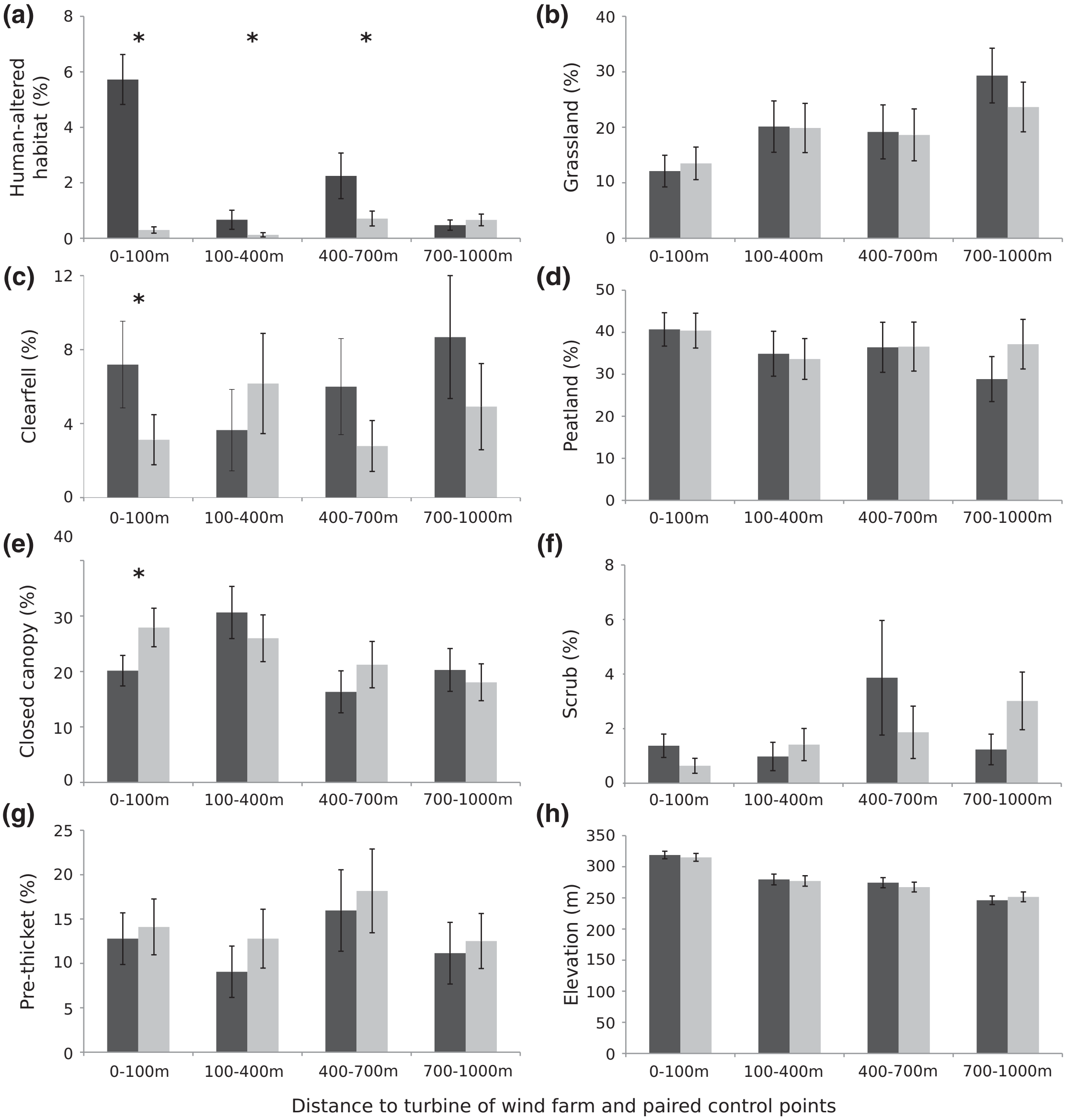

Figure 2. Mean (SE) (a–g) cover of different land-cover types and (h) elevations at wind farms (dark grey) and control sites (light grey) where bird point counts were conducted (, p < 0.05; values on x-axes differ). Control point values are represented at the distance of their corresponding wind-farm point pair.*

at wind farms independent of distance to turbines, although size of the wind farm was negatively related to their densities. These findings indicate a variation in the intensity and scale of the effects of wind-farm development that depends on the ecological association of bird species. Previous research suggests that sensitivity to displacement by wind turbines may be related to species' characteristics, such as their social behavior and habitat use (Stevens et al. 2013; Schuster et al. 2015).

Habitat changes resulting from wind-farm development may help explain the different responses of forest and open-habitat species. Because control survey points were selected to match the habitat and elevation of wind-farm points prior to wind-farm construction (Fig. 2), differences in habitat composition can be attributed to wind-farm construction. Wind-farm points close to turbines had proportionally less closed canopy cover and relatively more clearfell forest and human-altered habitats (bare ground, tracks, and buildings) than did matching control points. Ground clearing and clear felling are often undertaken to make space for wind-farm infrastructure or to maximize wind load (Nayak et al. 2010), whereas access roads increase the area of bare ground. These changes in land use had a net effect of decreasing natural habitat cover at wind farms. In our study, these changes particularly affected closed-canopy habitats, resulted in reductions of habitat for forest bird species, and ultimately led to lower recorded densities. Similar patterns have been observed in response to development of shale gas in forested areas, where changes in land use affect mature forest birds but not birds associated with early successional or disturbed habitats (Farwell et al. 2016). These patterns highlight the importance of planning the precise location of turbines, roads, and other infrastructure in determining which habitats and thus species will be affected by wind-energy development. Presence of wind turbines could also affect bird densities through blade noise, visual disturbance, increased predation risk, or human activity around these structures (Drewitt & Langston 2006; Helldin et al. 2012). Although our findings suggest that changes in land use played an important role, it is possible that these other indirect effects may have contributed to decreased forest bird densities.

Densities of open-habitat birds followed a different pattern from that of forest species. The lack of an apparent gradient in densities at increasing distance from turbines (Fig. 1d) could be explained if either the spatial scale of our study was insufficient (i.e., impact gradients occurred beyond 1000 m from turbines) or if these effects were occurring at a landscape scale. However, typical territory sizes of the open-habitat species are within this scale (Cramp 1988), and for forest species we detected gradient effects within 100 m of turbines. Therefore, it seems unlikely that our study scale was inappropriate, which suggests that for open-habitat birds, effects were operating at a landscape scale. Although there were no differences in extent of open habitat between wind-farm and control survey points (Fig. 2b, d), we did not assess the extent of these habitats in the wider landscape or their quality (e.g., plant species composition, vegetation height). Wind farms are typically located in areas of relatively low value for nature or where access is easy, which may in turn be associated with differences in habitat quality, land use, or habitat management. These, or other differences at a landscape scale that are indirectly linked to presence of wind farms, may play a role in determining bird densities (Lachance et al. 2005). Furthermore, the susceptibility of different species to disturbances (e.g., human activity, movement of turbine blades) may also determine the scale of the effect.

Previous research shows that the extent of wind-farm impacts on bird populations varies considerably across species and regions (Farfán et al. 2009; Pearce-Higgins et al. 2009; Sansom et al. 2016). Where reduced bird abundance at wind farms has been reported, this has generally been confined to areas close to turbines and has not extended into the wider landscape (Leddy et al. 1999; Drewitt & Langston 2006; Pearce-Higgins et al. 2009). Other studies report effects of wind farms specific to certain habitats or to their structure (Hale et al. 2014; Shaffer & Buhl 2016). However, these studies are typically restricted to a small number of species or wind farms, often with limited sample sizes, and efforts to assess impacts on multiple bird species across multiple sites have relied largely on meta-analyses or reviews (Drewitt & Langston 2006; Madders & Whitfield 2006).

Despite the large body of work on best practice for the assessment of effects of wind-energy development on wildlife in general, and birds in particular (Strickland et al. 2007; Astiaso Garcia et al. 2015; Schuster et al. 2015), few studies combine different assessment designs (i.e., before-after, control-impact, impact-gradient approaches) or cover multiple bird species, wind farms, or years (Shaffer & Buhl 2016). Our approach allowed us to compare areas with wind-farm development with control areas of similar environmental characteristics and avoid confounding temporal effects associated with before-after designs (Strickland et al. 2007). By combining this paired control-impact design with an impact-gradient approach, it was possible to evaluate the effects of wind turbine presence and changes in land use while maximizing our ability to detect displacement gradients (NRC 2007). Surveys of breeding birds targeting multiple species allowed detection of nonlethal effects on overall bird densities, as well as of differential effects dependent on species habitat associations.

Ours is one of the first studies to highlight differences in nonlethal effects of wind farms on different bird groups in relation to their ecological association and to demonstrate how the spatial scale of this response may be specific to each group (Pearce-Higgins et al. 2009, 2012). These findings are particularly relevant for planners and policy makers. The differential response of bird guilds reported here suggests that it is possible to locate wind farms and to plan changes in land use in accordance with conservation interests. Depending on regional conservation priorities, it may be possible to locate wind-farm infrastructure such that habitat changes will affect species and habitats of lower conservation concern or even benefit those in need of conservation action. Furthermore, consideration must be given to the ecological role of these habitats and species from a wider ecological perspective. Many of the birds recorded in our study are important prey for key flagship species such as Hen Harrier (*Circus cyaneus*), Merlin (*Falco columbarius*), or Short-eared Owl (*Asio flammeus*), predators that are the focus of considerable conservation effort (Glue 1977; Fernández-Bellon & Lusby 2011; Watson 2013). As such, understanding the effects of wind farms on prey populations and how this may influence these species' foraging habits near wind turbines is essential for their effective management and conservation.

Our study highlights the relevance of assessing the effects of wind farms or other developments on ecological communities or ecosystems as a whole, rather than solely on individual species. Further research into wind-farm impacts on birds should look beyond the effects of turbine presence and take into consideration effects of construction, associated infrastructure, and changes in land use and habitat composition. Similarly, wind-farm planners should consider these potential effects by taking into account not only the precise location of wind turbines, but also that of associated infrastructure (e.g., roads, buildings) and how changes in land use may affect wildlife. Understanding the ways in which land-use changes impact upland ecology is particularly important in the context of continued growth in wind-energy development in combination with other pressures such as afforestation, agricultural intensification, and climate change.

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Supporting Information

Details on site locations (Appendix S1), survey methods and density calculations (Appendix S2), and bird species recorded and their conservation status and densities (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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EXHIBIT

11

Conservation Biology

Contributed Paper

Changes in bird-migration patterns associated with human-induced mortality

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Abstract: *Many bird populations have recently changed their migratory behavior in response to alterations of the environment. We collected data over 16 years on male Great Bustards (*Otis tarda*), a species showing a partial migratory pattern (sedentary and migratory birds coexisting in the same breeding groups). We conducted population counts and radio tracked 180 individuals to examine differences in survival rates between migratory and sedentary individuals and evaluate possible effects of these differences on the migratory pattern of the population. Overall, 65% of individuals migrated and 35% did not. The average distance between breeding and postbreeding areas of migrant individuals was 89.9 km, and the longest average movement of sedentary males was 3.8 km. Breeding group and migration distance had no effect on survival. However, mortality of migrants was 2.4 to 3.5 times higher than mortality of sedentary birds. For marked males, collision with power lines was the main cause of death from unnatural causes (37.6% of all deaths), and migratory birds died in collisions with power lines more frequently than sedentary birds (21.3% vs 6.3%). The percentage of sedentary individuals increased from 17% in 1997 to 45% in 2012. These results were consistent with data collected from radio-tracked individuals: The proportion of migratory individuals decreased from 86% in 1997–1999 to 44% in 2006–2010. The observed decrease in the migratory tendency was not related to climatic changes (temperatures did not change over the study period) or improvements in habitat quality (dry cereal farmland area decreased in the main study area). Our findings suggest that human-induced mortality during migration may be an important factor shaping the migration patterns of species inhabiting humanized landscapes.*

Keywords: differential survival, Great Bustard, long-term monitoring, migration changes, migration costs

Cambios en los Patrones de Migración de Aves Asociados con Mortalidad Inducida por Humanos

Resumen: *El comportamiento migratorio de muchas poblaciones de aves ha cambiado recientemente como consecuencia de las alteraciones ambientales. Durante 16 años estudiamos la conducta migratoria de machos de Avutarda Común Otis tarda, un ave con un patrón de migración parcial (individuos sedentarios y migradores coexisten en los mismos grupos). Realizamos censos de población y seguimos a 180 individuos marcados con emisores de radio para examinar las diferencias en las tasas de supervivencia entre los machos migradores y los sedentarios; y evaluar los posibles efectos de estas diferencias sobre el patrón migratorio de la población. Globalmente, el 65% de los individuos fueron migradores y el 35% sedentarios. La distancia media entre las áreas de reproducción y las post-reproductivas de los migradores fue de 89.9 km y la de los sedentarios de 3.8 km. Ni el grupo reproductor ni la distancia de migración tuvieron efectos sobre la supervivencia. Sin embargo, los individuos migradores tuvieron entre 2.4 y 3.5 veces mayor riesgo de mortalidad que los sedentarios. La colisión con líneas eléctricas fue la principal causa de mortalidad de los machos marcados (37.6% de todas las muertes), y los migradores murieron por colisión con líneas eléctricas con mayor frecuencia que los sedentarios (21.3% versus 6.3%). El porcentaje de individuos sedentarios aumentó desde el 17% en 1997 al 45% en 2012. Estos resultados fueron confirmados por los datos procedentes de individuos marcados: la proporción de migradores disminuyó desde el 86% en 1997–1999 al 44% en 2006–2010. La disminución de la*

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tendencia migratoria no estuvo relacionada con cambios climáticos (las temperaturas no cambiaron durante el periodo de estudio) o con mejoras de la calidad del hábitat (la superficie de cultivos de cereal disminuyó en el área de estudio principal). Nuestros hallazgos sugieren que la mortalidad durante la migración provocada por las actividades humanas puede ser un factor muy importante en el desarrollo de los patrones de migración de las especies que viven en ambientes humanizados.

Palabras Clave: cambios en la migración, costes de migración, *Otis tarda*, seguimiento a largo plazo, supervivencia diferencial

Introduction

The migratory behavior of many bird species has changed in the last decades. The most frequently observed changes are related to timing of migration and migration distance traveled, both of which are usually explained by climate changes (Newton 2008; Møller et al. 2010). However, little is known about other causes of changes in migration, particularly for species inhabiting human-modified environments. Developed landscapes are characterized by dense networks of railways, motorways, electric power lines, and wind turbines. These infrastructures represent an important risk of mortality for many animals. For example, collisions with aerial cables and electrocution at dangerous pylons are major causes of casualties among birds (Loss et al. 2015). That some of the most spectacular migrations have decreased or disappeared due to human activities has led some to believe that animal migration is an endangered phenomenon that could eventually disappear (Wilcove & Wikelski 2008; Harris et al. 2009).

Mortality is frequently high during migration relative to the breeding and wintering periods; therefore, bird migration may have a large impact on annual survival and population dynamics of migratory species (Newton 2008; Strandberg et al. 2010; Klaassen et al. 2014). Mortality during migration has been associated with natural causes such as bad weather, predation, and poor feeding conditions at stopover sites and with human-induced causes such as habitat destruction or overexploitation, climate change, and human-made obstacles, all of which have been identified as major threats to migrating animals (Newton 2008; Wilcove & Wikelski 2008). Some migrants have lower survival than residents (Adriaensen & Dhondt 1990; Hebblewhite & Merrill 2011), but the question of how events during migration can affect the costs of bird migration is usually not addressed because it is difficult to sample casualties along migration routes (Knudsen et al. 2011).

Given the prevalence of partial migration among many migratory species, several authors highlight that little attention has been paid to how partial migrants respond to environmental changes. These authors recommend the use of long-term data sets to provide new insights (Chapman et al. 2011). Radio tracking large samples of individuals is the best way to determine whether mortality occurred in the nonbreeding areas or during migration, but these data are hard to obtain. Few studies have examined the specific effects of anthropogenic structures on displacement behavior and survival; thus, there is the need to investigate how human activities can affect migration in order to propose how to prevent declines of threatened migrants (Hovick et al. 2014; Klaassen et al. 2014; Sergio et al. 2014).

We investigated how anthropogenic mortality can influence the migratory pattern of a partial migrant. Using Great Bustards (*Otis tarda*) as a model species, we analyzed survival data of a large sample of radio-tracked individuals across multiple migratory annual cycles and long-term surveys of the study population.

The Great Bustard is a globally threatened species that survives in highly fragmented populations, mainly in dry cereal farmland across the Palaearctic, from the Iberian Peninsula to eastern China (Palacín & Alonso 2008; IUCN 2015). The migratory patterns of this species vary: partial and sexually differential in southern Europe (Palacín et al. 2009), facultative in central Europe (Streich et al. 2006), and obligate in the northernmost populations in Russia and Mongolia (Watzke 2007; Kessler et al. 2013). In Spain, Great Bustards are partial migrants; sedentary and migratory birds coexist in the same breeding groups. Migration pattern also differs by sex: many females migrate in autumn to extensive farmlands in the south, whereas males migrate northward in summer to areas where temperatures are lower than at breeding sites (Alonso et al. 2009*b*; Palacín et al. 2009, 2012). Males from the hottest, southernmost regions in Spain have a greater tendency to migrate and migrate longer distances northward. This phenomenon strongly suggests that males migrate to escape summer heat and thus that male partial migration depends on environmental factors (Alonso et al. 2009*b*). Furthermore, previous studies show that males fix their migratory pattern in their first 3 years of life, depending on whether the flock of adult males they integrated in is migratory. In this phase, each immature Great Bustard can change its migratory behavior between years. The decision to migrate is regulated by a complex combination of factors, but social learning plays an important role (Palacín et al. 2011). Although it is commonly accepted that a combination of environmental and genetic factors underlies partial migration (Newton 2008; Chapman et al. 2011; Pulido 2011), recent studies show that in long-lived species social learning is more important than genetic inheritance in modulating several aspects of migration (Hebblewhite & Merrill 2011; Jonker et al. 2013; Mueller et al. 2013). Great Bustards are long lived, and social transmission contributes greatly to the migratory tendency of young and immature individuals (Palacín et al. 2011).

We hypothesized that a human-induced increase in mortality during migration alters the partial migration pattern of a species. Theoretical studies propose that demographic factors can determine a shift between migratory and resident strategies (Taylor & Norris 2007). Moreover, migration mortality and specifically high mortality of migration leaders can lead to the collapse of the migratory fraction of the population (Fagan et al. 2012). However, empirical studies of these predictions are few. Therefore, we analyzed the difference in survival rates between migrant and sedentary individuals, sought to identify the causes of mortality during migration, and examined the effects of mortality on the migratory tendency of this species.

Methods

Study Area

We captured and radio tagged adult male Great Bustards in 29 breeding groups over most of the species' distribution in the Iberian Peninsula (Fig. 1). We defined a breeding group as an aggregation of males and females in a specific area for the purpose of reproduction. As a general rule, both sexes remain faithful to their breeding group throughout their lives. We marked young males and carried out censuses at 20 intensively studied breeding groups in our main study area in central Spain. This held approximately 1600 Great Bustards, of which about 1100 occurred in the special protection area for birds *Estepas Cerealistas de los Ríos Jarama y Henares* (SPA 139) (European Natura 2000 Network; 40°45'N 3° 30'W, 331 km^2, 792 m a.s.l.). In this region, cultivation of dry cereal farmland is extensive and the climate is Mediterranean semiarid.

Capture and Monitoring

We analyzed the survival probabilities of Great Bustards in 107 adult males captured and radio tagged when they were >3 years old and 73 immature males captured and radio tagged as young birds. This sample was composed of individuals >1 year old because it is after 1 year that males decide whether to migrate or not.

We captured adult males during the winters of 1991–2004 with rocket nets and young males in July 1995–2011, when they were 1–3 months old and still dependent on their mothers. Each bird was fitted with a backpack radio transmitter (Biotrack,Warehan, Uk, TW3, powered by 2 for young or 3 for adults AA batteries). The harness was an elastic band. The total weight of transmitter plus harness did not exceed 3% of the bird's weight. Birds were provided with polyvinyl chloride tags to aid visual identification in the field (dorsal tags glued to the transmitters in adult birds and wing tags in juveniles) and location of marked birds after transmitter batteries expired (battery life was up to 6 years in 2-battery units and up to 8 years in 3-battery units). We did not observe plumage damage or behavioral changes in the birds as a result of marking.

We located all radio-tagged individuals through triangulation and subsequent visual observation with telescopes at least once per month but more often several times per month (total 8622 tracking locations). Locations were recorded using a GPS (Garmin 12, Olathe, Kansas) on topographical maps (maximum error 100 m). When a marked bird could not be located from the ground, we searched from the air in an aeroplane (E-24 Bonanza, Beechcraft, Wichita, Kansas) for its signal and later went by car to observe the bird. Aerial tracking allowed us to obtain breeding and postbreeding locations of all marked birds and to avoid the bias derived from emigration outside the study area.

We considered individual migrants when they performed a regular seasonal movement between separate breeding and summering areas (Newton 2008). Migration distance was defined as the maximum distance between separate breeding and summering areas.

We recovered transmitters from dead bustards and estimated their mortality date based on the degree of decomposition of the carcass and our own experience from previous casualties with known death dates. In the few cases, when we found only feathers, bones, or just the transmitter, we considered the date of death the mean between the last time the bird was seen alive and the date when the remains were found. To determine the cause of mortality, we used criteria similar to those described in Martín et al. (2007) and Wolfe et al. (2007) (i.e., the presence of scavenger or predator tracks or other mortality hazards such as power lines or fences in the surrounding area).

Bird Censuses

We carried out censuses of Great Bustards in our main study area in central Spain (Fig. 1). Due to the large size of Great Bustards and to the sparse vegetation in their habitat, reliable censuses (absolute abundance counts) can be conducted that require no correction for detectability (Gregory et al. 2004). Each census was conducted by 2–3 teams. Each team consisted of 2 observers with extensive experience in counting Great Bustards. Teams followed preestablished routes in 4 × 4 vehicles traveling at low speed and stopped frequently to scan for birds with

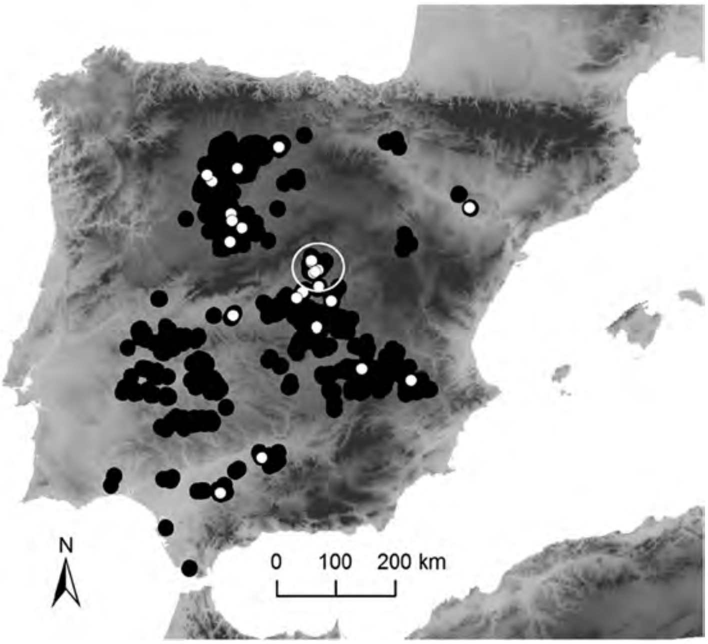

Figure 1. Distribution of Great Bustard breeding groups in Spain (black dots, Alonso et al. 2012); locations of sites where adult males were captured and marked at their breeding areas (white dots); and the location of our main study area (white circle), where population counts and intensive radio tracking were carried out from 1997 to 2012.

binoculars and telescopes (20–60 x). All Great Bustard flocks were mapped on 1:25,000 or 1:50,000 maps. To avoid double counts, teams surveying adjacent areas were in contact via radio. Over 16 years, all censuses were conducted by the same observers using identical methods, which minimized observer biases in the population-trend analyses.

Each year, we carried out at least 2 censuses. The first was in late March (spring), when birds gather at leks, to count breeding individuals. The second was in mid-September to determine their abundance in summer before the first arrivals of migratory individuals occur. In our main study area in central Spain, the first returns of migratory males occur in October, slightly later than the first returns for all of Spain (Fig. 2). Great Bustards show a strong site fidelity to postbreeding areas (94% for males [Palacín et al. 2009]). Thus, annual series of censuses at the same postbreeding areas may adequately represent the tendency of local populations. These counts, together with long-term radio-tracking data obtained from over 600 individuals over 20 years, provided a large data set relative to the dynamics of this metapopulation.

Temperature and Habitat Changes

The average July temperature was used as an indicator of a possible warming trend from 1994 to 2012. We selected July because it is the hottest month of the year in Spain, and summer temperature is the main triggering factor in male summer migration (Alonso et al. 2009*b*). The average temperature for central Spain was obtained from the Spanish Meteorological Agency (AEMET 2013). We measured land-use change during 1990–2000 and 2000–2006 with CORINE Land Cover Changes (EEA 2013) and ArcGis 10 (ESRI 2010).

Statistical Analyses

The Kaplan–Meier method and the log-rank test were used to estimate and compare survival probabilities (Kleinbaum & Klein 2005). The Kaplan–Meier estimator is based on observed data taken on a series of occasions, where animals are marked and released only at occasion 1 and the fate of a marked individual is known with certainty. Fates of individuals were binary coded (1, dead; 0, alive or censored [i.e., lost due to radio failure or other causes]). Binary coding is possible when individuals are radio tagged and the status of all tagged animals is determined at each sampling occasion. Thus, the precision of this method is quite high (Cooch & White 2012). To examine the relationship of migratory pattern, migration distance, and population to survival time, we used a Cox proportional hazard model (Kleinbaum & Klein 2005).

Statistical analyses were performed with SPSS Statistics 19 (IBM Company,Chicago, Illinois, [IBM 2010]). To estimate the annual survival of radio-tagged birds, we used the known-fate model included in MARK (Cooch & White 2012), which is appropriate for data derived from radio-tracking studies in which resighting probability is assumed to be 1. We used the month of marking as a starting date to estimate annual survival (adults were captured in January–February and young birds in July). The logit-link function was used throughout the modeling procedure, and likelihood ratio tests (LRTs) were used to compare different models (Lebreton et al. 1992). Population trends of males in central Spain were calculated using

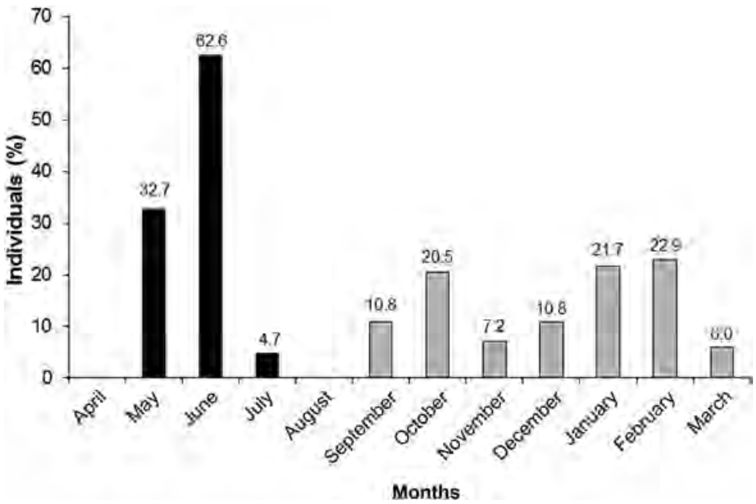

Figure 2. Migration phenology of migrant Great Bustard males (black bars, outward migration, n = *107; gray bars, return migration,* n = *84). Numbers above bars are percentages of migrant individuals.*

TRIM (trends and indices for monitoring data [Pannekoek & van Strien 2001]), which is specifically designed to fit log-linear Poisson regression models to wildlife census data. To test whether breeding and summering population trends differed, we used a model with seasonal effect and a linear effect of time. Nonparametric Spearman's rank correlation tests were used to determine whether the average July temperature in central Spain showed significant trends throughout the study period.

Results

Migratory Pattern and Survival

All breeding groups showed a partial migration pattern. Overall, 117 (65%) of the 180 marked males were migrants and 63 (35%) were sedentary. Migrant males traveled an average of 89.9 km (SD 60.7) between breeding and postbreeding areas (maximum distance 261 km). Sedentary males stayed at the breeding areas all year round and did not perform regular seasonal movements. Their longest movements averaged 3.8 km (SD 3.5). The bulk of outward migration occurred in May and June once mating was over (Fig. 2). The return migration to the breeding areas took place over a longer period, from September to March (Fig. 2).

The survival of adult males did not differ between breeding groups or with migration distance (Table 1). However, mortality of migrants was significantly higher than that of sedentary birds (2.4 higher mortality risk; Cox proportional hazard model, $p < 0.05$) (Table 1). The survival period after being marked was shorter in migrants than in sedentary males (respectively, mean 45.2 months [SD = 4.0], $n = 67$ individuals and mean 63.9 months [SD 3.9], $n = 40$ individuals; log-rank test, $p = 0.001$) (Fig. 3). The estimated annual survival (*S*) was higher in sedentary than in migrant males (respectively, $S = 0.9344$ [SE 0.0182] and $S = 0.8237$ [SE 0.0252]; LRT, $p < 0.001$).

In the sample of males marked as young birds, sedentary males also survived for a longer period than migratory males (respectively, mean 134.7 months [SD 12.0], $n = 23$ individuals and mean 90.6 months [SD 11.9], $n = 50$ individuals; log-rank test, $p = 0.01$). In this sample, migrant males also had higher mortality rates (3.4 higher mortality risk; Cox proportional hazard model, $p = 0.015$), and lower estimated annual survival rates than sedentary males (respectively, $S = 0.5238$ [SE 0.0777] and $S = 0.8663$ [SE 0.07174]; LRT, $p = 0.004$).

Mortality Causes

Collision with power lines was the main identified mortality cause (37.6% of the 77 birds found dead). Other known mortality causes were poaching (9.1%) and collision with fences (2.6%). In all other cases, the cause of mortality could not be identified with certainty. Migratory birds died more frequently by collision with power lines than sedentary birds (respectively, 21.3% of deaths, $n = 117$ males and 6.3% of deaths, $n = 63$ males; Yates corrected chi-square test, $\chi 2 = 5.76$, $p = 0.016$).

Changes in the Proportion of Migratory versus Sedentary Birds

The number of breeding males increased from 1997 to 2012 at the main study area in central Spain at a 5.7% annual rate (Supporting Information). Over this period, the number of males remaining sedentary also increased, but the number increased at a faster rate than the number of breeding males. Thus, the proportion of sedentary males showed a steady increase over the study period, from 17% in 1997 to 45% in 2012 (Fig. 4). The overall mean slope of the increase estimated from 1997 to 2012 was moderate for breeding males (0.0327 [SE 0.006]) and high for sedentary males (0.1032 [SE 0.0139]), and

Table 1. Parameter estimates of the Cox proportional hazard model for migration pattern, distance, and breeding group-dependent survival of adult male great bustards.

Variable	*Coefficient*	*SE*	*Wald*	*P*	*Hazard ratio**	*95% CI*	
Migration pattern	0.903	0.449	4.049	0.044	2.468	1.024	5.948
Distance	0.002	0.003	0.471	0.493	1.002	0.996	1.007
Breeding group	−0.009	0.013	0.467	0.494	1.001	0.996	1.017

Relative change in mortality risk (increase for values > 1 or decrease for values < 1) of a particular category relative to the corresponding reference category (107 males, 67 migrants, and 40 sedentary individuals).

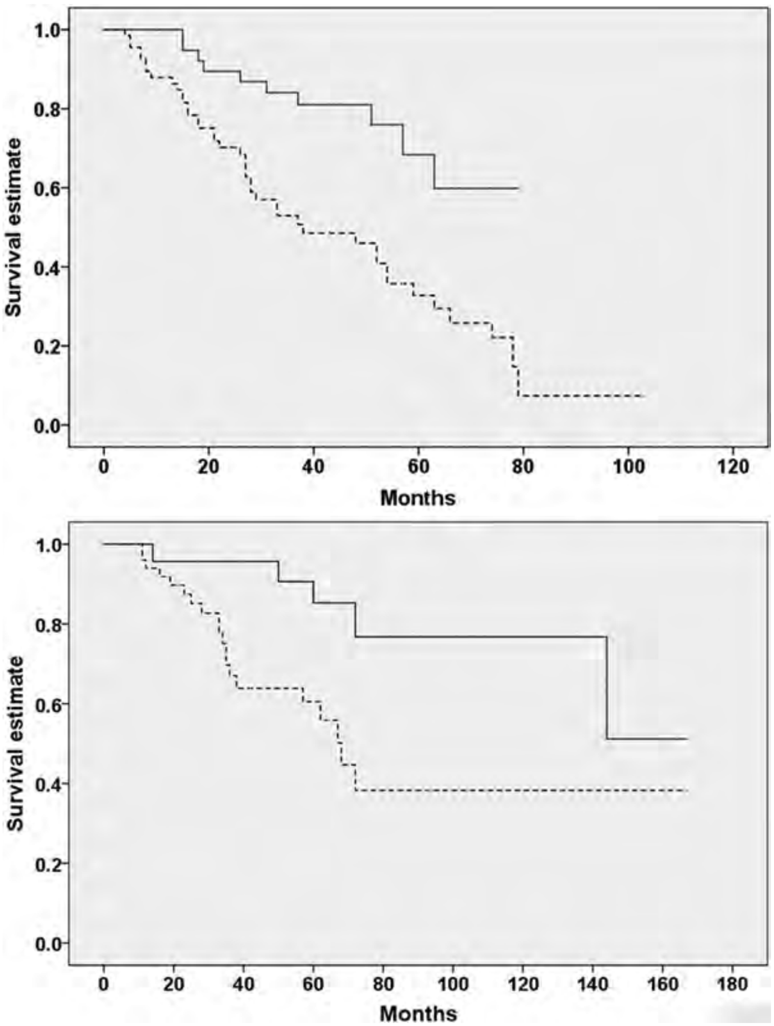

Figure 3. Kaplan–Meier survival probability estimates of sedentary (solid line) and migrant (dotted line) male Great Bustards: (top) birds marked as adults (n = 107) and (bottom) birds marked as juveniles (n = 73).

both trends differed significantly (Wald test = 24.91, df = 1, $p < 0.000$). Consistent with this trend, from 1997 to 2012, we observed a moderate although significant ($p < 0.05$) declining trend in the number of males at 2 summering areas in central Spain, where some of the migrant males from SPA 139 spent the summer (mean −0.362 [SE 0.0173]) (Supporting Information).

These results were consistent with those for males marked at our main study area. At the beginning of the study (1997–1999), the proportion of migratory males was 86% ($n = 22$ marked males), whereas at the end (2006–2010) that proportion decreased to 44% ($n = 16$ marked males) ($\chi^2 = 5.94$, $p = 0.015$). It is improbable that the numbers of males counted in summer at the main study area were influenced by movements from other areas because no marked bird from other Spanish regions spent the summer in our main study area. Finally, in a sample of 16 males marked in that area from 2006 to 2010, 3 birds shifted from migratory to sedentary when they were 2–3 years old, and they remained sedentary in subsequent years. We never observed a change from sedentary to migratory.

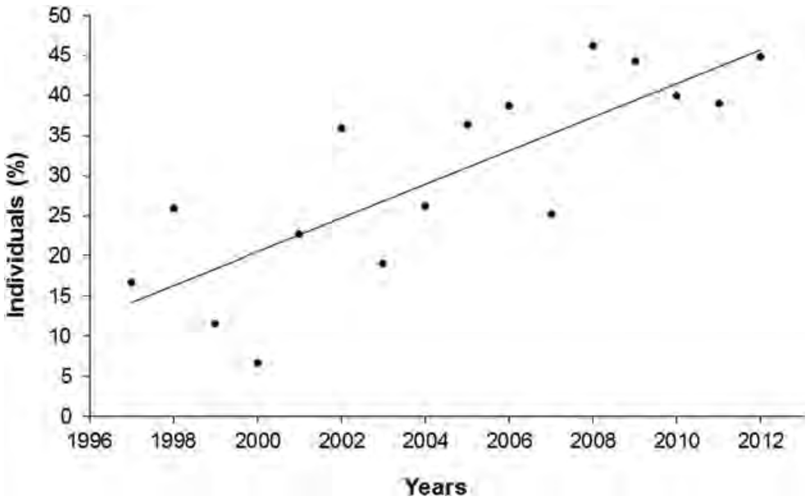

Figure 4. Percentage of sedentary male Great Bustards in the study area in central Spain from 1997 to 2012.

Changes in Temperature and Habitat

The average temperature of the hottest month (July) did not change significantly from 1994 to 2012 at the breeding areas in central Spain (rs = –0.049, $n = 19$, $p = 0.842$) (Supporting Information). The extent of dry cereal farmland in the main study area decreased by 7.2% from 1990 to 2000 and by 2.3% from 2000 to 2006.

Discussion

Migratory Great Bustard males had higher mortality rates than sedentary males. The same result was observed in immature and adult marked birds. Collision with power lines was by far the primary identified mortality cause. More importantly, power lines killed significantly more migrants than sedentary birds. These results show that casualties due to power lines are the most likely cause of decrease in the migratory fraction of the population. Therefore, we conclude that casualties at power lines may be inducing a change in the migration pattern of Great Bustards.

Our study represents a clear case of a human infrastructure causing higher mortality in migrants than in sedentary individuals in a species showing a partial migration pattern. A number of recent studies provide evidence for a rapid change in the migratory pattern of bird populations and both a progressive reduction of the migration distance and an increasing number of the sedentary individuals (Newton 2008; Møller et al. 2010; Pulido & Berthold 2010). A decrease in the migratory tendency in human-altered habitats also occurs with other vertebrates (Waples et al. 2007). Newton (2008) reviewed the recent changes in migratory behavior of birds and found that shifts in sedentary behavior were explained by an increase in the suitability of breeding sites over time. In our case, the increase in the sedentary pattern did not seem to be affected by habitat quality. Rather, habitat quality seemed to decrease over the study period because of the expansion of urbanization and infrastructure (Torres et al. 2011). Because marked birds from other areas of the Iberian Peninsula never spent the summer in our study area in central Spain, an increasing number of males coming from other breeding areas in the last years can also be discarded as a cause of the observed recent increase in the sedentary pattern.

In other long-lived species, social learning is more important than genetic inheritance in modulating several aspects of migration (Hebblewhite & Merrill 2011; Jonker et al. 2013; Mueller et al. 2013). In the Great Bustard, social learning and conspecific attraction could explain the increase of sedentary males as follows. We know that immature males develop their migratory or sedentary pattern during their first 3 years of life, and that their decision to adopt one or the other strategy is associated with their progressive integration into flocks of adult males (Palacín et al. 2011). If recently built power lines kill each year more migrants than sedentary birds, the proportion of sedentary males in each breeding group will grow over the years. Thus, each summer, immature birds deciding whether to migrate will increasingly decide to remain sedentary. All 3 males that changed from migratory to sedentary did it when they were 2 or 3 years old, after they had migrated one or 2 times but when they had not yet completely fixed their migratory strategy. Throughout the immature period, migration of males seems to be facultative, and their decision whether to migrate is an individual decision. After this immature phase, the migratory pattern of each adult male is fixed and does not change over its life (Alonso et al. 2009*b*).

The percentage of migratory males at the beginning of the study was 86%, whereas at the end it was 44%. A balanced payoff of sedentary versus migratory strategies may explain the coexistence of both strategies in a population (Lundberg 1988). At present, the 2 strategies are not balanced in our study population; migrants have higher mortality rates. Each year, there were fewer migrants, and therefore immature birds had more sedentary adults from which to learn a strategy, which led to an increase in the percentage of sedentary males we observed. The progressive loss of migration could have several negative effects. First, more sedentary males in the breeding areas in summer would increase intraspecific competition for resources. Second, in a large-bodied bird like the Great Bustard, individuals remaining sedentary in hot breeding areas incur higher thermoregulatory costs than migratory birds (Alonso et al. 2009*b*). Third, the disappearance of migration in Great Bustards would imply the loss of a mechanism used by some migratory species to expand their breeding range (Newton 2008). Fourth, gene flow could be altered and lead to a reduction of genetic diversity (Clobert et al. 2012). Finally, cessation of migration could eventually lead to the extinction of the population (Fagan et al. 2012).

Climate warming has also been suggested as one of the main factors causing changes in migration patterns (e.g., Møller et al. 2010). In our case, a temperature increase would have caused an increase in the number of migrants because summer migration of Great Bustard males represents an adaptation to escape the summer heat (Alonso et al. 2009*b*). However, there was no clear change in the average summer temperature in our study area. Thus, we discarded temperature as a relevant factor in the shift to sedentary behavior we found.

Power-line casualties may have population-level impacts for other large-bodied species vulnerable to collisions, mainly raptors, cranes, grouse, storks, and waterfowl (Jenkins et al. 2010; Klaassen et al. 2014; Loss et al. 2015). Collision with power lines by Great Bustards may be facilitated by their large body mass (Alonso et al. 2009*a*), which probably limits their flight maneuverability (Janss 2000). Bustards are also particularly prone to collide with power lines because of their reduced frontal visual field (Martin 2011). To solve this problem, considerable funds are currently being invested in central European countries (e.g., European Union LIFE projects [Raab et al. 2012]). This should be considered in Spain, where approximately 70% of the Great Bustard world population lives (Alonso & Palacín 2010) and high-voltage power lines have increased from 1000 km in 1960 to nearly 40,000 km in 2014 (REE 2014; Supporting Information).

Collision with power lines is also a main cause of mortality for other threatened bustards species (Jenkins et al. 2010; Silva et al. 2010; Dutta et al. 2011; Martin 2011). In these species, migration mortality may limit population growth because bustards' demography is sensitive to small changes in adult survival (Combreau et al. 2001; Palacín et al. 2016). Many of their populations are declining, and all 26 bustard species are threatened (IUCN 2015). In addition, power lines may also cause avoidance of some habitat or act as barriers to movement in other grassland and steppe birds (Pruett et al. 2009; Silva et al. 2010). We strongly suggest that plans for new power lines, such as plans for wind-energy facilities, take into consideration the distribution ranges, stopover sites, and migration routes of species vulnerable to collisions, especially in developing countries where power-line infrastructure is expanding quickly.

We found that human-induced mortality may be an important factor modifying the partial migration pattern of Great Bustards and suggest that it may also affect other partially migratory species. The demographic effects of these anthropogenic alterations on many threatened migratory species are still largely unknown and should be further investigated.

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Supporting Information

Results of Great Bustard surveys from 1997 to 2012 in our main study area, trends in mean July temperature in that area from 1994 to 2012, and the amount of high-voltage power lines in Spain from 1960 to 2014 are available online (Appendix S1). The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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EXHIBIT
12

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Mitigating wind-turbine induced avian mortality: Sensory, aerodynamic and cognitive constraints and options

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Because of the fast rate of wind-energy development it will become a challenge to verify impacts on birdlife and construe ways to minimise these. Birds colliding with wind turbines are generally perceived as one of the major conflict issues for wind-energy development. Development of effective and practical measures to reduce bird mortality related to offshore and onshore wind energy is therefore paramount to avoid any delay in consenting processes. The expected efficacy of post-construction mitigation measures for wind-turbine induced avian mortality can be expected to be species-specific with regard to audible, optical and biomechanical constraints and options. Species-specific sensory faculties limit the ability to observe a wind turbine in a given circumstance. Their consequent cognitive perception may depend on the possibilities for associating wind turbines with risk, and discriminating these from other sources. Last but not least, perceived risks may only be evaded when their aerodynamic, locomotive physiology enables them to do so in due time. In order to be able to identify and construe functional mitigation measures these aspects need to be taken into account. Measures eliciting a series of intermittent strong stimuli that are variable in frequency may limit habituation effects; these should only be elicited specifically to mitigate imminent collision. Thus measures either adjusting turbine operation or warning/deterring birds approaching turbines are expected to be most functional. Warning signals may either be based on optical or audible stimuli; however, birds' hearing is inferior to humans while their visual acuity and temporal resolution is higher, but with great differences among species. Implementing effective mitigation measures could reduce the general level of conflicts with birdlife and thus enable both the development at new sites, at sites that have been declared having too high conflict levels, and utilise the wind resources better at specific sites without increasing the conflict levels.

Contents

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1. Introduction

Reducing emission of greenhouse gases to prevent anthropogenic climate change has boosted the innovation, development and application of renewable energy sources like wind. Unfortunately the ecological and societal footprints may be substantial [1]. Successful development and implementation of wind energy depends on the technological advances and the ability to address environmental challenges. Energy systems for the future must acknowledge simultaneously the challenges of climate change and biodiversity loss.

Focus on unintended bird mortality has become increasingly important recognising that the cumulative effect of mortality from anthropogenic sources may be detrimental to some species. Several reviews have summarised different bird mortality sources and have identified structures posing the highest risk [2–5]. Recent reviews have assessed the extent of annual bird mortality caused by anthropogenic causes to be in the magnitude of 500 million to possibly over 1 billion individuals in the United States alone [6,7]. It is now recognised that for some red-listed species with dwindling populations, human-induced mortality could be fatal [8]. Thus, identifying the causes of mortality and species-specific vulnerability to man-made structures is vital to enable functional design of mitigating measures. Regarding bird mortality due to collision with power lines this was recognised several years ago, in particular the importance of species-specific biomechanical and optical characteristics [9–11]. In a review on bird mortality caused by wind-turbines [12], a main conclusion was that these two aspects should be addressed in particular.

The step from documenting the extent of the mortality caused by anthropogenic factors to successful mitigation is normally a very long one [13]. Mitigating wind-turbine induced bird mortality is particularly complicated due the fact that birds are exposed to collisions with the static structure, as well as being hit by the rotating turbine blades. Thus, it is vital to identify proximate and ultimate factors causing different bird species (or groups) to become wind turbine victims. Targeting these factors is vital to tailor effective mitigating measures for the target species and bird groups [12,14–18]. Still there are reasons to believe that some bird species or groups might be "no-cure species".

Here we review the literature on post-construction mitigating measures to reduce bird mortality due to collisions with wind-turbines and wind-power plants, and evaluate their efficacy from an avian sensory, aerodynamic and cognitive perspective. Mitigation options for other man-made structures were included only where relevant also to mitigation of wind-turbine induced collisions. Pre-construction mitigation measures (e.g. wind-power plant siting) and compensatory measures are not included. We use the term wind turbine for the whole structure that produces energy, including the base (tower), the turbine housing (nacelle) and the rotating rotor blades. A wind-power plant includes several wind turbines and the accompanying infrastructure (e.g. buildings, roads and boat routes, and possible power lines). We also restrict the review to tubular towers, which was early recommended as an important measure for bird survival due to the lack of perches for raptors [19]. Therefore, this review includes (1) minimising impacts by limiting the degree or magnitude of the action (wind-energy production) and its implementation, (2) rectifying the impact by repairing, rehabilitating, or restoring the affected environment, and (3) reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action [15]. The main focus is collision mitigation related to birds. Mitigation options for bats and marine mammals were only included where relevant to birds as well.

2. The sensory and aerodynamic ecology of birds

2.1. Bird vision

Vision is the dominant sense of most birds; crucial while flying, finding food, recognising mates or conspecifics, and evading predators. However, behaviour and life-history strategies differ, and birds being e.g. active in periods with poor light at high latitudes, twilight at dawn and dusk as well as nocturnal species, are expected to be vulnerable to crashing into artificial obstacles [20,21]. Activity patterns when the light is poor are a major and complex aspect of bird behaviour, and flight under such conditions does not take place without risks, and "nocturnal behaviour in birds requires an unobstructed habitat" [20].

Regarding vision acuity there is a great variety of adaptations among birds [22,23], a majority being classified as central monofoveal [24], having a single fovea (an area on the retina of very good acuity or resolution due to the high visual cell density) located near the centre of the retina. However, typical predators or hunters (e.g. hawks, bitterns and swallows), have two areas (bifoveal retina) [22,24]. A bifoveal retina and frontal eyes of a falcon allow about 60° binocular or three-dimensional perception but at an expense of a 200° blind zone [22]. An extensive blind zone may help to explain why even some raptors with highly binocular vision e.g. fly into power lines [9,25]. Some birds, like gallinaceous species, are afoveal [24], i.e. they lack or have a poorly developed fovea. This is interesting since tetraonids seem particularly vulnerable to collide with power lines [26]. Birds have a restricted range of flight speeds to adjust information gain when visibility is reduced [27], and e.g. fast-moving object at close distance may escape notice due to "motion smear" (also known as "motion transparency" or "motion blur") [28,29].

Birds are tetra- and pentachromatic (being able to differentiate between two different wavelengths of UV), compared to the human eye, which is trichromatic. This is a common ability of diurnal birds and is due to their special UV-sensitive rods. This ability plays an important role in inter- and intraspecific communication based on plumage UV-reflection, and the ability to, e.g., identify and assess fruit ripeness based on varying UV-reflection of fruit wax layers. As such it is an important factor in understanding bird behaviour [30–34]. Birds probably employ lateral vision for the detection of conspecifics, foraging opportunities and predators, which is normally more important to them than looking ahead during flight in the open airspace [25].

2.2. Hearing in birds

The general anatomy of the bird ear has evolved in a similar way as in mammals, including human [35–38]. However, the auditory pathway is different and more complex, especially in birds most dependent on sounds [39]. Avian ears are located behind and below the eyes, and the openings are protected by feathers. The bird ear, the shape of the head and the location of the two ears enable the bird to determine sound direction and distance [35,40]. This may be of relevance to acoustically alert birds in the vicinity of wind turbines. Directional sensitivity has evolved to a state of great precision in nocturnal hunters as owls listening for small noises made by their prey [38,41], and asymmetry in the outer ear enables some owls to localise sound in the vertical plane [42]. The ears are funnel-shaped to focus sound, and consist of three parts, external, middle and inner ear. The length of the *cochlea* in the inner ear is an index for a bird's sensitivity of sounds [43,44], which is especially long in several wader, pigeon and passerine species, but short in e.g. sea eagle and geese [45,46]. Birds are most sensitive to sounds at 1–5 kHz, with an upper hearing limit at about 10 kHz, but in general have a smaller frequency range and lower sensitivity compared to humans [37,46,47]. Large birds are especially sensitive to low frequency sounds, small birds to high frequency sounds [45]. Hereby, acoustic mitigation measures may be attuned to the specific species at risk. Birds are sensitive to pitch, tone and rhythm changes, and able to recognize other individual birds, even in noisy flocks [35]. As part of their social life, species have specific songs, calls and alerts for different situations; and some species even use sound to echolocate [38,40]. Birds are able to hear details in a sound, and have acute sound recognition skills. Thus they are able to recognize if a call is from predator or conspecific, indicate warning, advertise territory or render information about food [40,48]. This means that also conspecific warning or predator-specific calls may be effective in alerting birds to wind turbines.

2.3. Other senses

Olfaction is a chemical sense (chemoreception) and exploits information encoded in molecules moving through air or water [38]. The main characteristics of olfaction are the possibilities to receive information from a stimulus at a greater distance, and the duration of the stimulus may be for a longer time than other sense modalities. The importance of olfaction is direction-dependent. The olfaction in birds has generally lower sensitivity than in human, and has received less research interest than birds' vision and hearing [49]. However, there is evidence that birds may navigate using olfactory cues [50], and have been important in early birds [51]. Information received through olfaction also may become more important as ambient light levels decrease [52]. Olfaction seems to be more important in some bird groups, including several marine bird groups, as fulmars, shearwaters and storm petrels [49]. Several ultimate questions about olfaction are still unanswered, i.e. how birds use their olfactory system. Olfaction is known to play an important role in both foraging and predation risk in some bird species [53,54]. Olfactory cues may thereby both attract or repel birds to/from an area. Magnetoreception, the ability to receive and exploit information about magnetic fields, is documented as important in navigation and orientation in birds [55–58]. This sense makes it possible for the birds to extract information from the Earth's magnetic field, and it has been found in all major groups of birds, both in long-distance migrating and non-migrating groups [56,58]. However, the involved mechanisms at all levels are yet poorly understood, but seem to involve several different mechanisms, even in the same bird [59]. Ruminants have been shown to be disrupted in their body alignment by the extremely low-frequency magnetic fields generated by high-voltage power lines [60]. Thus also man-made electromagnetic fields may affect orientation in magnetic-sensitive species such as birds.

2.4. Bird flight performance

Most bird species are able to fly; however, there are major differences among bird taxa with respect to how they master the aerosphere. A species' susceptibility to collisions with e.g. wind turbines may be due to their biomechanical abilities, i.e. their manoeuvrability and agility. Manoeuvrability has been defined as the minimum radius of turn attained by a flying animal and agility as the maximum roll acceleration during the turn initiation, i.e. how fast can the bird change its flight path [61]. Theoretical models for bird flight are reviewed by several authors [27,62–65]. Applying principal component analysis to wing morphology [66] derived statistically independent measures of size and wing proportions. He grouped the major bird taxa within six main categories, determined by differences in aerodynamic performance: “poor” flyers, water birds, diving birds, marine soarers, aerial predators and thermal soarers. Rayner [66] emphasised that species categorised as “poor” flyers probably never had experienced strong evolutionary pressure to enhance their flight efficiency. In a review Bevanger [67] related Rayner's six categories to data derived from the literature on bird species frequently colliding with overhead wires like power lines and found that gallinaceous birds, rails, coots and cranes (“poor flyers”) are among the species most commonly and numerously recorded as victims in America and Europe. “Aerial predators” like several raptor species possess excellent flying abilities (and binocular vision). However, they spend a major part of their life in the air and the probability of crossing power lines (and colliding) is higher compared to ground-dwelling species, which may explain why aerial predators are regularly recorded as collision victims, although in seemingly small numbers [68]. How susceptible “thermal soarers”, i.e. birds with large and broad wings and a decreased wing loading, are to collision is difficult to predict. In short, it seems to be empirical evidence to say that species with high wing loading and low aspect, i.e. the “poor flyers” [66], should be classified in a high risk group as regards collisions with utility structures. The “poor flyers” are characterised by rapid flight and the combination of heavy body and small wings obviously restricting swift reactions to unexpected obstacles. As Rayner [66] emphasised, there are significant variations within some bird groups regarding wing load and aspect ratio, underlining the importance of making accurate analyses among species in the same family to predict the species-specific collision hazard.

3. Cognition and behaviour in birds with respect to disturbance

Species-specific sensory faculties (e.g. vision, hearing), physiological considerations (e.g. body condition, aerodynamics, age, breeding status), behavioural aspects (e.g. motion, response to external stimuli, flight and feeding behaviour), and the surroundings (e.g. food availability, light conditions) limits the birds ability to perceive and respond to wind turbines and wind-power plants. Cognitive perception of wind turbines as risk factors might depend on individual and species-specific possibilities for associating them with risk, and the ability to discriminate from other sources of risk and disturbance [69–71]. Other impulses acting upon the bird simultaneously through its behaviour (e.g. foraging, displaying) may affect detection/perception of wind turbines. In general, continuous exposure to a certain risk may lead to increased discrimination (latent inhibition), but decreased associability (habituation). The spatial cognitive abilities of a species simultaneously enable it to build up a cognitive map of its surroundings where wind turbines may function as landmarks [70,72]. These spatial cues may be processed cognitively either unconsciously (i.e.

the acquisition of knowledge through experience, without awareness of the knowledge thus acquired) or consciously [70]. Thus, the individual's perception may consequently result in either a "passive" or a more stress-related "active" response.

3.1. Perception of disturbance risk

In order to evaluate the possible efficiency of post-construction mitigation measures to reduce bird collisions with wind turbines it might be useful to adopt the hypothesis that nonlethal disturbance stimuli caused by humans are analogous to predation risk [69,71]. However contrary to the framework discussed by Frid and Dill [69] the disturbance stimuli (i.e. wind turbines) are stationary, albeit with moving rotor blades, and the animal is approaching the stimuli instead of being approached. The perceived risk of a wind turbine can only then be evaded when (1) it is being associated with fear by the approaching individual which is generally amplified by increased distance to refuge and prior experience with the risk [69,71], and (2) its locomotive morphology (e.g. wing load, wing aspect) and aerodynamic capability enables the bird to do so in due time [9,63,66]. The efficacy of post-construction measures for mitigating avian collisions with wind turbines therefore depends on the interplay of a species' sensory faculties, behaviour, consequent cognitive perceptions and aerodynamic capabilities for evasion. Many impulses that affect vigilance may act simultaneously upon the bird through its behaviour (e.g. foraging, courtship or territorial defence), and limit the detection and/or perception of wind turbines as potential dangers [73]. Social learning about predators (i.e. a wind turbine), and increased vigilance, may be faster and more robust in species in which alarm behaviour reliably predicts high risk [74]. Blumstein [75] reviewed flight initiation distance (FID), as a metric of awareness, in 150 species of birds. His findings strongly suggest that an important first step in implementing mitigation measures based on FIDs should be to evaluate the potential, site-specific, species at risk, and their life-history strategies. FID is measured in relation to an approaching moving object (a human walking towards the bird in focus) so it might not be directly related to bird's behaviour against a stationary object such as a wind turbine. However, it might be regarded as important in order to be able to judge the prospects of mitigation measures where information on species-specific FIDs can be used to develop mechanisms that might prevent birds from colliding with wind turbines by increasing their FIDs. In that aspect one should, however, strongly consider the possibilities that distracting elements (sounds, flashing lights etc.) could reduce FIDs rather than increase them [76] or increase vulnerability to predation [77]. In order to use bird vigilance as a tool for developing mitigation measures two factors should be considered: (1) the stimuli presented should, as far as possible, resemble a predation situation or a situation that the target species recognises as a potential danger that should be avoided, and (2) it should be presented in a way that minimises the risk of habituation – i.e. it has to be strongly correlated with the probability of colliding with the wind turbine if the stimuli is absent.

3.2. Habituation and learning

Continuous exposure to either the actual wind turbine or a proposed post-construction measure for mitigating avian collisions with wind turbines are subject to learning in birds, and may lead to decreased associability with disturbance, and also increased habituation. If it is possible to introduce a mitigation measure increasing the birds' awareness of the dangerous turbine blade or tower, and maintain this awareness over time, this measure will be more effective. Depending on the measure proposed, its efficacy may deteriorate over time when birds habituate to them or learn by association their harmlessness [78–81]. Stimuli that are only elicited with increased collision risk, enables birds to habituate to this specific stimulus while leaving it responsive to other stimuli (i.e. stimulus specificity) [78]. In relation to post-construction measure for mitigating avian collisions with wind turbines, their efficacy over time may be maintained by taking into account aspects enhancing dis-habituation such as eliciting multiple stimuli and repetitions of these. According to behavioural characteristics of habituation [78], mitigation measures should elicit a series of intermittent strong stimuli that are variable in frequency. The stimulus should, however, not become too repetitive, and specifically be elicited to mitigate collision only. There seem to be no mitigation study at wind turbines examining factors and stimuli leading to learning by association, habituation or other learning mechanisms in birds [81,82], although several proposals have mentioned the problem, especially when using auditory measures. In this review we use the term habituation, the simplest form of learning [79,81,82], to represent and including all mechanisms of learning, because there have been no mitigation study revealing the relative importance of habituation (waning of responsiveness), associative (classical and operational conditioning) or social learning mechanisms. Birds may learn by association [81–83], both to perceive the danger of the turbines and the harmlessness of a specific mitigation stimulus. Birds also use social learning e.g. in recognition of predators and disturbances [81,84], and this may be used by birds also near wind turbines, i.e. when birds perceive a collision by other individuals, and may be important also at several mitigation measures.

4. Assessment of measures mitigating avian collisions with wind turbines

4.1. Methodology

The overview of possible post-construction mitigation measures is based on existing reviews on the topic [12,15,18,19,85–89], keyword searches in ISI Web of Science, Google Scholar and Internet sites (see Table 1 for keywords used), and by contacting experts internationally (researchers, and representatives from industry and government agencies) directly. This broad approach was deemed appropriate to retrieve as much information as possible both from scientific (peer-reviewed journals, books) and grey literature (reports, articles, commercial patents/products, brochures, web sites). In total 77 references to 26 possible mitigation measures to reduce bird collisions with wind turbines were collected (Supplementary appendix). Possible mitigation options to reduce collisions between birds and wind turbines in existing wind-power plants can be categorised as either turbine-based or bird-based. Mitigation options on turbines encompass

Table 1
Keywords used literature databases (ISI Web of Knowledge) and on Internet search browsers (Google, Google Scholar).

General searches were combined with "wind turbine*" AND bird*:
mitigation/mitigate/mitigating/mitigate*
mitigation experiment*
temporary shutdown
bird collision*
bird mortality
avian collision*
avian mortality
deterrent/deterrence*
Including different combinations of these keywords

wind-power plant design, micro-siting of turbines, repowering and operation. Such measures have small or only indirect effects on bird behaviour, but may have high effects on bird mortality. The other approach is to directly affect bird behaviour. The mitigation options affecting bird behaviour encompass turbine design, deterrence/harassment and habitat alterations. The latter may be either inside (decreasing the attractiveness of the area), or outside the wind-power plant area (increasing the attractiveness of other areas).

To evaluate the efficacy of the proposed measures to mitigate wind-turbine induced bird mortality we employed a set of six qualitative criteria; partially divided into (1) turbine-specific or (2) bird-specific aspects. Criteria I–III focus on the expected efficacy of the stressor-exposure-response gradient used in ecological risk assessments [90]. Criteria IV and V assess the potential for ensuring effectiveness over time [78]. Criterion VI assesses the costs involved from an operational, economic and societal perspective. The six criteria are defined as follows:

Criterion I – Stressor: The proposed measure elicits a weak/medium/strong stimulus with regard to the (1) turbine-specific event (e.g. operational, design), or (2) bird-specific intensity (e.g. luminance, decibel) and/or spectral/auditory sensitivity (e.g. visibility, wavelength range).
Criterion II – Exposure: The stressor of the proposed measure results in low/medium/high detection with regard to (1) turbine-specific event regime (e.g. schedule, trigger distance), or (2) bird-specific perceptual range and exposure regime (e.g. exposure time, repetition).
Criterion III – Response: The exposure to the stressor of the proposed measure elicits a weak/medium/strong (1) turbine-specific risk reduction, or (2) bird-specific evasive response.
Criterion IV – Habituation: The proposed mitigation measure results in high/medium/low levels of habituation or other forms of learning in birds, reducing its efficacy.
Criterion V – Specificity: The proposed mitigation measure has a low/medium/high specificity to mitigate collision only, and/or repetitive levels.
Criterion VI – Implementation: The proposed mitigation measure comes at a high/medium/low cost for installation, maintenance and/or energy production; or may result in societal conflict (e.g. annoying lights or noise).

The assessment builds on the expected or – when available – observed, estimated or tested efficacy of the proposed mitigation measure. For each mitigation measure the six criteria were scored from one to three with three as most preferable (Table 2).

4.2. Turbine-specific mitigation options

Measures to mitigate collision risk through adjustments in turbine design and/or operation do not directly affect the sensory faculties, but rather aim at reducing the risk by reducing the birds' exposure to the hazard (i.e. the potential for collision irrespective of events; risk = hazard × exposure). The stressor (Criterion I) may here be interpreted as a form for incentive, rather than a negative stimulus.

Table 2
Evaluation of the efficacy of measures to mitigate turbine-induced mortality in birds.

Mitigation measures		**Criterion I: stressor**	**Criterion II: exposure**	**Criterion III: response**	**Criterion IV: habituation**	**Criterion V: specificity**	**Criterion VI: implementation**	**Total score**
Turbine-specific								
Wind-power plant design		1	2	2	1	1	1	1.33
Repowering/larger turbines		1	3	2	2	1	2	1.83
Removing selected turbines		2	2	2	2	3	1	2.00
Relocating selected turbines		2	1	2	2	2	1	1.67
Altering turbine speed		3	3	3	2	3	3	**2.83**
Temporary shutdown		3	3	3	2	3	2	**2.67**
Bird-specific								
Visual cues								
Marking/painting	☼	2	3	1	1	1	2	1.67
Visibility: reducing motion smear	☼	1	2	2	2	2	3	2.00
UV-coating	☼	2	2	2	2	2	3	2.17
Reflectors	☼	2	3	3	2	2	3	**2.50**
Minimal turbine lighting	☽	1	1	1	3	1	3	1.67
Turbine lighting regime	☽	2	2	2	3	2	3	2.33
Visual deterrence	☽	3	3	3	3	3	1	**2.67**
Laser	☽	3	3	2	3	3	2	**2.67**
Acoustic cues								
Acoustic harassment		3	1	2	1	2	2	1.83
Audible deterrence		2	3	3	3	3	2	**2.67**
Other sensory cues								
Electromagnetism		1	1	1	3	1	2	1.50
Olfaction		3	3	2	2	1	2	2.17
Habitat alterations								
On-site								
Habitat quality		2	1	2	2	1	2	1.67
Food availability		1	1	1	2	1	3	1.50
Off-site								
Habitat quality		2	3	2	2	1	2	2.00
Food availability		2	3	2	2	2	3	2.33
Breeding habitat		2	2	2	2	2	2	2.00
Roosting places		2	2	2	3	2	3	2.33
Other measures								
Funding wildlife research		NA	NA	NA	NA	NA	NA	NA
Monitoring fatalities		NA	NA	NA	NA	NA	NA	NA

Recently, movement models have shown to be able to provide insight into and identify possible impacts of offshore wind power plants at the planning state [91]. Changing the design of a wind-power plant by placing turbines in tight clusters was assessed to have limited efficacy. Although the total impact area is reduced by clustering turbines; at the same time the entire area will become inaccessibly to the birds due to reduced openness. Tighter placed turbines may be perceived as a single landmark (versus several turbines within natural habitat) to be avoided. However, it remains as yet unclear to which extent this results in possible adjustments in their spatial cognitive map [72] and how this affects a species' behaviour and spatial ecology [73]. Also, implementation costs in a post-construction situation are high; both with regard to relocating turbines and due to reduced wind capture. In general, fewer and larger turbines are thought to be preferred over many small turbines with regard to minimising collision risk to birds. Primarily in wind-power plants in the USA, older turbines with lattice towers and/or smaller turbines were replaced by larger tubular towered turbines. Repowering may result in dramatic changes with regard to exposure; and has been observed to lead to clearly reduced mortality in the Altamont Pass Wind Resource Area [18,92–95]. Other studies have however shown little [96,97] or even opposite effects [98] on fatality rates. However, birds may habituate to these larger structures, especially because repowering does not involve any specificity towards collision-reduction. Also, any benefit may only occur in old-generation wind-power plant facilities, such as was the case in the Altamont Pass Wind Resource Area. The implementation costs are lower relative to changing wind-power plant design because repowered turbines are likely more efficient in generating energy.

Micro-siting options (i.e. removing or relocating turbines) aim at identifying locations with increased risk for collisions. In wind-power plants where turbines were placed at more hazardous locations to bird collisions, these were either removed or relocated. Micro-siting has been proposed in agricultural areas [99], wetlands [100] and along ridges with many soaring raptors [14,18,93,94,101]. Removing “problem” turbines will specifically reduce mortality at that location, but may possibly lead to a shift of the problem to other turbines. Relocation of “problem” turbines instead may create increased collision risk elsewhere; and has therefore a lower expected efficacy. It has for example been suggested that outer turbines and turbines at the end of each row may experience higher risk of collision [14,102]. If this is the case, removing outer turbines will not remedy, only shift, the problem. Unless “problem” turbines were placed at specific hazardous locations, such as breeding sites [103], migration bottlenecks [12,104] or topography creating thermals [104,105], the collision risk may be expected to be reduced when such turbines are removed or relocated. The efficacy of micro-siting options is likely very site-specific and should preferably be done prior to the construction of the wind-power plant.

Most proposed mitigation measures focus on adjusted operation; either through altering turbine speed (cut-in speed, feathering) or temporary shutdown of turbines. These measures may only mitigate mortality due to collisions with rotor blades, and not for birds colliding with the turbine structure. Several studies have shown the highest activity of bats or birds at low wind speed [104,106–111]. To minimise collisions at low wind speeds, when energy output may be marginal, the cut-in wind speed at which the turbines start to produce energy was increased. For bats this usually happened around 6 m/s [106–109,111], for raptors collision risk declined at wind speed over 8 m/s [104]. Whether changing the cut-in speed at lower wind speeds, possibly at specific turbines, may be an effective way of reducing mortality depends on the species' flight behaviour. For birds that are mainly active at lower wind speeds, such as large soaring birds (e.g. raptors, herons and storks) that use thermal updrafts [112–114], the measure may specifically reduce the risk in such situations. Such a reduction of the risk window may come at relatively low costs because energy generation at low wind speed is limited (annual power loss $\leq 1\%$ of total annual output) [106,108]. Temporary shutdown has been tested in periods with high bird activity, or when birds moved too close to the turbines [93,115–119]. Methods used to assess when birds flew too close to turbines were either through visual observations [116,118] or avian radar [119,120]. An effective use of this measure, however, depends on a good monitoring scheme to limit unnecessary shutdown and thereby loss of energy generation. Especially when shutdown is restricted to specific events of near-collisions, the efficacy will likely improve as this will limit possible habituation effects. Too large shutdown periods may cause birds to adjust to this new situation, leading to reduced avoidance of the turbines [121,122]. However, other studies indicated that birds may primarily be affected by the actual turbine structures [123].

4.3. Bird-specific mitigation options

Another option for mitigation of collisions is to alert birds to the turbines or affecting bird behaviour. Alerting birds to the turbine structure may encompass making the rotor blades more visible, where reduction of motion smear [29] has been the major incentive. Alternatively mitigation measures have been proposed to dissuade birds from coming too close to the turbines through sensory cues. The efficacy of such measures is dependent on the birds' perception and response to the sensory cues (i.e. stressors). It is therefore crucial to take into account the sensory constraints placed upon the species of focus [124]. Mitigation options include passive and active visual cues (e.g. painting or lighting), audible deterrence/harassment, and to a lesser extent other sensory cues (e.g. olfaction, microwaves). In addition, habitat alterations either within or outside of the wind-power plant area may affect the birds' behaviour. Although great differences exist among species, generally birds' hearing is inferior to humans while their visual acuity and temporal resolution is higher [29,37]. Consequently, most measures are based on visual cues.

Mitigation measures based on passive visual cues include use of marking, reducing motion smear, reflectors or UV-coating. Marking patterns that have been proposed include scarecrows, conspecific/raptor models or displaying conspecific corpses. Stimuli placed on the ground have been suggested be most visible to birds due to the higher resolution of their lateral fields of view [25]. However, due to the lack of movement habituation may be more pronounced [125]. Because of this, and the lack of specificity towards reduction of collisions the efficacy of marking patterns is deemed limited. As a result of the work by Hodos [29], reduction of motion smear have been proposed as a measure to increase the conspicuity of the rotor blades enabling birds to take evasive action in due time. The ex-situ experiments by Hodos [29] indicated that painting one of three blades black reduced motion smear most. This measure has not been tested in-situ and merits further investigation [88,126]. Depending on whether decreased visibility of rotor blade tips is the cause of collisions, reducing motion smear may enhance the exposure potential. Especially when the motion smear pattern appears to be “moving” this may benefit its efficacy, and reduce habituation, as the frontal vision in birds may be more tuned for the detection of movement [25]. However, this measure does not directly reduce collision risk, but rather alerts birds to the presence of the rotor blades. As for all measures based on passive visual cues, UV-coating only works during daytime. UV-coating on rotor blades to increase their visibility has been proposed and tested in the USA with unclear conclusions on its efficacy [127,128]. This measure is expected to have similar effects as for reducing motion smear, although we scored it higher on the stressor criterion because the UV-coating lies within a, for birds, sensitive spectral wavelength [129]. Reflectors in the form of mirrors and aluminium/silvered objects – one could even think of holograms – may also provide to be an effective way of scaring birds [125]. However, reflectors will only be effective when they reflect (sun)light and lose their efficacy between sunset and sunrise, they were recommended in combination with other methods of scaring [125]. At daytime, when also most birds are active, they may create an ever-moving myriad of lights reflecting off the blades. Due to these changing reflections, the blades may become more visible and may attract attention to them resulting in increased responsiveness in the birds. However, as this measure is not specifically minimising collisions, but rather aims at increasing the conspicuity of the blades and alerting birds to their presence, habituation may occur. Implementation costs should be relatively low, although reflectors on the blades may require regular cleaning.

Mitigation measures based on active visual cues include minimal use of turbine lighting, adjustment of turbine lighting regimes, visual deterrence or laser. Minimal use of turbine lighting has been proposed especially for bats and nocturnal migrating birds. However, observations showed no differences in fatality rates between lit and unlit turbines [130–132]. Even though nocturnal (migrating) birds may be attracted to the (red) flashing or steady-burning safety lights [87,133]. Although the implementation costs – air traffic safety implications aside – should be limited, minimal use of lighting may have limited impact for reducing collisions. Although nocturnal birds may be prevented being attracted to the turbine lights, they are also not alerted their presence.

Adjustment of turbine lighting regime on the other hand has given more promising results. Using pulsating lights instead of steady-burning lights reduced bird fatalities at guyed communication towers significantly [134]. White strobe lights have also been proposed instead of the standard red lights [88,126]. However, experiments have shown that nocturnal migrating birds were least attracted and disoriented by blue and green lights especially on overcast nights [135]. Adjustment of turbine lighting regime therefore scores higher on the stressor-exposure-response scale, compared to minimal use of turbine lighting. Although this still has to be implemented and tested in-situ, this measure aims at alerting birds to the turbines while minimising detrimental attraction and disorientation.

Visual deterrence includes the use of strobing, flashing, revolving lights causing a temporary blinding and thereby confusion effect [136]. This measure will be most effective at low light levels, and may therefore mainly help mitigate collisions of nocturnal birds. Habituation may be reduced through randomized selection of at least two strobe frequencies; however use of bright lights may cause visual nuisance for local residents [125]. Also, its efficacy will be enhanced greatly when the visual deterrents are emitted only in situations when birds are in close vicinity of a turbine. This requires a functional, e.g. based on video [137] or avian radar [119,120], system to continuously monitor bird flight behaviour. Depending on the exact wavelength, luminance and exposure regime used this will likely result in high levels of evasive responses. For example, aircraft mounted with lights led to quicker evasive responses in Canada geese *Branta canadensis*, and was suggested to be most effective – given their spectral sensitivity – when the lights peak in the ultraviolet/violet range (380–400 nm) [138]. However, the implementation may be more challenging as such deterrence systems should be installed on all ("problem") turbines and require trustworthy triggering of the deterring stimulus (i.e. both with regard to Type I and Type II errors). Using laser renders similar efficacy as for visual deterrence. The difference being that laser may be directed more accurately at an approaching bird [125,136]. However this accuracy may also be its limitation as it assumes that it will be possible to pinpoint a flying bird. The visual nuisance of laser may however be less pronounced than for lights. Lasers also work best under low light levels. Something that has not been proposed is to utilise UV lasers that sweep upwards during night time encircling the rotor swept zone. UV lasers are invisible to the human eye but may deter nocturnal birds from entering the rotor swept zone.

Acoustic-based mitigation measures can either be in the form of audible harassment or deterrence. Audible harassment has been implemented especially at airports, agriculture and aquaculture [139–142]. It involves emitting hard sounds to scare away birds from an area. Methods used include: gas cannons, shooting, pyrotechnics, and ultrasound [125,143]. Most of these sounds will have to be emitted at high intensity and will therefore create audible nuisance for local residents. Ultrasound should largely be inaudible to humans, but has shown varying results in deterring birds [142,143]. Also, auditory harassment is subject to habituation and may therefore only have short-term benefit [19,37,125,136,142]. Effectiveness may be enhanced by varying firing frequency and direction, and/or using a combination of methods [136,142]. Dooling [37] suggested, based on his review on birds' hearing and options for mitigation, that an acoustic "whistling" cue in the region of best hearing for birds (2–4 kHz) help birds hear the blades while adding almost nothing to overall noise level. Instead of using artificial sounds, also bio-acoustic sounds may be used, such as bird alarm and distress calls [125,144]. Because of their biological meaning, these are thought to be more resistant to habituation. Although the response to bio-acoustic sounds likely is very species-specific, it may also evoke responses in other species [145]. Whereas acoustic harassment aims at scaring birds irrespective of where they are, audible deterrence warns/dissuades birds when approaching a turbine. Similar to visual deterrence, this requires functional monitoring systems to record hazardous bird flights [137]. What remains as yet unclear is at what wavelength and decibels sound should be emitted to evoke the most urgent response and be most effective [146,147]. Also the exposure regime (i.e. schedule, trigger distance) when replaying e.g. distress calls to deter birds, and variety in these parameters, affect its efficacy [136]. This may limit habituation effects, especially when in multiple-stressor set-up.

Other sensory cues that have been proposed as deterrence measures are electromagnetism and olfaction. Magnets and especially microwaves can create magnetic fields that are thought to disorient birds. Although this seemed effective for bats [148,149], it is expected to be of limited effect to deter birds from an area [140,150]. A behavioural evasive response may only occur when electromagnetic radiation is so intense to pose a potential health hazard to the birds but also humans [140]. Olfaction is known to play an important role in both foraging and predation risk in some bird species [53,54]. At airports, distributing toxicants in sub-lethal doses may cause disorientation and erratic behaviour and birds [125]. Applying behavioural repellents, however, has little specificity to reduce collision risk, its spatio-temporal permanence may depend on terrain and weather conditions (e.g. wind direction and speed, precipitation) and habituation may occur. Also, when too high doses are applied this may present a hazard to (non-targeted) birds [140].

4.4. Habitat alterations for mitigation

Finally, birds may be discouraged either by making areas near the turbines less attractive, or to enhance the habitat quality outside the wind-power plant. On-site habitat alterations (i.e. inside the wind-power plant area) which have been proposed include clear-cutting forests [131,151] or making open vegetation near turbines less attractive for either birds or their prey [87,99]. The efficacy of on-site habitat alterations likely depends on the importance of the habitat for the given species. When a wind-power plant is located in prime habitat for a species, this area may function as an ecological trap [152]. Still, unless the preferred habitat is altered dramatically (i.e. non-habitat), the area may still be frequented. Also, habitat alterations will result in habitat loss, or gain, for other non-targeted species (previously) not affected by the turbines. The loss of e.g. foraging or breeding habitat may lead to shifts in range use; however it does not preclude moving through the wind-power plant. The specificity is therefore limited, and the extent of habituation may depend on e.g. population density, territoriality and the availability of quality habitat in the surrounding landscape. Alternatively, the prey availability may be reduced inside the wind-power plant. This has mainly been proposed for e.g. eagles [153,154], vultures [155,156] and owls [115]. Obligatory scavengers aside, removal of carcasses or live prey (e.g. through rodent control) may have limited efficacy to reduce collisions within a wind-power plant. Only in specific situations when birds of prey or scavengers are attracted to the turbine bases to forage for prey using the rocky foundations as (burrowing) habitat or for collision fatalities [14,18,94] may localised rodent control or removal of fatalities show any effect. Better, however would be to alter the rocky substrate at the tower base to less attractive habitat for prey.

Off-site habitat alteration measures aim to increase the attractiveness of other areas outside the wind-power plant. These include the creation of novel habitats, breeding sites, food availability, and roosting sites or perches for birds. Although attraction of birds to improved or novel habitats outside the wind-power plant may present the birds with a stronger stimulus to shift their habitat preferences spatially, this has so far not been documented [99,157,158]. Simultaneously altering habitat quality both on- and off-site may, considering habitat alteration options alone, maximise its efficacy. However, the lack of specificity of this measure with regard to the species which are targeted may make this of less interest from a conservation point of view. Some success has been observed when presenting birds of prey with alternative feeding opportunities outside a wind-power plant [155,159]. However, this assumes the possibility for off-site prey base improvements relative to the on-site foraging quality [160]. Specifically protecting existing or creating artificial breeding sites has been proposed for raptors [19,153]. Another option is to erect perching towers outside a wind-power plant, which was suggested to have potential for offshore birds [88,126]. Although this may indirectly enhance breeding success or survival in a local population affected by increased turbine-induced mortality, it does not preclude these birds moving through and utilising the wind-power plant to forage. Any reduced exposure therefore influences only part of their ecology. Removal of existing breeding sites in the vicinity of a wind-power plant has so far not been proposed as a possible mitigation option due to the fact that this will lead to an additional impact on an already vulnerable population. Increased perching opportunities previously not available to the birds (e.g. offshore) may also attract them to the turbines, reducing its efficacy. Much of the same conditions as for habitat alterations will apply also for breeding sites and roosts/perches; the location of the turbines with regard to available quality habitat in the surrounding landscape greatly affects its expected efficacy.

4.5. Other measures for mitigation

Finally, some mitigation options have been proposed which may benefit the species indirectly. When mitigation may not be possible or did not have its desired effect on the species at risk, funding research may render new insights into the species' ecology for long-term conservation [87]. In many cases, the knowledge base on which mitigation measures are proposed is insufficient. An improved understanding on why, when and where a species may be expected to be most at risk can be assessed by studying e.g. flight behaviour, habitat and food preferences and causes of mortality. This may offer novel options for offsets at biological appropriate locations. Employing appropriate fatality monitoring programmes [17,161] does not directly reduce collisions, but may render increased insight into where and when which species are most at risk. This may then in the future direct possible operational – or other – mitigation measures. However, such a monitoring scheme only sets focus on possible spatial and temporal correlates in fatality patterns; it does not include other biologically relevant aspects such as habitat preferences and flight behaviour.

5. Concluding remarks

Minimisation of impacts from wind-energy development should always be addressed in the consenting process through the "avoid – minimise – compensate" mitigation hierarchy [162]. Collision-reducing mitigation measures should therefore always be preceded by a thorough siting process. As becomes clear in this review, post-construction mitigation measures should be species-specific and directed towards the most collision-prone species. However fatalities may also be highly seasonal and site-specific. For instance, white-tailed eagle [163] and griffon vulture (*Gyps fulvus*) [116] mortalities have been demonstrated to be highly seasonal, and related to habitat structure; most fatalities were clustered to a limited number of turbines. This fact was used when implementing a programme where the wind turbines were stopped when griffon vultures were observed near them, reducing vulture mortality rates by 50% while the energy production was only reduced by 0.07% per year [116]. The choice of mitigation measures should therefore be tailored for the species-at-risk at each wind-power plant separately. For instance, at the Smøla wind-power plant in Norway impacts on white-tailed eagles are perceived to be significant [163–165]. Studies, however, indicate that this day-active species neither actively avoids nor is displaced by the turbines [103,166,167]. Collision risk reduction was therefore proposed to be done either through audible deterrence or enhancing the visibility of the rotor blades.

On-site mitigation measures proven to have been effective may also have an indirect effect on the overall habitat quality. As a result of visual or acoustic deterrence measures, birds may choose to move away from the wind-power plant area to other possibly suboptimal habitat. The effect of such measures on the entire population may therefore be larger than the effect of some birds colliding with wind turbines. Although there is a general preference for on-site mitigation over off-site mitigation, sometimes off-site mitigation may result in greater net benefits to affected species and their habitats [86]. Possibly development of wind energy and transmission line construction on disturbed lands may offer the potential to dramatically reduce associated wildlife impacts [1]. In addition, preclusion of construction activity near breeding territories and/or during the breeding season may be preferred [168].

Because sound intensity is reduced with square number of the distance, possibilities to use audible deterrence as mitigation measure will be best at small distances. Given the social importance of sound in birds, utilising sounds with a biological meaning (e.g. predator sounds or warning calls) may be useful in mitigation measures [46]. In general acoustic devices are effective only for a short time [37,47], and the most effective use of acoustic signals is when they are reinforced with activities that produce death or a painful experience to some members in a population [46]. Sound-level changes of only a few decibels and stimuli duration may e.g. be important to improve the use of acoustic devices to birds' responses [146]. Utilisation of multiple stressors may be more effective to minimise collision risk. For instance, with respect to visual cues combining passive measures (e.g. coating) with active measures (e.g. lighting) reduce collision risk both at high and low light levels, respectively. We would like to stress that some measures actually should be considered to become common practise in turbine design and construction, such as turbine lighting regimes and bird-friendly micro-siting of turbines.

Finally, a prerequisite for successful mitigation is to map baseline information, and doing research on the vulnerable species as a part of the mitigation project [14,17,87,88]. Monitoring of fatalities is especially important, employing a scientifically defensible monitoring method [14,18,86,88,97,169–171].

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.10.002

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EXHIBIT
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Short communication

When the excrement hits the fan: Fecal surveys reveal species-specific bat activity at wind turbines

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ABSTRACT

The reasons why bats are coming into contact with wind turbines are not yet well understood. One hypothesis is that bats are attracted to wind turbines and this attraction may be because bats perceive or misperceive the turbines to provide a resource, such as a foraging or roosting site. During post-construction fatality searches at a wind energy facility in the southern Great Plains, U.S., we discovered bat feces near the base of a wind turbine tower, which led us to hypothesize that bats were actively roosting and/or foraging at turbines. Thus over 2 consecutive years, we conducted systematic searches for bat feces on turbines at this site. We collected 72 bat fecal samples from turbines and successfully extracted DNA from 56 samples. All 6 bat species known to be in the area were confirmed and the majority (59%) were identified as *Lasiurus borealis*; a species that also comprised the majority of the fatalities (60%) recorded at the site. The presence of bat feces provides further evidence that bats were conducting activities in close proximity to wind turbines. Moreover, feces found in areas such as turbine door slats indicated that bats were using turbines as night or foraging roosts, and further provided evidence that bats were active near the turbines. Future research should therefore aim to identify those features of wind turbines that bats perceive or misperceive as a resource, which in turn may lead to new minimization strategies that effectively reduce bat fatalities at wind farms.

As the demand for renewable energy has grown, it has led to the rapid installation of wind power facilities worldwide. As a result, many utility-scale wind farms became operational before it was apparent that wind turbines could have a negative impact on bats (Arnett and Baerwald, 2013). Subsequently there have been reports of bat fatalities, many of which represent multiple mortality events, from operational wind facilities globally (O'Shea et al., 2016; Chou et al., 2017). The majority of these mortality events appear to involve highly mobile or migratory bat species that cover a large geographic range (Arnett and Baerwald, 2013; Lehnert et al., 2014; Roscioni et al., 2014) and can potentially be impacted by the cumulative effects of multiple wind farms (Roscioni et al., 2013). With continued wind energy expansion, there are increasing concerns that there could be population-level implications for bats (O'Shea et al., 2016; Frick et al., 2017).

Thus, understanding why bats are coming into contact with wind turbines is crucial if we are to implement minimization strategies that effectively reduce bat fatalities. One hypothesis proposed by Cryan and Barclay (2009) is that bat fatalities occur because bats are attracted to wind turbines. By identifying the source of the bats' attraction we could potentially devise more targeted minimization strategies that limit bat activity in proximity to wind turbines, which in turn would reduce bat fatalities. A possible explanation for why bats may be attracted to wind turbines is that the turbines themselves provide a resource(s) for bats, such as foraging, mating, or roosting sites (Horn et al., 2008; Rydell et al., 2016). In support of this rationale, Cryan et al. (2014) suggested that the bat behavior they observed on the leeward side of wind turbines was similar to bat behavior seen at tall trees; structures that would provide bats with roosting, foraging, and mating opportunities. Another study by Long et al. (2011) demonstrated that the light grey color of turbine towers and blades attracted insects, suggesting that wind turbines could serve as a foraging resource that would be attractive to insectivorous bats. Given that wind turbines could potentially provide or be misperceived to provide one or more resources, the next step would be to identify those features of wind turbines that could be attractive to bats. Moreover, as the resource requirements of bats are species-specific, the features of wind turbines that attract bats will likely vary among species (e.g., Ammerman et al., 2011).

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For any bat species to be actively roosting and/or foraging at wind turbines, we would expect to find other signs or evidence of use by bats on or around the turbines, not just bat fatalities. For example, there are 3 signs that would indicate that bats are roosting at wind turbines: 1) the presence of roosting bats; 2) the presence of feces within or beneath a suitable roost site; and 3) staining, the brown patches left when bat urine evaporates beneath or on the walls of a roost site (Mitchell-Jones and McLeish, 2004). Furthermore, if bats were to frequently spend time, for example, foraging in close proximity to wind turbines we would expect fecal material to be deposited on the wind turbines and transformers. During post-construction fatality searches at a wind energy facility in the southern Great Plains, U.S., we discovered bat feces on a wind turbine tower. These observations led us to hypothesize that bats were actively roosting and/or foraging at the turbines. Thus over 2 consecutive years, we conducted systematic searches for bat feces around the bases of wind turbine towers at this wind facility to determine if any or all of the 6 bat species known to be in the area were active at turbines.

Our study site was Wolf Ridge Wind, LLC (33°43′53.5″N, 97°24′18.2″W) in the cross timbers and prairies ecoregion of north-central Texas. This facility, owned by NextEra Energy Resources, became operational in October 2008 and consists of 75 1.5-megawatt (MW) General Electric wind turbines (model GE 1.5xle) extended over 48 km^2. The wind turbines have a hub height of 80 m, blade length of 42 m, maximum tip height of 122 m, and are spaced at least 1 ha apart in a general east-west direction across open agricultural land used predominantly for cattle grazing (pastures), native hay harvesting, and winter wheat *Triticum aestivum* cultivation. There is an extensive shrub-woodland along the northern boundary of the wind resource area that leads down to the Red River escarpment. During a 5-year period (2009–2013) in which post-construction fatality monitoring took place at this site, 916 bat carcasses were collected (551 *Lasiurus borealis*, 258 *Lasiurus cinereus*, 3 *Lasionycteris noctivagans*, 22 *Perimyotis subflavus*, 49 *Nycticeius humeralis*, 30 *Tadarida brasiliensis*, and 3 unidentified bats; Bennett and Hale 2014), and species identifications were confirmed using DNA barcoding (Korstian et al., 2016).

From July to November 2011 and April to October 2012, we searched all 75 wind turbines for bat feces. These searches were conducted once a week over 2 consecutive days, in which half the wind turbines were searched the first day and the other half were searched on the second. Searchable areas at the wind turbines were separated into 3 sections: 1) the turbine tower (up to 3 m from the ground), stairs, and associated concrete pad; 2) the turbine door; and 3) the transformer and associated concrete pad. We then divided each of these sections into specific zones, parts, or sides. The turbine tower was divided into 5 zones, comprising four quarters of the turbine tower (i.e., zone 1 started after the stairwell next to the transformer), and the stairwell area leading to the turbine door (zone 5). The turbine door was divided into 4 parts including the door frame and light fixture, door face, and 2 sets of slats in the door face (an upper and lower set). Finally, the transformer next to the turbine tower was divided up by its 4 sides and top.

Searching for bat feces, we slowly walked around each wind turbine and transformer making sure we inspected 1) the door slats and gills of transformers (i.e., sides 1, 2 and 4), 2) the surface of the turbine tower, stairwell, door, light fixture, and flat surfaces of transformers (i.e., side 3 and the top), and 3) all areas with concrete, including the 0.5 m wide concrete pad surface surrounding the base of the turbine tower and 0.25 m wide concrete platform of the transformer. Once found, we placed bat fecal pellets in 1.5 ml plastic tubes and stored them at room temperature.

We extracted DNA from each fecal sample collected using the QIAamp DNA Stool Mini-kit (Qiagen Genomics, Valencia, CA). A negative control was used with each round of extraction to ensure that the extraction reagents used were not contaminated. All extractions were completed in a dedicated extraction AirClean® 600 PCR workstation to minimize contamination and the subsequent polymerase chain reactions (PCR) were conducted in a separate dedicated PCR workstation. We employed the DNA barcoding procedure described in Korstian et al. (2015) to identify each fecal sample to species. We reviewed species composition and explored whether there were any trends or species-specific patterns in the locations where fecal samples were found on wind turbines and across the wind facility.

Each of the 75 wind turbines was surveyed 53 times (22 in 2011 and 31 in 2012) for a total of 3975 searches. Fecal samples were found in 29 of the 53 weeks the turbines were searched. We collected a total of 72 bat fecal samples from the surfaces of turbines, transformers and associated concrete pad. The most samples per month were found in July in 2011 (n = 24) and May and June in 2012 (n = 13 and n = 16, respectively), while all other months had <10 samples. DNA was successfully extracted from 56 of these samples (i.e., 78%). The DNA in the remaining 16 bat fecal samples was found to be degraded and could not be processed successfully to identify species.

Among the samples that were identified to species, all 6 bat species known to be in the wind resource area were confirmed: *Lasiurus borealis* (n = 33 samples), *Lasiurus cinereus* (n = 4 samples), *Lasionycteris noctivagans* (n = 2 samples), *Perimyotis subflavus* (n = 7 samples), *Nycticeius humeralis* (n = 9 samples), and *Tadarida brasiliensis* (n = 1 sample). Fecal samples from *Lasiurus borealis* comprised the majority (59%) of the 56 samples.

We found bat feces in all searched areas of the wind turbines, except for the lower slats of the door (Fig. 1). Nineteen fecal samples (26% of the 72) were collected from between the upper slats of the door, between the gills of the transformer, on the frame beneath the gills of the transformer, and beneath the stairwell on the plastic-covered steel rods anchoring the base of the turbine tower. Note that in order for fecal samples to be in these locations, bats would have to physically be within the structures as it is not possible for wind or water to have moved the feces into such locations. Species composition of the fecal samples in these locations comprised *Lasiurus borealis* (n = 8 samples), *Perimyotis subflavus* (n = 4 samples), *Nycticeius humeralis* (n = 3 samples), *Tadarida brasiliensis* (n = 1 sample), and unknown bats (n = 3 samples).

Of the 75 wind turbines searched, we found bat feces on 41 of them: 20 wind turbines had 1 fecal sample, 13 had 2 samples, 6 had 3 samples, and 2 wind turbines had 4 fecal samples collected from them (Fig. 2). The bat fecal samples were widely distributed on turbines across the wind facility, ranging from wind turbines in close proximity to wooded areas to turbines in open cattle pastures. With regards to species-specific patterns, fecal samples from *Lasiurus borealis* were found throughout the site, whereas fecal samples from *Nycticeius humeralis* appeared to be concentrated in 2 areas, one at the western end of the wind farm and a second towards the center of the wind farm. Fecal samples from *Perimyotis subflavus* were primarily found at turbines near the scrub-woodland area located towards the center of the wind farm. Finally, despite the low number of fecal samples found for *Lasiurus cinereus* and *Lasionycteris noctivagans*, these appeared to be distributed across the wind facility.

The presence of bat feces provides further evidence that bats are conducting activities in close proximity to wind turbines. Furthermore, DNA analysis of the fecal samples confirmed that all 6 bat species known to occur in north-central Texas were active at wind turbines and concurs with fatality data reported at our study site. As expected, the majority of fecal samples were identified as *Lasiurus borealis* (59%), corresponding with the proportion of *Lasiurus borealis* carcasses found in fatality monitoring surveys at the site (60%; Bennett and Hale, 2014).

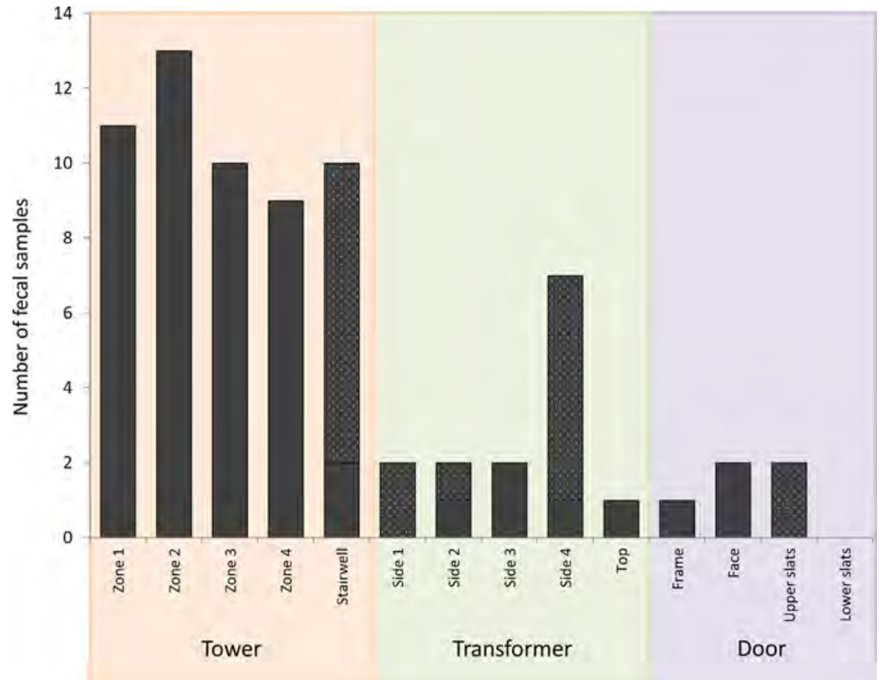

Fig. 1. Number of bat fecal samples collected from searchable locations on wind turbine towers, transformers, and doors at Wolf Ridge Wind, LLC in north-central Texas. Solid color represents fecal samples that were collected from wind turbine surfaces, whereas dots identify feces that were found in structures associated with wind turbines, such as between the slats in the door.

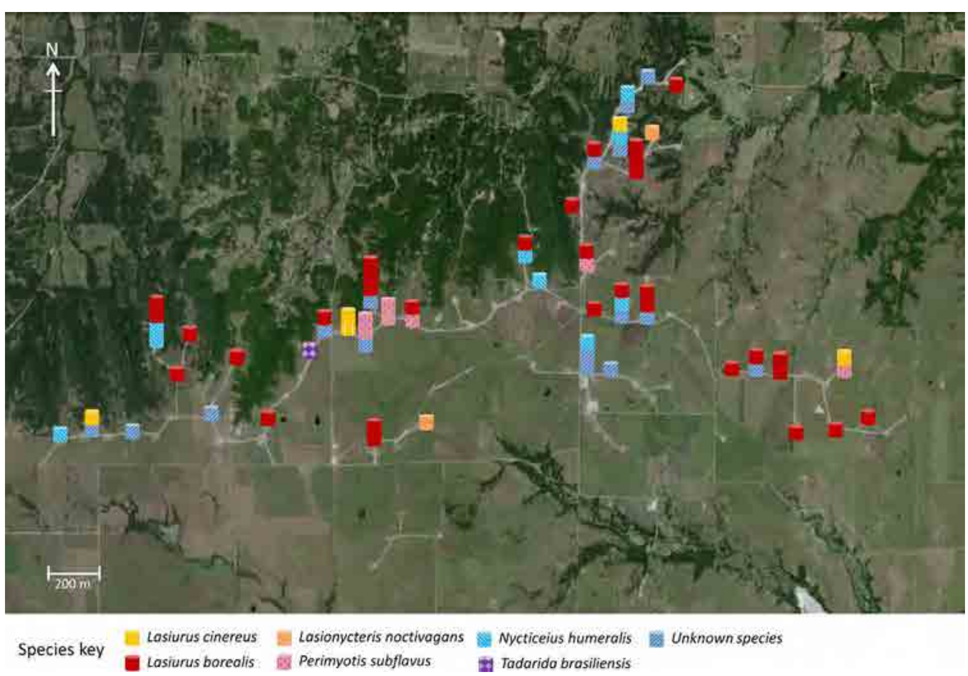

Fig. 2. Number of bat fecal samples by species found on wind turbines at Wolf Ridge Wind, LLC in north-central Texas.

Our findings appear to support the attraction hypothesis and contribute to the mounting evidence that bats are conducting activities, such as foraging, at wind turbines (Horn et al., 2008; Rydell et al., 2016). As bat feces are small (<5 mm in length) and relatively light weight, the likelihood that pellets will be deposited onto searchable areas of a wind turbine is inevitably very low. In addition, there are numerous instances that occur during any given search interval that can remove or destroy feces. For example, over the 2 years we conducted weekly searches, the site experienced rain showers, thunderstorms, and moderate to high winds on a regular basis. The consequence of these events ultimately reduced our ability to successfully locate and collect fecal samples. Furthermore, the ecology of each bat species can also influence our ability to find feces. For example, 3 of the species identified in this study, *Lasiurus cinereus*, *Lasionycteris noctivagans*, and *Tadarida brasiliensis*, are known to forage at greater heights (i.e. above tree canopy height) than *Lasiurus borealis*, *Perimyotis subflavus*, and *Nycticeius humeralis* (Ammerman et al., 2011). Again, the higher bats fly, the less likely fecal pellets will be deposited onto the searchable areas of the wind turbines. Thus, as we were able to retrieve 72 fecal samples during our surveys, including feces from the 3 high-flying bats, it is a testament to the amount of bat activity that occurs in close proximity to wind turbines. In other words, it indicates that bats, in particular *Lasiurus borealis*, the species most frequently found in fatality searches at this site, are active at wind turbines (Bennett and Hale, 2014).

Moreover, the location of bat feces may indicate bats are using wind turbines as roost sites. We found fecal pellets in between the upper slats of the door, between and beneath the gills of the transformer, and on rods under the stairwell; an indication that bats were likely hanging in or above these areas. For most insectivorous bats, there are 2 general types of roost site: 1) day roosts and 2) night or feeding roosts. Day roosts, as the name suggests, are used by bats during the day and their purpose is to protect bats (and potentially their young) from exposure to the elements (i.e., inclement weather conditions, sunlight, and overheating) and from predators (Agosta et al., 2005; Knight and Jones, 2009). Given that the aforementioned areas from which we collected bat feces do not offer protection from the elements, it is more likely that these areas act as night roosts. Night or feeding roosts can be more exposed, as bats use these sites to simply hang and digest food between successive foraging bouts at night (Agosta et al., 2005; Knight and Jones, 2009). Thus, the slats of the doors, gills of the transformer, and the area under the stairwell all represent suitable night roosting opportunities. Furthermore, behavioral surveys using night vision technology undertaken by McAlexander (2013) noted 5 instances over 80 survey nights in which bats were observed entering or exiting the slats of doors or gills of the transformers where the bats remained beyond the length of the survey trial (10 min) or had been prior to the start of the survey trial, respectively. These observations appear to support our findings that bats are using these structures as night roosts. In contrast, over a 5-year period in which standardized fatality monitoring surveys were conducted every other day during the bat activity season (July–September), we also searched the turbine door, stairwell, and gills of the transformer for live bats. Among these fatality monitoring surveys along with the two years of fecal surveys, we only reported the presence of live bats on a turbine once (V.J. Bennett and A.M. Hale, Texas Christian University, unpublished data). On this occasion, 4 *Tadarida brasiliensis* were found in the upper slats of the door and immediately flew away as we approached the turbine door. Note we also found 2 additional *Tadarida brasiliensis* fatalities at this turbine during that fatality monitoring survey not far from the stairwell. As *Tadarida brasiliensis* only make up a small proportion of the fatalities at our site, we considered this finding to be an unusual event. Thus, if indeed bats were effectively able to use wind turbines as day roosts, we would likely have more observations of bats roosting in wind turbines at our site during the day.

Finally, we found that the distribution of fecal samples from wind turbines across the wind facility varied by species. For example, fecal samples from *Lasiurus borealis* were collected at wind turbines in areas that had available resources such as scrub-woodland, and from areas that provided little or no obvious resources (i.e., wind turbines located in open agricultural fields). In contrast, for species such as *Perimyotis subflavus* and *Nycticeius humeralis*, fecal samples were more frequently collected from wind turbines near areas with potential resources (i.e., the scrub-woodland habitat). These observations in all three species also concur with patterns in species-specific fatalities recorded at our site, thus demonstrating that the locations of feces, and therefore where bats are active at wind turbines, correspond with bat fatalities.

Our study provides further evidence that bats are active at wind turbines as they appear perceive or misperceive them to provide a resource and may therefore be attracted to the turbines. Future studies should therefore focus on identifying the specific characteristics of wind turbines that underlie these perceptions in bats and determine if it is possible to alter these features so that bats show little or no interest in them. For example, Gorresen et al. (2015) are investigating how to use low-level ultraviolet lighting as a way to help bats discern between wind turbines and trees and Bienz (2015) has been conducting research to develop a texture coating that may be used to prevent bats from potentially perceiving wind turbine towers to be a foraging or water resource. Such information may then be used to devise minimization strategies that can be implemented to limit bat activity at wind turbines, thereby reducing bat fatalities at wind energy facilities.

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EXHIBIT
14

BRIEF COMMUNICATION
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nature ecology & evolution

Wind farms have cascading impacts on ecosystems across trophic levels

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Wind farms are a cleaner alternative to fossil fuels for mitigating the effects of climate change, but they also have complex ecological consequences. In the biodiversity hotspot of the Western Ghats in India, we find that wind farms reduce the abundance and activity of predatory birds (for example, *Buteo*, *Butastur* and *Elanus* species), which consequently increases the density of lizards, *Sarada superba*. The cascading effects of wind turbines on lizards include changes in behaviour, physiology and morphology that reflect a combination of predator release and density-dependent competition. By adding an effective trophic level to the top of food webs, we find that wind farms have emerging impacts that are greatly underestimated. There is thus a strong need for an ecosystem-wide view when aligning green-energy goals with environment protection.

Wind energy is the fastest-growing renewable energy sector in the world, with current capacity estimates at ~500,000 MW per year (4% of global energy demand)[1,2]. With land requirement of as high as 34 hectares MW^{-1}, close to 17 million hectares of land is currently used for wind energy generation worldwide[3]. Despite the benefits of this renewable energy production, wind farms have ecological costs[4]. Wind turbines cause high mortality in birds and bats from direct impacts[5,6], impede bird migration routes[7], and reduce the density and activity of terrestrial mammals[8,9]. It is often assumed that the greatest impacts of wind turbines are restricted to volant species[9], resulting in significant reduction in local population density (but see ref. [10]). Here, we show that the effects of wind turbines are much larger and are akin to adding an apex predator to natural communities. By reducing the activity of predatory birds in the area, wind turbines effectively create a predation-free environment that causes a cascade of effects on a lower trophic level.

Predator-induced trophic cascades are most apparent in ecosystems where top predators are removed or added, and are often driven by numerical changes in predator densities[11]. Changing predation pressure can affect the local density of prey through direct consumption[12,13], but predation risk can also cause non-consumptive effects by altering the behaviour, physiology and morphology of prey that survive[14–18]. Our study area—the lateritic plateaus in the Western Ghats of India—is ecologically unique, with high endemism in flora and fauna[19]. Wind farms here have been functioning for 16–20 years[20]. To detect legacy effects of wind farms on small vertebrates, we used a space-for-time substitution[21] and compared areas with and without wind turbines on the same plateau (Supplementary Fig. 1). Apart from the presence or absence of wind turbines, the habitats of sites with ($n = 3$; ~0.5 km^2 each) and without wind turbines ($n = 3$; ~0.5 km^2 each) were indistinguishable (Supplementary Figs. 2 and 3, and Fig. 1a,b).

Many studies have demonstrated reduced avian density in areas with wind turbines[22–26], but this in itself would not affect lower trophic levels unless there is a concomitant decrease in predation pressure for prey. Raptors regularly prey on small terrestrial vertebrates and are among the most important diurnal lizard predators in this landscape. We found that both the abundance of predatory birds ($Z = -13.91$, $P < 0.001$, Cohen's $d = 0.84$; Fig. 1d) and the frequency of predation attempts (dive attacks) by raptors on ground-dwelling prey ($Z = -4.45$, $P < 0.001$, Cohen's $d = 0.29$; Fig. 1e) were almost four times lower in sites with wind turbines than those without. As expected from reduced predation pressure, the density of the most dominant terrestrial vertebrate species in this ecosystem, the endemic superb fan-throated lizard *Sarada superba* (Fig. 1c) was significantly higher in sites with wind turbines compared with those without ($Z = 8.93$, $P < 0.001$, Cohen's $d = 0.48$; Fig. 1f).

However, predation is a strong selective force and terrestrial lizards in sites with wind turbines showed differences in physiology, behaviour and even morphology that were consistent with the non-consumptive effects of predator release[14,17,18]. Signatures of reduced predation pressure in sites with wind turbines compared with those without were detected in the lower stress-induced ($t = -2.61$, $P = 0.05$, Cohen's $d = 0.43$) but not baseline ($t = -0.76$, $P = 0.48$) levels of circulating corticosterone in free-ranging *S. superba* (Fig. 2a). Physiological stress coping strategies, especially those mediated by the steroid hormone corticosterone, are sensitive to changes in predation pressure and play a vital role in influencing energy mobilization, as well as behavioural and cognitive processes[27]. In some terrestrial mammals, proximity to wind turbines causes an increase in glucocorticoid levels[9,28], presumably because of the stress and interference induced by mechanical noise and infrasound. In contrast with these findings, the downregulation of the hypothalamus–pituitary–adrenal axis for stress reactivity, but not homoeostatic processes, in lizards from sites with wind turbines, is a good indicator of habituation to an environment with fewer intense (predation) stressors[15]. In response to controlled simulated 'predator attacks' by an approaching human, lizards at sites with wind turbines showed significantly lower approach distances ($Z = -5.41$, $P < 0.001$, Cohen's $d = 0.12$) and flight initiation distances (FIDs) compared with those without ($Z = -5.86$, $P < 0.001$, Cohen's $d = 0.52$). Lizards from sites with wind turbines had FIDs that were five times shorter than those from sites without, allowing researchers to approach within 3 m before fleeing (Fig. 2b). This reduction in the escape responsiveness of lizards in areas with wind turbines directly follows expectations from the low stress-induced levels of corticosterone[29,30]. The study plateau is used for various anthropogenic activities besides clean energy production; local communities graze livestock and extract non-timber resources. Despite the prevalent human activity in the area, lizards showed relaxed physiological stress responses and

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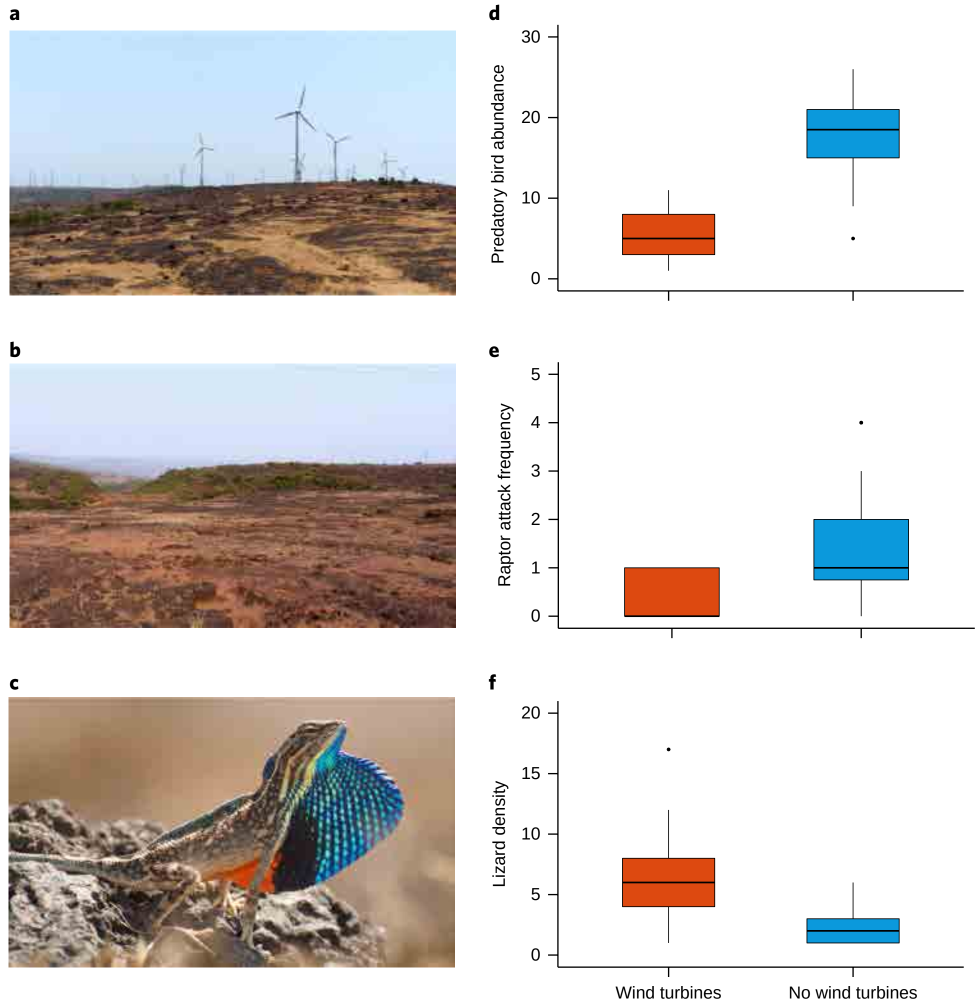

Fig. 1 | Numerical effect of wind turbines on predatory birds and lizard prey. a,**b**, Lateritic habitat on the Chalkewadi plateau (**a**) with ($n=3$ sites) and (**b**) without wind turbines ($n=3$ sites). **c**, The endemic superb fan-throated lizard *S. superba*, which lives on the Chalkewadi plateau. **d**–**f**, Areas with wind turbines (red box plots) had (**d**) a significantly lower abundance of predatory birds (birds per 3 h), (**e**) a significantly lower frequency of raptor attacks on ground-dwelling prey (attacks per 3 h) and (**f**) significantly higher densities of lizards (lizards per 100 m belt transect) compared with areas with no wind turbines (blue box plots). Box plots show the medians, quartiles, 5th and 95th percentiles, and outliers.

anti-predator responses in sites with wind turbines, consistent with the perception of lower predation pressure.

The numerical effects on prey density, as well as shifts in the physiological and behavioural responses to stressors in lizards from sites with wind turbines, are typical effects of predator release on prey in many ecosystems[31]. However, prey can also experience indirect effects of reduced predation pressure mediated through other regulatory mechanisms. Lower predation risk allows for greater foraging opportunities by prey, which can enhance prey growth[32]. However, we found the opposite pattern; free-ranging *S. superba* from sites with wind turbines had lower body condition (that is, they were thinner) than those at sites without (scaled body mass index; $t=24.5$, $P<0.001$, Cohen's $d=0.22$; Fig. 2c). Although we found no differences in habitat or substrate structure, areas with wind turbines may still have lower per-capita food availability (arthropods) because of the higher local lizard densities[33], thereby reducing the body condition of individuals.

Notably, these density-dependent effects in areas with wind turbines not only affected body condition, but also influenced the expression of secondary sexual characteristics. Males of *S. superba* have highly conspicuous blue, black and orange patches on their dewlaps, which are used during inter- and intrasexual communication[34]. We found that males from sites with wind turbines had lower chroma and brightness of the blue (chroma: $t=-3.995$, $P=0.01$, Cohen's $d=0.32$; brightness: $t=-3.40$, $P=0.02$, Cohen's $d=0.23$) and orange (chroma: $t=-2.23$, $P<0.001$, Cohen's $d=0.30$; brightness: $t=-5.40$, $P<0.001$, Cohen's $d=0.30$) patches on their dewlap compared with those from sites without wind turbines (Supplementary Fig. 4). The intensity of colours is a signal of individual quality in many taxa[35]; thus, a reduction in the chroma and brightness of colours in males from areas with wind turbines can have consequences for sexual selection in this population. Sexual ornamentation is known to be enhanced when predation risk decreases[36] and sexual selection increases[37]. Instead, we found that density-dependent competition was a high cost of predator release. High lizard densities under low avian predation risk resulted in greater competition for potentially limiting resources (for example, beetles with high carotenoid content) that are needed to develop enhanced ornamentation.

Wind farms can affect ecological communities in ways that are unexpected and complex. Despite the fact that our study was restricted to a single plateau, we found multiple lines of evidence

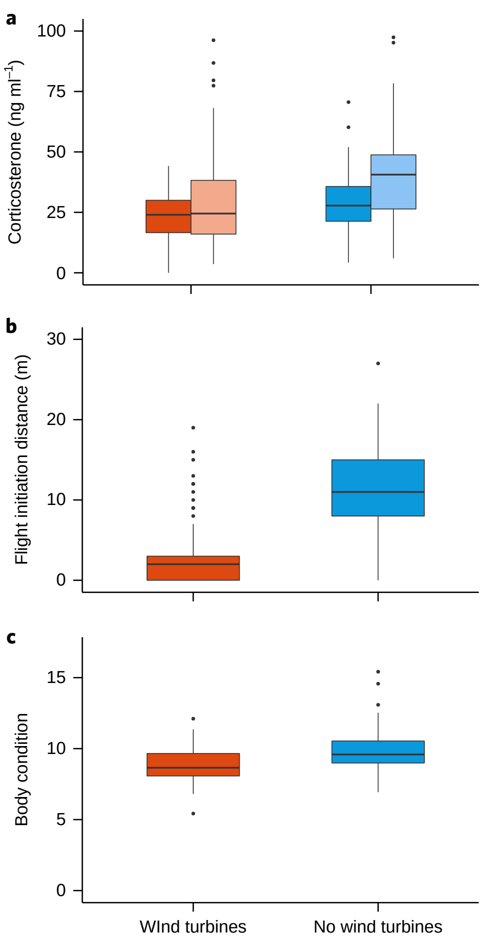

Fig. 2 | The presence of wind turbines influences the phenotypic trait responses of lizards. a–c, *S. superba* from sites with wind turbines (red box plots) had significantly (**a**) lower stress-induced (light box plots), but not baseline (dark box plots), corticosterone levels ($n = 81$ from sites with wind turbines; $n = 63$ from sites without), (**b**) lower anti-predator responses, as measured by FID ($n = 106$ in sites with wind turbines; $n = 73$ in sites without) and (**c**) lower body condition, as measured by scaled body mass index ($n = 89$ from sites with wind turbines; $n = 64$ from sites without) compared with those from sites with no wind turbines (blue box plots). Box plots show the medians, quartiles, 5th and 95th percentiles, and outliers.

for a green-energy-induced trophic cascade. We found that wind turbines do not significantly alter habitat or substrate structure, but they do reduce avian predator abundance and hunting activity (see also refs [23,24]). This large reduction in predator activity lowered the predation pressure for small diurnal terrestrial vertebrates in that area. Numerical changes in prey population size are one of the most conspicuous and rapid consequences of predator release[11]. Consistent with this, we found that densities of the most common lizard species were three times higher in sites with wind turbines compared with those without. We also found strong trait-mediated effects of predator release: lizards at sites with wind turbine not only had lower stress-induced corticosterone levels and anti-predator behavioural responses, but they also had lower body condition and intensity of sexual ornamentation. These population- and individual-level changes in lizards seem to be driven by both the direct (lowered predation pressure) and indirect (increased competition) effects of reduced predation pressure from the top predator guild.

Increasing evidence suggests that humans are an unchecked 'super predator' globally, through their removal of animals[38] and by their induction of fear[39]. Our work shows that even without the direct presence of humans, anthropogenic disturbances such as wind farms act as effective apex predators. By reducing the impact of predatory birds in the area, wind turbines cause a cascade of changes in terrestrial prey, driven primarily by the ecological processes of predator release and density-mediated competition. The loss of apex predators worldwide has resulted in far-reaching consequences for ecosystem processes and stability[11]. Since the locations of wind farms are mainly determined based on economic rather than environmental considerations[40], we stress that the consequences of wind farms are greatly underestimated. While conservation efforts are a necessary global priority, wind farms in unique or biodiverse ecosystems illustrate an unexpected conflict between the goals from the United Nations Paris Agreement[2] for climate change mitigation and Aichi targets from the Convention on Biological Diversity[41].

Methods

Study area. Lateritic plateaus, formed from intense physical and chemical weathering of basaltic rocks, are a unique feature of the northern Western Ghats[19]. These high-altitude (>1,000 m) flat table-topped mountains are characterized by low soil cover and exposed sheet rocks that are mostly devoid of large woody vegetation, giving them a barren appearance. Th s has led to lateritic plateaus being classifi d as 'category 22: barren rocky/stony waste' by the Department of Land Resources, India, even though they support a high diversity of endemic fl ra and fauna[19,20,26]. The unique topographical features of these plateaus, primarily high elevation and absence of large woody vegetation, make them suitable for wind farms. As a consequence, many high-elevation lateritic plateaus in the northern Western Ghats already have wind farms, or are proposed sites for new wind farms[20]. Our study site—the Chalkewadi plateau in Satara district in the northern Western Ghats—has one of the largest and longest-running (~16–20 years) wind farms in the region[20]. Large parts of the Chalkewadi plateau and the adjacent valley lie within the Sahyadri Tiger Reserve and Koyna Wildlife Sanctuary, which are protected and harbour pristine forest habitats[19] (see Supplementary Fig. 1 for a map). These protected areas do not have wind turbines[19,26]. The close spatial proximity of wind farms and undisturbed habitats provides an excellent system for comparison. Although there are no large permanent settlements on the plateau itself, both the eastern and western slopes of the plateau are dotted with several small villages, supporting a substantial pastoralist population. These communities use the plateau as grazing grounds. Hence, there is high human and cattle activity on the plateau, in areas both with and without wind turbines[20].

In this matrix of disturbed habitats (sites with wind turbines) and pristine plateau habitats, we selected six sites (Supplementary Fig. 1): three with wind turbines (13–15 wind turbines in each site) and three without. These sites were approximately 0.5 km^2 in size and about 2 km apart (except 'Enercon' and 'Medha', which were ~1 km apart)—the maximum distance that small-sized agamids (for example, superb fan-throated lizards with a snout-to-vent length (SVL) of <8 cm) are thought to disperse. During the summer months, when this study was conducted, all sites were similar in habitat structure, as determined by a classification of substrate types (see below).

All statistical analyses were done using R statistical software[42]. For all linear and generalized linear models, the model fit was assessed qualitatively, using the distribution of residual versus fitted values, and quantitatively, by comparing small-sample-size-corrected Akaike information criterion (AICc) values of all the competing models. Differences in AICc values (ΔAICc) between the best and second best models are reported for all tests.

Habitat classification. The habitat structure of sites with and without wind turbines was classified at two spatial resolutions. We used remote sensing data with supervised correction methods to classify land-cover types on the entire Chalkewadi plateau into three main categories: (1) rocks/bare ground, (2) vegetation and (3) anthropogenic built-up structures. A satellite image of the plateau containing three bands in the visible-light spectrum (red, blue and green) at a spatial resolution of approximately 5 m for April 2015 was downloaded from an open-source data platform (Bing Maps) and converted into a '.TIFF' format raster before processing in ArcGIS 10.3.1. Pixel reflectance values for bare ground and rocks were indistinguishable and were pooled. We calculated the percentage land cover for each type across the entire plateau and for the individual study areas, and used chi-squared tests to compare the relative proportions of land-cover type between sites with wind turbines and those without. The results from this analysis are reported in Supplementary Fig. 2.

Dry grass is particularly difficult to discriminate from bare ground during the dry summer season using satellite imagery. We therefore also classified substrate types at a finer scale, using sampling plots (1 × 1 m) that we placed randomly at each site ($n = 10$ per site; $n = 60$ in total) during the peak study period (Supplementary Fig. 3). Plots were photographed with a Canon 5D Mark III and Canon 17–55 mm lens. The open-source image-processing software ImageJ was used to measure the relative proportion of the three dominant substrates: (1) rocks, which included boulders and lateritic sheet rocks; (2) bare ground, characterized as the absence of rocks and vegetation; and (3) vegetation (both green and dry). In most of our plots, vegetation was primarily senescent grasses (Supplementary Fig. 3). For each land-cover type, we ran separate generalized linear mixed models with site as a fixed effect and plot as a random effect with negative binomial distribution. To ensure that the six study sites within areas with and without wind turbines did not differ in substrate, we performed post-hoc Tukey's pairwise comparisons using the 'glht' function in the 'multicomp' package in R. The results from this analysis are reported in Supplementary Fig. 3.

Predation pressure. To determine whether small terrestrial vertebrates such as lizards experience lower predation risk in areas with wind turbines, we estimated the abundance of predatory birds and the frequency of raptor attacks on ground-dwelling prey. Predatory bird abundance was estimated from 500 m time-bound transects ($n=32$ 3 h transects) in areas with and without wind turbines over a period of 8 months from August 2012 to March 2013. We sampled four transects per month on two separate days (one day at the start of the month and another at the end). On each day, H.B. walked two transects (once during the morning from 09:00–12:00 and once in the evening from 16:00–19:00). Hence, we had a total of 96 h of observations for each of our treatments. We classified the birds observed during the transect walks as lizard predators based on information from published bird guides[43,44].

Additionally, to get a more direct measure of predation risk, we conducted point counts over the same 8-month period ($n=32$ sampling events) in areas with and without wind turbines. We followed a sampling protocol similar to the one used to measure bird abundances: we sampled each area four times per month on two separate days (one day at the start of the month and another at the end). Each day involved 3 h of observations in the morning (09:00–12:00) and 3 h in the evening (16:00–19:00). For this measure, we selected a vantage point that provided the best possible 360° view of the area with or without wind turbines, at a larger scale than for the replicate site sampling. H.B. counted the number of times an avian predator dived towards the ground. Predator species that were actively hunting mainly included buzzards (*Buteo* and *Butastur* species), eagles and kites (*Elanus* species). The success of avian predator attacks is difficult to ascertain and thus all attempted attacks were counted. We examined differences in bird abundances using a generalized linear mixed model with Poisson error distribution (ΔAICc = 6.66), with treatment (with or without wind turbines) as a fixed effect and month as a random effect. Similarly, for raptor attack frequency, we ran a generalized linear mixed model with Poisson error distribution (ΔAICc = 3.20), with treatment (with or without wind turbines) as a fixed effect and month as a random effect.

Lizard densities. Study sites were far enough apart to restrict the movement of small territorial diurnal lizards between sites during the study period; thus, we were able to accurately estimate site-level lizard density during the peak activity period. At each of the 6 sites, we marked 100 m × 20 m parallel belt transects that were separated by 100 m. The number of transects per site depended on the size and shape of the site. Belt transect surveys are a widely used method for reptile density estimation[45], and work particularly well for non-cryptic species, such as the fan-throated lizard[46,47]. Two observers (A.Z. and H.B.) walked all transects ($n=10$ transects in each site with wind turbines and 10–16 transects in each site without) during the field season in 2014, and recorded the number and sex of lizards that were observed within 10 m on both sides of the transect line. We alternated sampling between sites with wind turbines and those without across days; thus, sampling was done at a new site with new transect locations on each day (that is, there were no repeated measures of the same transect). The numbers of lizards from all transects at each site were analysed using a generalized linear mixed model with a Poisson error distribution (ΔAICc = 36.76), where treatment (with or without wind turbines) was a fixed effect and site as was a random effect.

Hormonal stress reactivity. To measure hormonal stress reactivity, we quantified corticosterone levels from two blood samples obtained from each lizard ($n=144$ in total). Lizards ($n=29$–32 males from each site with wind turbines; $n=15$–30 males from each site without) were captured by hand and the first blood sample was collected within 3 min of sighting ('baseline'). The stress-induced level of corticosterone was determined from a blood sample obtained 30 min after capture, during which a standardized stress-inducing protocol was implemented where lizards were kept in dark cotton bags[48]. All blood samples were taken within a two-month period during the peak breeding season for the species (April to May 2013), and sites with and without wind turbines were visited on alternate days while sampling. Blood samples (70–100 µl each) were collected from the retro-orbital sinus using a heparinized microhaematocrit tube—a standard sampling method that poses little subsequent risk to individuals[29]. All captured individuals were marked on their ventral side with a permanent non-toxic marker and released at the capture site. Blood samples were stored on ice while in the field. Within 6 h of collection, samples were centrifuged and the isolated plasma was stored in 100% ethanol (1:10 dilution). Corticosterone levels were measured from the plasma samples using enzyme immunoassay kits (DetectX; Arbor Assays) after optimization[49]. Baseline and stress-induced samples were diluted at ratios of 1:20 and 1:40, respectively, and assayed in duplicate across 14 plates. The intra-assay coefficient of variation was 4.81%, based on two standards run with each assay plate, and the interassay coefficient of variation was 5.93%. We ran separate linear mixed models (baseline: ΔAICc = 52.65; stress-induced: ΔAICc = 4.76), with treatment (with or without wind turbines) as a fixed effect and site as a random effect to examine the differences in baseline and stress-induced corticosterone levels.

Anti-predator behaviour. FID is a widely used assessment of anti-predator responsiveness in lizards and other animals[50,51] that directly reflects the economics of fleeing[51,52]. Anti-predator behaviours of lizards were collected between 09:00 and 12:00 from all sites within a single week in April 2014. We alternated sampling between sites with wind turbines and those without on subsequent days, such that each site was sampled once, with no opportunity for habituation to our measurement protocol. We measured FID by approaching male and female lizards from the study sites ($n=31$–43 lizards from each site with wind turbines; $n=15$–34 lizards from each site without) at a constant pace, and recording the distance between the lizard and the researcher when the lizard initiated flight. For all lizards ($n=179$ in total), we also recorded the approach distance as the distance between the lizard and observer when the lizard was first spotted and the approach was initiated. After the lizard initiated flight, approach distances and FIDs were measured with a tape measure (if less than 5 m) or range finder (if greater than 5 m). To determine whether FIDs and approach distances varied between treatments (with or without wind turbines), we ran separate generalized mixed models with negative binomial distribution (FID: ΔAICc = 83.73; approach distance: ΔAICc = 31.93), with treatment and site as fixed and random effects, respectively.

Morphology and colour measurements. We caught a total of 153 males ($n=29$–32 lizards from each site with wind turbines; $n=15$–30 lizards from each site without) by hand and measured their mass and SVL using 10 or 20 g Pesola scales (least count = 0.1 g) and standard rulers (least count = 1 mm), respectively. Mass and SVL data were used to calculate a scaled mass index, which is a measure of body condition[53]. To examine differences in body condition, we ran a linear mixed model (ΔAICc = 124.24), with treatment (with or without wind turbines) as a fixed effect and site as a random effect.

To quantify the magnitude and intensity of sexual colouration on lizards[34], we extended and photographed the dewlap of males ($n=29$–32 lizards from each site with wind turbines; $n=15$–30 lizards from each site without) under full sunlight in the field against a neutral grey standard. We used band ratios to classify dewlaps into 'blue', 'black', 'orange' and 'others' (in C++), and extracted red, green and blue (RGB) values for each patch. A linearization function for the camera, in the form of $y=a\times\exp(b\times x)+c\times\exp(d\times x)$, was derived from a photograph of a colour checker standard (X-Rite) taken under the same conditions. Here, a, b, c and d are empirically derived constants specific to the camera and depend on the response of the camera to known reflectance values of six grey scale standards under specific light conditions[54]. Linearized RGB values were then corrected for possible variation in lighting conditions using grey standards in each of the photographs[54]. We used these linearized and equalized RGB values to derive a two-dimensional representation of the colour space, in which the x axis is the standardized difference between red and green channels, calculated as $(R-G)/(R+G+B)$, and the y axis is the difference between green and blue, calculated as $(G-B)/(R+G+B)$. In this colour space, the distance from the origin is the chroma, calculated as $r=(x^2+y^2)^{1/2}$, and the hue is the angle relative to the axis, calculated as $\Theta=\tan^{-1}(y/x)$[55,56]. Brightness is the sum of the red, green and blue values.

Despite some limitations, we chose the photographic method for colour quantification because it has clear advantages over spectrophotometry, especially for field studies[54,57]. Spectrophotometry only provides point measures of colour with no spatial or topographical information. The standardized photographic method of colour analysis enabled us to obtain multiple measures (hue, chroma and brightness) for all the colour patches on male dewlaps[58]. We compared the chroma and brightness of the two colour patches on males between sites with and without wind turbines using linear mixed effect models (blue chroma: ΔAICc = 14.92; blue brightness: ΔAICc = 9.78; orange chroma: ΔAICc = 7.15; orange brightness: ΔAICc = 31.65), with colour measures as the response variable, and treatment and sites as fixed and random effects, respectively.

Ethical approval. This research was approved by the Institutional Animal Ethics Committee at the Indian Institute of Science (CAF/Ethics/396/2014).

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available from the corresponding author upon request.

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Author contributions

M.T. and A.Z. conceived and designed the study, analysed the data and wrote the paper. H.B. conceived and designed the bird data collection. A.Z. and H.B. collected the data. M.T. contributed materials.

Competing interests

The authors declare no competing interests.

Additional information

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n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
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☐	☒	Clearly defined error bars *State explicitly what error bars represent (e.g. SD, SE, CI)*

Our web collection on statistics for biologists may be useful.

Software and code

Policy information about availability of computer code

Data collection	All data were collected in the field by the authors
Data analysis	All data were analysed in R, and we wrote a custom code in C++ to extract color values from digital images of animals.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers upon request. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

The data that support the findings of this study are available from the corresponding author upon request.

Field-specific reporting

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☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/authors/policies/ReportingSummary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We conducted a field experiment where we compared multiple parameters in areas with (n=3 WT study areas) and without windturbines (n = 3 NWT study areas). Each study area was approximately 0.5 km2. We controlled for geography by selecting replicate sites on the same plateau where windturbines (main treatment effect) have been in the same locations for at least 16-20 years. All data were collected over two years, in the peak activity season for lizards (March to June). For land-cover measures, we analysed remote sensed data for the entire plateau. For substrate type analysis, we analysed 10 sampling plots (1x1m) in each of the 6 study areas (N=60 plots total). For avian predator abundance, we walked 4 (3 hour long) transects a month for 8 months, where half the transects were in the morning and the other half were in the evening. For raptor predation events, we conducted 32 vantage point counts (3 hour observation periods each) over 8 months. For lizard density measures, we walked 30 belt transects in WT areas and 39 in NWT areas and recorded all lizards seen. Parallel belt transect was 100 m x 20 m each, separated by 100 m. For hormonal stress reactivity, we measured 81 male lizards from WT areas, and 63 male lizards from NWT areas. Two blood samples were taken from each animal (baseline and stress-induced). Antipredator behaviours were measured by approaching 106 lizards in WT areas and 73 lizards in NWT areas and recording escape responses. Gross morphology was measured on 89 male lizards from WT and 64 male lizards from NWT sites. Dewlap colour measurements were taken from 89 males from WT areas and 60 males from NWT areas.
Research sample	Habitat and substrate measures of the study area were taken from remote sensing and on-ground measurements to demonstrate no significant differences between the structure of windturbine and non windturbine areas. Behavioral assays of predation risk was measured by (1) counting the number of avian predators seen, and (2) counting the number of times a raptor (typically Buteo sp., Butastur sp., or Elanus sp.) was seen dive bombing the ground. The rest of the samples were measures of behaviour, morphology and physiology of the superb fan-throated lizard, Sarada superba that live in areas with and without windturbines.
Sampling strategy	For the landscape-level measurement of landcover, we measured the entire study area. Sample size for substrates on the ground were decided based on overall low variability seen on the plateau. Sampling plots were evenly dispersed across each study area (see Supplementary figure 1). Sample sizes for lizards varied based on the measurements. For blood sampling, only lizards caught within 3 min of sighting were included to ensure a baseline measure of corticosterone. Capture of lizards also had to be spread out in space to ensure that capture of one individual did not elevate the stress hormones of neighbouring lizards. A similar spacing protocol was used for the measure of antipredator behaviour so that the "attack" of one individual would not affect the response of nearby individuals. Sample sizes for morphology and dewlap colour were based on the number of lizards that we were permitted to catch based on our research permit and ethics clearance. Lizards used for morphological measurements were also a different subset from the lizards that were sampled for the antirpredator and hormone measures to ensure than prior disturbance by us would not adversely influence the morphology and colour.
Data collection	All data were collected in the field by AZ and HB during the peak activity period of the lizard species. Data was collected continuously and the different measures were taken throughout the sampling season.
Timing and spatial scale	Everyday from March to June on 2013 and 2014
Data exclusions	No collected data were excluded from the analysis.
Reproducibility	These data were generated from field measures and thus could not be examined for experimental reproducibility. Analysis of data from replicate sites within treatments (windturbine vs no-windturbine) show low variance and thus support the fact that within treatment variation is lower than between treatment variation. We include cohen's d for all the statistical analyses.
Randomization	Visit to sampling sites were randomized across days and sampling type (behaviour, morphology, physiology). Care was taken to spread sampling out across space to ensure as much coverage of the environment as possible.
Blinding	Field data on wild caught animals (density, behaviour, morphology) could not be collected blind. Analyses of blood samples and dewlap colour from digital images were conducted blind, with relabeled codes.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Rocky lateritic plateau with little vegetation cover. Average temperature during the study season = 34degC (range = 21degC - 45degC). Average precipitation during the study season = 122mm (range =6mm - 152mm). Annual temperature = 26degC and annual precipitation = 91mm
Location	Chalkewadi plateau in the Western Ghats, Mahahastra, India. 17deg36'40"N; 73deg47'27"E

Access and import/export	We have Animal ethics permits from the Indian Institute of Science Animal Ethics Committee and collection/research permits from the state forest department. No import/export permits were required.
Disturbance	Disturbance of the environment was minimal, as most measurements were observational data. And all animals caught were returned to site of capture.

Reporting for specific materials, systems and methods

Materials & experimental systems

n/a	Involved in the study
☒	☐ Unique biological materials
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☐	☒ Animals and other organisms
☒	☐ Human research participants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Animals and other organisms

Policy information about studies involving animals; ARRIVE guidelines recommended for reporting animal research

Laboratory animals	none
Wild animals	Several raptor species: only obervational data. Superb fan-throated lizard, Sarada superba. For density estimation and antipredator behaviours, adults were not captured. For morphology, males were captured by hand, measured immediately, and released at site of capture within 30 min. For physiology, males were capture by hand, and were placed in individual cotton bags for up to 30 min before a second blood sample was taken (stress-induced corticosterone measure). While in cloth bags, lizards were kept in the shade. All lizards captured for physiological measurements were released at their exact location of capture within 45 min.
Field-collected samples	Blood samples were stored in microcentrifuge vials in ETOH and kept cool until analysis in the lab.

EXHIBIT
15

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Wind Turbine Noise and Sleep: Pilot Studies on the Influence of Noise Characteristics

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Abstract: The number of onshore wind turbines in Europe has greatly increased over recent years, a trend which can be expected to continue. However, the effects of wind turbine noise on long-term health outcomes for residents living near wind farms is largely unknown, although sleep disturbance may be a cause for particular concern. Presented here are two pilot studies with the aim of examining the acoustical properties of wind turbine noise that might be of special relevance regarding effects on sleep. In both pilots, six participants spent five consecutive nights in a sound environment laboratory. During three of the nights, participants were exposed to wind turbine noise with variations in sound pressure level, amplitude modulation strength and frequency, spectral content, turbine rotational frequency and beating behaviour. The impact of noise on sleep was measured using polysomnography and questionnaires. During nights with wind turbine noise there was more frequent awakening, less deep sleep, less continuous N2 sleep and increased subjective disturbance compared to control nights. The findings indicated that amplitude modulation strength, spectral frequency and the presence of strong beats might be of particular importance for adverse sleep effects. The findings will be used in the development of experimental exposures for use in future, larger studies.

Keywords: wind turbine noise; sleep disturbance; experimental study; amplitude modulation; polysomnography

1. Introduction

Wind is a renewable, sustainable source of power. Gross electricity consumption from wind energy in the European Union (EU) member states increased more than threefold between 2004 and 2014, a trend which can be expected to continue in order to fulfil EU climate goals for 2020 [1]. However, with the increase in wind power, more people will consequently live near wind turbines and are at risk of exposure to wind turbine noise (WTN).

According to the World Health Organization (WHO), an estimated 1.0–1.6 million healthy life years are lost each year due to environmental noise in Western Europe alone [2]. Sleep disturbance is the greatest contributor to this loss, accounting for approximately 900,000 years lost annually. Sleep is a physiological state necessary for maintaining mental and physical well-being [3]. Disturbed sleep can have a negative impact on many aspects of health and wellbeing, including impairment of attention [4], memory consolidation [5,6], neuroendocrine and metabolic functions [7,8], mood [9] and overall quality of life [10]. Night-time noise also affects autonomic functions [11,12], and epidemiological studies have demonstrated that long-term exposure to night-time environmental noise may increase the risk for developing cardiovascular disease [13,14].

While sleep disturbance by certain types of environmental noise has been relatively well investigated, particularly transportation noise from rail, air and road traffic [11], there is a relative lack of knowledge regarding the effects of WTN on sleep. Cross-sectional studies in communities with nearby wind farms have demonstrated that WTN causes both annoyance [15–19] and self-reported sleep disturbance [18,19] in a proportion of residents. A recent meta-analysis reported that self-reported high sleep disturbance increased with each A-weighted 10 dB increase in predicted outdoor nocturnal WTN (odds ratio = 1.60, 95% confidence interval: 0.86–2.94) [20]. However, this effect was not statistically significant, and the authors of the meta-analysis concluded that studies with objective measures of sleep and WTN were needed. The results of the meta-analysis were used by the WHO to conclude recently that public health recommendations could not be made for night-time WTN levels, since the quality of evidence was too low [21], assessed via the GRADE approach [22] adopted by the WHO. Low quality evidence in the GRADE approach can be interpreted as "further research being very likely to have an important impact on the certainty of the effect estimate and is likely to change the estimate" [21].

At present, effects of WTN have mainly been evaluated using subjective means, and only a few studies have investigated the physiologic response to WTN during sleep. Using wrist actigraphy, Michaud et al. measured sleep of individuals living 0.25–11.22 km from operational wind turbines to examine whether there was an association between objectively measured sleep disturbance and calculated outdoor WTN levels [23]. They found no consistent relationship between sleep disturbance and sound pressure level (SPL) averaged over one year. In another study, Jalali et al. measured sleep using polysomnography (PSG) in participants' homes, both pre- and post- wind turbine installation and operation [24]. They found no significant differences for any of the measured sleep variables. However, they also did not find any significant differences in SPLs measured in the bedrooms prior to- and after the wind turbines began operating.

Disturbance from noise depends not only on SPL but also on the characteristics of the noise [25]. The main source of noise from modern wind turbines is aerodynamic noise generated when air passes over the rotor blades [26]. Varying wind speed at different locations in the space swept by the rotor blades can lead to an amplitude modulated sound [27], which may be a possible source of disturbance as it is easily perceived and poorly masked by ambient background noise [15]. WTN is also unpredictable as it varies with wind speed and meteorological conditions [28]. Additionally, WTN is not necessarily attenuated during night-time; in fact, WTN levels may increase during stable atmospheric conditions which occur during the night to a greater extent than during daytime [29,30].

When dose-response curves for WTN levels and annoyance have been compared to previously established dose-response curves for other types of environmental noise (industrial and transportation noise), higher proportions of annoyed residents have been found for WTN at equal SPLs [17,31]. It is likely that several factors other than noise level contribute to response, including respondents' general attitude towards wind turbines and the experience of procedural fairness or injustice. Furthermore, one possible source of additional annoyance could be that certain characteristics of WTN are more disturbing [31] than those of other types of environmental noise. It is unclear at present whether such acoustical characteristics of WTN are also of relevance for noise-induced effects on sleep.

Because of the need for further research, we implemented a project named Wind Turbine Noise Effects on Sleep (WiTNES), the primary aim of which is a better understanding of causal links between WTN and sleep impairment. Within the project, a method was developed for synthesising WTN, allowing us to generate WTN with no background noise such as traffic, wildlife or meteorological phenomena, and also allowing for manipulation of different acoustical parameters of the noise [32]. Frequency-dependent outdoor to indoor attenuation curves for WTN level were also developed, allowing us to reproduce WTN spectra for indoor locations such as bedrooms, which is relevant for effects on sleep [33]. The present paper presents two pilot studies investigating the effect of wind turbine noise on physiologically measured sleep, conducted with the intention to guide the design and implementation of a larger-scale main study. Of primary interest was aiding the design of sound exposures for the main study. To our knowledge, these are the first studies investigating the effects of wind turbine noise on sleep under controlled laboratory conditions.

2. Methods

2.1. Experimental Design Overview

Two experimental studies were performed: Study A and Study B. Both studies used a within-subject design, with participants sleeping for five consecutive nights in a sound environment laboratory. Baseline sleep measured during a control night was compared to sleep measured during three nights where participants were exposed to WTN. These exposure nights involved variations of outdoor SPLs and frequency content due to outdoor-indoor filtering, simulating a bedroom with a window being slightly open or closed. Furthermore, within exposure nights there were variations in the acoustic characteristics of WTN.

2.2. Experimental Procedure

In order to make the study environment as ecologically valid as possible, the laboratory was outfitted to resemble a typical apartment, with further details and photographs available elsewhere [34]. It contained a combined kitchen and living area, three separate bedrooms and three lavatories. This allowed three individuals to participate concurrently during a given study period, sharing communal areas but sleeping privately. Each of the bedrooms was furnished with a single bed, a desk, a nightstand, chair and lamps. Low frequency noise (≤125 Hz) was introduced through eighty-eight loudspeakers (Sub-Bass modules, Mod. 4 × 10 in, Jbn Development AB, Örnsköldsvik, Sweden) mounted in the ceilings of the bedrooms. Higher frequencies (>125 Hz) were reproduced via two loudspeaker cabinets in the upper corners of the rooms (C115, frequency response 80–20,000 Hz, Martin Audio, High Wycombe, United Kingdom). Lights out was at 23:00 and an automated alarm in the bedrooms woke the participants at 07:00. To ensure there was sufficient time for PSG electrode placement (see below) and relaxation before going to bed, participants were required to arrive at the laboratory by 20:00 each evening. In order to allow participants to adapt to the unfamiliar environment and the PSG equipment used to measure sleep, the first night was a habituation night without exposure to WTN. Data from this night were not used in the analyses. The second night was an exposure-free control night used to measure baseline sleep. During nights 3–5, participants were exposed to WTN. The order of exposure nights was varied between study weeks, however there were only two study weeks in each of the studies and hence the order of nights was not perfectly counterbalanced. A low background noise (18 dB L_{Aeq}) simulating ventilation noise was played into the bedrooms throughout the study, as otherwise the background level was unnaturally low (≤13 dB L_{AEq}). Questionnaires were completed by study participants within 15 minutes of waking up. To avoid potential confounders that might affect sleep, participants were prohibited from daytime sleeping, caffeine consumption after 15:00 and alcohol consumption at any time during the studies.

2.3. Polysomnography

Sleep can be broadly classified into two states, rapid eye movement (REM) sleep and non-REM (NREM) sleep. NREM is further divided into three stages which are—in order of increasing depth—N1, N2 and N3 [35]. Different sleep stages have different characteristics in the electroencephalogram

(EEG), so we measured physiologic sleep using PSG. We recorded the surface EEG with derivations C3-A2, C4-A1, F3-A2, F4-A1, O1-A2 and O2-A1, electrooculogram and submental electromyogram. Additionally, the electrocardiogram was recorded with two torso electrodes, and pulse, blood oxygen saturation and plethysmogram were recorded using a finger pulse oximeter. Sampling and filter frequencies and placements of electrodes were in line with the American Academy of Sleep Medicine (AASM) guidelines [35]. All data were recorded offline onto an ambulatory PSG device (SOMNOscreen Plus, Somnomedics, Randersacker, Germany). Scoring of the PSG data was performed in line with AASM guidelines [35] by a single experienced sleep technologist who was blind to the study design. EEG arousals, which are abrupt changes in the EEG frequency and sometimes considered indicators of sleep fragmentation [36], were scored as per the American Sleep Disorders Association criteria [37]. Arousals lasting longer than 15 s were classed as awakenings.

Objective sleep variables of interest were sleep onset latency (SOL); total duration and maximum continuous time in stages wake (W), N1, N2, N3 and REM sleep; REM and N3 latency; sleep efficiency (SE); sleep period time (SPT): total sleep time (TST); wakefulness after sleep onset (WASO); timing of first and final awakenings; and the number and frequency of sleep stage changes (SSCs), arousals and awakenings. SOL was the time from lights out until the first non-wake epoch. REM and N3 latencies were the time from sleep onset until the first occurrence of REM or N3 respectively. SPT was the time from sleep onset until the final awakening. WASO was the time spent in W after sleep onset until the final awakening. TST was SPT minus WASO. SE was TST divided by time in bed (TIB, 480 min). SSCs were defined as transitioning from one sleep stage to a lighter stage. Transitions to W were not defined as SSCs but as awakenings. REM sleep was defined as the lightest sleep stage and hence no SSCs could occur from REM. Therefore, SSCs could occur from N3 to N2, N1 or REM, from N2 to N1 or REM and from N1 to REM.

2.4. Questionnaires

In laboratory studies, numerical scales with fixed end points and Likert scales have previously proved capable of detecting the effects of single nights of noise on morning tiredness and perceived sleep quality and depth [38,39], and have been correlated with certain objective sleep measures [40]. Subjective sleep quality was therefore assessed both using an eleven-point numerical scale (anchor points Very poor–Very good) and a five-category Likert scale (Very good; Good; Not particularly good; Poor; Very poor). Nocturnal restoration (anchor points Very tired–Very rested; Very tense–Very relaxed; Very irritated–Very glad) and self-assessed sleep (anchor points Easy to sleep–Difficult to sleep; Better sleep than usual–Worse sleep than usual; Slept deeply–Slept lightly; Never woke–Woke often) were assessed using eleven-point numerical scales.

Questions pertaining to noise-specific effects on sleep were adapted from recommendations for annoyance questions by the International Commission on the Biological Effects of Noise [41]. An eleven-point numerical scale was used to assess how much participants perceived that WTN disturbed their sleep (anchor points Not at all–Extremely) and four five-category Likert scales were used to investigate whether WTN caused poor sleep, wakeups, difficulties falling back to sleep and tiredness in the morning (Not at all, Slightly, Moderately, Very, Extremely). Also included on the questionnaire were items regarding perceived sleep latency, number of awakenings and whether participants found it difficult or easy to fall asleep following awakenings. The complete questionnaire is presented in the Supplemental Methods.

2.5. Noise Exposure: Study A

Following analysis of field measurements of WTN, three eight-hour night-time exposures of WTN were synthesised (hereafter termed Nights A1, A2 and A3) [32,33]. We varied the noise levels to correspond to different outdoor sound pressure levels in the three nights and used different outdoor-indoor filters to simulate the bedroom window being slightly open (window gap) or closed (Table 1). These resulting indoor noise spectra are given in Supplemental Figure S1. To allow investigation of differential effects of different WTN scenarios, eight periods with different sound character, each 400 s in duration, occurred in each hour of each night. Across the eight hours of the night, the ordering of these sound character periods was balanced in a Latin square so that any period would only follow and precede any other period once. Each hour ended with a 400 s period with no WTN. Based on analysis of existing sound characteristics of WTN [32], the noise scenarios differed in SPL, amplitude modulation (AM) strength (3–4 dB, 7–9 dB, 12–14 dB), rotational frequency of the turbine blades, AM frequency bands (low- or middle-frequency) and the presence or absence of strong beats (Table 2). AM is a rhythmic fluctuation in the noise level, and its calculation is described in detail elsewhere [32]. Beats are in this context defined as strong AM in the frequency range 400–2500 Hz. The spectrum for each sound character period is presented in Supplemental Figure S2.

Table 1. Simulated outdoor and indoor sound pressure levels and frequency filtering used in exposure Nights A1, A2 and A3 in Study A.

Exposure Night	$L_{AEq,8h,outdoor}$ (dB)	$L_{AEq,8h,indoor}$ (dB)	Filtering
Night A1	40	29.5	Window gap
Night A2	45	34.1	Window gap
Night A3	50	33.7	Window closed

Indoor levels were measured at the pillow position. $L_{AEq,8h,outdoor}$ = Outdoor A-weighted equivalent noise level over the 8 h night-time period. $L_{AEq,8h,indoor}$ = Indoor A-weighted equivalent noise level over the 8 h night-time period.

Table 2. Overview of the 400 s sound character periods within each hour in Study A.

Period	L_{AEq} Relative to 8-h Level (dB)	Rotational Frequency (rpm)	AM Strength	AM Frequency Band (Hz)	Beats
1	−2.5	15	7–9 dB	500–2000	No
2	-	15	7–9 dB	500–2000	No
3	+2.5	15	7–9 dB	500–2000	No
4	-	13	7–9 dB	80–315	No
5	-	17	12–14 dB	500–2000	Yes
6	-	14	3–4 dB	500–2000	No
7	-	15	12–14 dB	500–2000	No
8	-	18	12–14 dB	500–2000	Yes
9	No WTN				

Sound character was varied in level, turbine rotational frequency, amplitude modulation (AM) strength, AM frequency band and presence or absence of strong beats. Periods 1–8 were counterbalanced across the 8 night-time hours. Period 9 was always the final 400 s of each hour. L_{AEq} = A-weighted equivalent noise level.

2.6. Noise Exposure: Study B

In Study B the noise level, outdoor-indoor filtering and the frequency band of the amplitude modulation were varied between nights (Table 3). These resulting indoor noise spectra are given in Supplemental Figure S3. Within nights, there were variations in AM strength, rotational frequency and the presence or absence of beats. Unlike Study A, each factor had only two levels, giving a 2 × 2 × 2 factorial design, in order to allow comparison between specific sound characters (see Table 4). Each period was 400 s in duration and each hour ended with a WTN-free 400 s period. The periods were presented in a Latin square as described for Study A. The noise spectrum was kept the same for each sound character period, and is given in Supplemental Figure S4.

Table 3. Outdoor and indoor sound pressure levels, frequency filtering and AM frequency bands used in exposure Nights B1, B2 and B3 in Study B.

Exposure Night	$L_{AEq,8h,outdoor}$ (dB)	$L_{AEq,8h,indoor}$ (dB)	Filtering	AM Frequency Band (Hz)
Night B1	45	32.8	Window gap	160–500
Night B2	45	32.8	Window gap	80–315
Night B3	50	30.4	Window closed	80–315

Indoor levels were measured at the pillow position. $L_{AEq,8h,outdoor}$ = Outdoor A-weighted equivalent noise level over the 8 hour night-time period.

Table 4. Overview of the 400 s sound character periods within each hour in Study B.

Period	Rotational Frequency (rpm)	AM Strength	Beats
1	13	3–4 dB	No
2	17	3–4 dB	No
3	13	12–14 dB	No
4	17	12–14 dB	No
5	13	3–4 dB	Yes
6	17	3–4 dB	Yes
7	13	12–14 dB	Yes
8	17	12–14 dB	Yes
9	No WTN		

Sound character was varied in turbine rotational frequency, amplitude modulation (AM) strength, and presence or absence of strong beats. Periods 1–8 were counterbalanced across the 8 night-time hours. Period 9 was always the final 400 s of each hour.

2.7. Participants

For each of the two studies, six young, healthy participants were recruited via public advertising. Participants in study A (4 women, 2 men) had a mean age of 22.2 years, (standard deviation SD ± 1.3 years) and a mean body mass index (BMI) of 22.6 kgm^{-2} (SD ± 2.4 kgm^{-2}). Participants in study B (5 women, 1 man) had a mean age of 24.0 years (SD ± 2.3 years) and a mean BMI of 20.7 kgm^{-2} (SD ± 0.4 kgm^{-2}). Participants were screened prior to acceptance with the following exclusion criteria: any self-reported sleep-related disorders; sleeping patterns deviating from the intended sleeping hours in the study; tobacco or nicotine use; dependent on caffeine; regular medication affecting sleep; any self-reported hearing disorders including but not limited to hearing loss, tinnitus and hyperacusis. In order to avoid an increased risk of breathing problems or obstructive sleep apnoea among participants, they were required to have a BMI within the normal range (18.5–24.99 kg/m^{-2}). Before acceptance, participants had their hearing tested using pure tone audiometry between 125–8000 Hz to a screening level of 15 dB HL. All participants in both Study A and Study B were classed as being noise sensitive via a single item in the screening questionnaire. All subjects gave their informed consent for inclusion before they participated in the study, and were financially compensated for taking part in the studies. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Gothenburg Regional Ethical Review Board (Dnr 974-14).

2.8. Statistical Analysis

Statistical analyses were performed in SPSS 22 (IBM Corp., Armonk, NY, USA), employing non-parametric methods. Differences between nights were tested using Friedman tests (within-subject), and if a main effect was found then pairwise comparisons were performed using Wilcoxon signed-rank tests. As a pilot, the primary aim of Study A was not hypothesis testing, but rather to inform on the exposures to be used in future, larger studies [42]. Therefore, analyses were restricted to differences between-nights for PSG variables. In Study B, differences across nights for sound character periods 1–9 across nights were additionally analysed. Time in sleep stages N1, N2, N3 and REM were analysed as fractions of TST. To avoid overlooking any potentially relevant outcomes, a significance level of <0.1 was used, and corrections for multiple comparisons were abdicated. All results should therefore be interpreted with this consideration. Median and interquartile range (IQR) values are reported.

3. Results

3.1. Study A: Sleep Micro- and Macro-Structure

Mean values of each PSG variable in each study night are given in Supplemental Table S1. One female participant was excluded from analysis of absolute variables as she woke herself up early following two exposure nights. The ratio of events per hour of TST was analysed for cortical reactions:

SSCs, arousals, awakenings and combined EEG reactions (the latter taking all three together). There was a significant main effect of the frequency of awakenings (χ^2(df = 3) = 9.0, p = 0.029, Figure 1). Awakenings occurred more frequently during nights with indoor noise levels of 34 dB (window closed, Night A3) than in the control night (p = 0.046) and nights with 30 or 34 dB with the window slightly open, (Nights A1 and A2, p = 0.028 and p = 0.028 respectively).

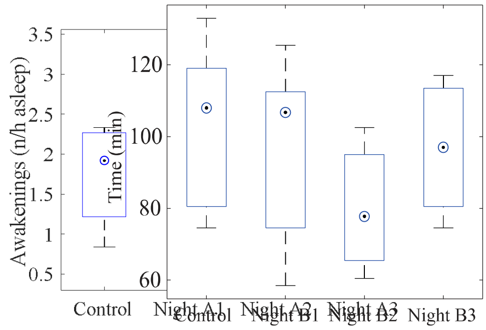

Figure 1. Frequency of awakenings per hour in Study A. Median (◉), interquartile range (boxes) and maximum/minimum values (whiskers).

There were no significant main effects between nights for the frequency of arousals, SSCs or combined EEG reactions, or for measures of sleep macrostructure SOL, N3 latency, WASO, time or maximum continuous time in stages W, N1, N2, N3 or REM.

3.2. Study A: Self-Reported Sleep

There was a significant main effect of perceived sleep disturbance by WTN (Table 5) where, relative to the control night, disturbance was greater in Night A2 (p = 0.042) and Night A3 (p = 0.066). There was also a significant difference in WTN causing tiredness in the morning, with post-hoc tests revealing that Night A3 caused more tiredness in the morning compared to the control night (p = 0.059). No significant main effects were found for any of the variables relating to sleep quality, nocturnal restoration, perceived sleep latency or number of recalled awakenings.

Table 5. Self-reported sleep variables where a main effect of night was found in Study A.

Sleep Measure	Median (IQR) Control	Night A1	Night A2	Night A3	χ^2	p Value
Sleep disturbance by WTN (0 = Not at all, 10 = Extremely)	0 (0–0.75)	0 (0–2.5)	1.5 (0.75–4)	2.5 (0–4.75)	7.227	0.065
WTN cause tiredness in the morning (Not at all = 1; Extremely = 5)	1 (1–1)	1 (1–2.25)	1 (1–2.25)	2 (1–2.25)	6.400	0.094

IQR = Interquartile range.

3.3. Study B: Sleep Micro- and Macro-Structure

3.3.1. Differences between Nights

Mean values of each PSG variable in each study night are given in Supplemental Table S2. There was a main effect on time spent in N3 (χ^2(df = 3) = 6.310, p = 0.097, Figure 2A), with a significant reduction in N3 sleep in exposure Night B2 compared to the control night (p = 0.043) and Night B3 (p = 0.046). There was a significant main effect of first awakening (χ^2(df = 3) = 9.400, p = 0.024, Figure 2B), with the first awakening occurring earlier in Night B2 compared to Night B1 (p = 0.028) and Night B3 (p = 0.028). There was a main effect of maximum continuous time in stage N2 ($N2_{max}$), (χ^2(df = 3) = 10.200, p = 0.017, Figure 2C), where $N2_{max}$ was shorter in Night B1 (p = 0.027) and Night B3 (p = 0.027) compared to the control night. Furthermore, $N2_{max}$ was shorter in Night B1 (p = 0.046) and Night B3 (p = 0.028) compared to Night B2. No significant main effects were found for SOL, REM or N3 latencies, total number of SSCs, WASO or SPT.

B3 ($p = 0.028$). There was a main effect of maximum continuous time in stage N2 ($N2_{max}$), ($\chi^2(df = 3) = 10.200$, $p = 0.017$, Figure 2C), where $N2_{max}$ was shorter in Night B1 ($p = 0.027$) and Night B3 ($p = 0.027$) compared to the control night. Furthermore, $N2_{max}$ was shorter in Night B1 ($p = 0.046$) and Night B3 ($p = 0.028$) compared to Night B2. No significant main effects were found for SOL, REM or N3 latencies, total number of SSCs, WASO or SPT.

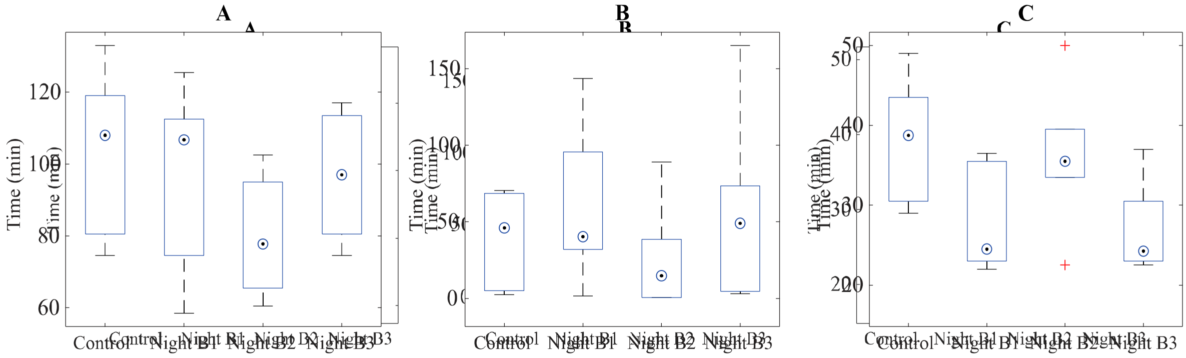

Figure 2. Median (⊙), interquartile range (boxes) and maximum/minimum values (whiskers) for objective sleep parameters from Study B. (**A**) Total time in N3. (**B**) Time between sleep onset and first awakening. (**C**) Maximum continuous time in N2 sleep.

3.3.2. Effects of Sound Character Period between Experimental Nights

Main effects were found for percentage of N1 sleep in Period 6, percentage of N3 sleep in Period 4 and for time awake in Period 3 and 7 (Table 6). Participants spent more time awake in Period 7 in Night B1 ($p = 0.042$) and Night B3 ($p = 0.026$) compared to in the control night. However, post-hoc comparisons revealed no significant between-night differences for time awake in Period 3. The percentage of N1 sleep in Period 6 was higher in Night B2 compared to the control night ($p = 0.028$). There was a higher percentage of N1 sleep in Period 6 in Night B2 compared to the control night ($p = 0.028$). The percentage of N3 sleep in Period 4 was significantly lower in Night B2 compared to the control night ($p = 0.046$), Night B1 ($p = 0.028$) and Night B3 ($p = 0.028$).

Table 6. Objective sleep variables where a main effect of WTN sound character period was found in Study B.

Sleep Measure	Period	Median (IQR) Control	Night B1	Night B2	Night B3	χ^2	p-Value
Time awake (min)	3 [a]	1 (0.50–1.63)	0.75 (0.50–1.25)	1.75 (0.75–5.13)	2 (0.88–2.88)	7.000	0.072
Time awake (min)	7 [b]	0.75 (0.38–1.13)	1.75* (1.50–2.0)	1.25 (0.50–2.75)	6.63* (5.74–7.52)	8.509	0.037
N1 (%)	6 [c]	6.63 (5.74–7.52)	6.37 (0.71–13.84)	11.32* (8.47–15.64)	4.69 (1.81–5.27)	11.400	0.010
N3 (%)	4 [d]	26.77 (21.24–29.41)	29.12 (13.60–33.02)	4.60*† (0–13.58)	27.22 (18.72–32.89)	10.900	0.014

[a] 13 rpm, strong AM, no beats; [b] 13 rpm, strong AM, beats; [c] 17 rpm, weak AM, beats; [d] 17 rpm, strong AM, no beats. Significant ($p < 0.05$) post-hoc differences to the control night are denoted *. Significant ($p < 0.05$) post-hoc differences to both Night B1 and Night B3 are denoted †. IQR = Interquartile range.

Cortical reaction frequencies (arousals, awakenings and SSCs) were calculated for similar sound character periods and analysed to examine whether any specific sound characteristic was of particular importance (Supplemental Figure S5). There were no significant main effects for arousals ($p = 0.649$), awakenings ($p = 0.197$) or SSCs ($p = 0.191$).

3.3.3. Study B: Self-Reported Sleep

Main effects between-nights were found for tiredness in the morning, tension in the morning, difficulties falling asleep, perceived sleep disturbance due to WTN. Furthermore, main effects were found for whether WTN caused poor sleep, awakenings difficulties falling asleep after awakenings or tiredness in the morning (Table 7).

Table 7. Self-reported sleep variables in Study B.

Sleep Measure	Median (IQR)				χ^2	*p*-Value
	Control	Night B1	Night B2	Night B3		
Sleep quality (Very good = 0, Very poor = 10)	3 (2.75–6.50)	4.5 (2–5.5)	4.5 (1–7.5)	6 (4.25–6.25)	0.911	ns
Verbal sleep quality (Very good = 1, Very poor = 5)	2 (2–2.25)	2 (1.75–4)	2 (1–2.75)	3 (2–3.25)	3.692	ns
Very rested (0)–Very tired (10)	2.5 (1.75–3.25)	5.5 * (1.75–6.25)	2.5 (1.5–6.75)	5.5 * (4–7)	9.367	0.025
Very relaxed (0)–Very tense (10)	3 (2.5–3.5)	4.5 (1–6)	3 (1–4.25)	5.5 *† (4.5–7)	8.625	0.035
Very glad (0)–Very irritated (10)	2 (0.75–4.75)	3.5 (1.75–7)	4 (1–4.5)	5.5 (3.75–6.25)	5.308	ns
Time to fall asleep (min)	15 (8.75–22.5)	27.5 (15.5–38.75)	15 (8.75–46.25)	25 (16.25–42.50)	3.808	ns
Estimated number of wakeups (n)	2 (2–3)	2 (2–4.25)	2.5 (1.75–4)	3 (1.75–3)	0.796	ns
Easy to sleep (0)–Difficult to sleep (10)	3 (0.75–4)	6 * (2.75–8)	2.5 (1–7.25)	6.5 * (4.25–8)	8.793	0.032
Slept better than usual (0)–Worse than usual (10)	5 (4.25–7.25)	6 (4.75–8.25)	5 (2.75–7.5)	7 (6–8.25)	3.982	ns
Deep sleep (0)–Light sleep (10)	3 (2.5–4.25)	6 (2–7.5)	3.5 (1.75–6.75)	6 (3–7.25)	3.911	ns
Never woke (0)–Woke often (10)	6.5 (5–7.25)	4 (2.75–9)	4 (3.25–5)	6 (2.75–7)	0.661	ns
Sleep disturbance by WTN (0 = Not at all, 10 = Extremely)	0 (0–0.25)	2.5 *† (2–7.25)	2.5* (1–4.5)	6 *‡† (3.5–6.25)	14.722	0.002
WTN cause poor sleep (Not at all = 1, Extremely = 5)	1 (1–1)	2 * (1–3.25)	2 (1–3)	3 * (2–3)	10.432	0.015
WTN cause awakenings (Not at all = 1, Extremely = 5)	1 (1–1.25)	1.5 (1–3.25)	1.5 * (1–2.25)	2.5 * (1.75–3.25)	9.250	0.026
WTN cause difficulties falling back to sleep (Not at all = 1, Extremely = 5)	1 (1–1)	2.5 * (1.75–4)	2 * (1.75–2)	3 * (1.75–3.25)	9.889	0.020
WTN cause tiredness in the morning (Not at all = 1, Extremely = 5)	1 (1–1.25)	2 * (2–4)	2 (1.75–3.25)	3 *† (2.75–4)	15.125	0.002

Sleep quality was coded such that the scales are in the same direction as for other items, i.e., a higher value indicates worse sleep. *p*-values relate to tests of main effects. ns = not significant ($\alpha = 0.1$). Significant ($p < 0.1$) post-hoc tests are denoted * (compared to control night); ‡ (compared to Night B1); † (compared to Night B2). IQR = Interquartile range.

Relative to the control, after Night B1 participants were more tired ($p = 0.063$), had greater difficulty falling asleep ($p = 0.072$) and were more disturbed by WTN ($p = 0.026$). In Night B1, WTN-induced poor sleep ($p = 0.066$), WTN-induced difficulty falling asleep after awakenings ($p = 0.041$) and WTN-induced tiredness ($p = 0.024$) were rated deleteriously compared to the control night. Additionally, perceived disturbance from WTN was greater in Night B1 than Night B2 ($p = 0.066$).

Relative to the control, participants in Night B2 were more disturbed by WTN ($p = 0.027$) and reported more WTN-induced awakenings ($p = 0.083$) and WTN-induced difficulty falling asleep after awakenings ($p = 0.025$).

Relative to the control, participants in Night B3 were more tired ($p = 0.026$), more tense ($p = 0.041$), had more difficulty falling asleep ($p = 0.027$) and were more disturbed by WTN ($p = 0.027$). Furthermore, they indicated more WTN-induced poor sleep ($p = 0.023$), more WTN-induced awakenings ($p = 0.038$), greater WTN-induced difficulty falling asleep after awakenings ($p = 0.039$) and increased WTN-induced tiredness in the morning ($p = 0.024$). Furthermore, tension ($p = 0.043$) and WTN-induced sleep disturbance ($p = 0.068$) were greater following Night B3 than Night B2. WTN-induced tiredness was higher following Night B3 than Night B1 ($p = 0.083$) and Night B2 ($p = 0.059$).

4. Discussion

Two studies investigating the effects of nocturnal wind turbine noise on physiologically measured sleep in a laboratory setting have been presented. They were intended to serve as pilot studies prior to a subsequent larger study, and they had the main objective of providing indications of specific sound character of WTN that may be of particular relevance for effects on sleep. Regarding an overall effect of WTN on sleep, there was some evidence that participants had more frequent awakenings, reduced amounts of N3 ("deep") sleep, reduced continuous N2 sleep, increased self-reported disturbance and WTN-induced morning tiredness in exposure nights with WTN compared to WTN-free nights.

Furthermore, there was limited evidence from Study B that wakefulness was adversely affected by strong amplitude modulation and lower rotational frequencies, N3 sleep seemed to be adversely affected by higher rotational frequency and strong amplitude modulation and N1 sleep increased with high rotational frequency and beating. However, the current analyses have not accounted for potential interaction effects between sound character periods and exposure night. For instance, it cannot be excluded that an interaction between the exposures used in exposure Night B2 in Study B (50 dB outdoor level with a closed window) and the sound characteristics of Period 4 (high RPM, strong AM, no beats) in the same night is responsible for the observed reduction in N3.

Awakenings occur spontaneously during sleep, but an increased awakening frequency can disrupt the biorhythm of sleep, causing sleep fragmentation and often resulting in an increase in wakefulness and stage N1 ("light") sleep with corresponding decreases in deep and REM sleep [38,43]. Deep sleep is believed to be important for nocturnal restoration [44], while N1 may be of little or no recuperative value [45]. Additionally, deep sleep is thought to be important for consolidation of declarative memory, while REM sleep may be important for more implicit memory processes, such as procedural memory [46,47]. While the current studies cannot and do not aim to say anything regarding potential after-effects of the observed changes, the observations of reduced N3, increased N1 and an increased wakefulness under certain sound characteristics of WTN warrants further research.

In Study A, physiologic sleep was generally most impacted during the night with 33.7 dB $L_{\mathrm{AEq,8h,indoor}}$ closed window and in Study B by nights with low frequency band AM and 32.8 dB $L_{\mathrm{AEq,8h,indoor}}$ slightly open window. Both cases represent experimental nights with the highest or close to highest SPL in the respective studies, although differences to the lowest WTN levels were at most 4 dB. This provides some small support for the level-dependence for WTN-induced sleep disturbance that has sometimes been seen previously in the field for self-reported measures [19]. In both Studies A and B there were however exposure nights with similarly high noise levels where no effects on sleep were seen, although there were also differences in the AM frequency band or spectral content of the noise due to outdoor-indoor filtering. A possible frequency dependency of WTN-induced effects on sleep should be considered in future work.

The studies are limited by both the low sample size, and the representativeness of the study population. The low sample size means that only large effect sizes were likely to be detected, even after relaxing the criterion for statistical significance. The participants, being young and healthy individuals with good normal sleep, are not representative of the typical population that may be exposed to WTN at home. However, considering that the aim was to evaluate whether WTN at these levels could have an impact on sleep and whether certain sound characteristics would have a higher impact, the generalisability to a larger population was not the primary concern. Nevertheless, sleep generally deteriorates with increasing age [48], and the prevalence of sleep-related disorders may be around 27% in field settings [49]. It is therefore plausible that the study population represent a particularly robust group, and any WTN-induced effects on sleep may be worse in the field.

The experimental WTN levels were above the recommended outdoor levels for Sweden [50], although within the recommended outdoor levels for many other countries [51]. The levels were selected to represent worst-case conditions that may occur under unfavourable weather conditions and to increase the likelihood of detecting any effects of WTN despite the low sample size. However, this also means that the findings should not be taken as clear evidence of sleep disturbance due to WTN. The studies were conducted with the aim of providing guidance in the implementation of a larger study, preliminary results of which are available elsewhere [52], and results should be treated accordingly.

5. Conclusions

There were some indications that WTN led to objective sleep disruption, reflected by an increased frequency of awakenings, a reduced proportion of deep sleep and reduced continuous N2 sleep. This corresponded with increased self-reported disturbance. However, there was a high degree of heterogeneity between the two studies presented, precluding firm conclusions regarding effects of WTN on sleep. Furthermore, there was some limited evidence from the second study that wakefulness increase with strong amplitude modulation and lower rotational frequency, the deepest sleep was adversely affected by higher rotational frequency and strong amplitude modulation, and light sleep increased with high rotational frequency and acoustic beating. These findings will be used in the development of noise exposures for a larger-scale sleep study that will implement more naturalistic WTN and use a more representative study population.

Supplementary Materials: The following are available online at http://www.mdpi.com/1660-4601/15/11/2573/s1. Morning questionnaire. Figure S1: Indoor average spectra across the full 8-hour exposure period for each WTN night in Study A. Figure S2: Outdoor spectrum (40 dB $L_{AEq,8h}$) for each sound character period in Study A. Figure S3: Indoor average spectra across the full 8-hour exposure period for each WTN night in Study B. Figure S4: Outdoor spectrum (45 dB $L_{AEq,8h}$) for each sound character period in Study B. Table S1: Mean and standard deviation (SD) of sleep macro- and micro-structure data for each night in Study A. Table S2: Mean and standard deviation (SD) of sleep macro- and micro-structure data for each night in Study B. Figure S5: Median, interquartile range, maximum/minimum values and outliers for cortical reaction frequency across periods of different character WTN. A) Arousals. B) Awakenings. C) Sleep stage changes.

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Glossary

AM	Amplitude modulation. A time-varying increase and decrease in sound pressure level, which can vary for different frequencies of the same sound signal
A-Weighting	Frequency weighting filter applied to a sound measurement to mimic the frequency-dependence of human hearing
dB	Decibel, relative to the threshold of human hearing (2×10^{-5} Pa)
EEG	Electroencephalogram
L_{AEq}	A-weighted equivalent continuous sound pressure level, expressed in decibels. Can be considered the "average" of a time-varying sound pressure level over a specified period
$L_{AEq,8h,indoor}$	A-weighted equivalent continuous indoor sound pressure level over 8 h
$L_{AEq,8h,outdoor}$	A-weighted equivalent continuous outdoor sound pressure level over 8 h
NREM	Non-rapid eye movement
PSG	Polysomnography
SSC	Sleep stage change
REM	Rapid eye movement
WHO	World Health Organization
WTN	Wind turbine noise

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The effect of wind turbine noise on sleep and quality of life: A systematic review and meta-analysis of observational studies

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ABSTRACT

Noise generated by wind turbines has been reported to affect sleep and quality of life (QOL), but the relationship is unclear. Our objective was to explore the association between wind turbine noise, sleep disturbance and quality of life, using data from published observational studies. We searched Medline, Embase, Global Health and Google Scholar databases. No language restrictions were imposed. Hand searches of bibliography of retrieved full texts were also conducted. The reporting quality of included studies was assessed using the STROBE guidelines. Two reviewers independently determined the eligibility of studies, assessed the quality of included studies, and extracted the data. We included eight studies with a total of 2433 participants. All studies were cross-sectional, and the overall reporting quality was moderate. Meta-analysis of six studies ($n = 2364$) revealed that the odds of being annoyed is significantly increased by wind turbine noise (OR: 4.08; 95% CI: 2.37 to 7.04; $p < 0.00001$). The odds of sleep disturbance was also significantly increased with greater exposure to wind turbine noise (OR: 2.94; 95% CI: 1.98 to 4.37; $p < 0.00001$). Four studies reported that wind turbine noise significantly interfered with QOL. Further, visual perception of wind turbine generators was associated with greater frequency of reported negative health effects. In conclusion, there is some evidence that exposure to wind turbine noise is associated with increased odds of annoyance and sleep problems. Individual attitudes could influence the type of response to noise from wind turbines. Experimental and observational studies investigating the relationship between wind turbine noise and health are warranted.

1. Introduction

The last few decades have seen governments attempting to decrease greenhouse gas emissions (Olander et al., 2012). This response – to changes in the earth's temperature – has seen the rise of wind power (Leithead, 2007). This alternative energy source, generated by wind turbines, is one tool being employed to generate cleaner energy.

Wind turbine generators (WTGs) are devices that convert wind power into kinetic energy, and are regarded as one of the most important renewable sources of power (Leithead, 2007). Energy generated from WTGs can be used to produce electricity and drive machinery (Caduff et al., 2012; Chang Chien et al., 2011; Li and Chen, 2008). It is thought that large scale utilization of these devices can improve global climate by extracting energy from the atmosphere and altering the pattern of gaseous flow in the earth's atmosphere (Keith et al., 2004).

More recently, exposure to noise from WTGs has been reported to have negative effects on human health (Jeffery et al., 2013). People living near WTGs have reportedly experienced sleep disturbances and a reduction in the quality of life; it has been suggested that a combination of turbine noise, infrasound (sounds with frequency <20 Hz) and ground currents (stray current from electrical equipment which passes through the earth) could be responsible for these symptoms (Havas and Colling, 2011). Cases of litigation because of the unwanted health effects allegedly caused by the noise from WTGs have been reported both in the UK (Daily Mail, 2011) and the US (Oregon Herald, 2013). Very recently, the UK parliament passed a bill restricting the number, height and location of WTGs in England (UK House of Commons Library, 2015).

Studies investigating the effects of wind turbines on sleep and quality of life in individuals living in their proximity have been conducted. While the findings from a pooled meta-analyses of three studies suggested a relationship between exposure to WTG noise and annoyance (Janssen et al., 2011), a more recent review concluded that there was no evidence of a consistent relationship between WTG noise and adverse health effects (Merlin et al., 2013). Therefore, the objective of this systematic review was to explore the association between wind turbine noise, annoyance, sleep and quality of life, and also explore

Abbreviations: WTG, wind turbine generator; ESS, Epworth Sleepiness Scale; PSQI, Pittsburgh Sleep Quality Index.

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the influence of other moderating factors on these outcomes, using data from published observational studies.

2. Methods

We conducted electronic searches in the following databases: Medline, Embase and Global health. Each database was searched from inception till June 2014. MeSH terms used included wind turbine, wind energy, clean energy, annoyance, sleep, and quality of life (a MEDLINE search strategy is included as a web Appendix 1). We also searched Google Scholar for relevant conference proceedings, and hand searched the bibliography of retrieved full texts. An updated search of the databases was conducted on November 28, 2014. Case–control, cross-sectional, and cohort studies were considered for inclusion. To be included in the review, studies had to report annoyance, sleep or quality of life as outcomes in subjects living in proximity with wind turbines. Studies not comparing participants based on the proximity of their homes to WTGs were excluded. No age, language or time restrictions were imposed. Where necessary, contact with study investigators was made to request additional data.

The reporting quality of included studies was evaluated using a checklist adapted from the STROBE (Strengthening of Reporting of Observational Studies in Epidemiology) guidelines (von Elm et al., 2007). Data was systematically extracted by two reviewers [IJO and JOS] using a piloted spreadsheet of pertinent variables including baseline demographics, study location, distances of homes from wind turbines, SPLs, assessment of exposure and outcome. These were independently cross-checked by two other reviewers [MJT and CJH]. Disagreements were resolved through consensus. Our main outcomes were annoyance, sleep disturbance and quality of life (QOL). We also examined the influence of other background noise, visual perception and socio-economic factors on reported outcomes.

Odds ratios (ORs) were used to measure associations between wind turbine noise and annoyance or sleep disturbance. Using the random-effects model of the software for meta-analyses (Review Manager, Version 5.3 (2011)), we calculated the ORs and 95% confidence intervals (CI) for the studies which had sufficient data for statistical pooling. We used sound pressure level (SPL) reference ranges of <40 dB for lower exposure and >40 dB for higher exposure to wind turbine noise in the analyses; these limits correspond to the World Health Organisation (WHO) guideline recommendations for indoor community noise levels suitable for night-time sleep (Berglund et al., 1999). Where SPLs were not available, we used the reported near ("near group") and far ("far group") distances from WTGs for high and low SPLs respectively. Subgroup analyses by SPLs or distances from WTGs were used to test the robustness of overall analyses. Sensitivity analyses by meta-analysing studies with larger sample sizes or with higher respondent rates (≥50%) were used to investigate heterogeneity using the I^2 statistic; values of 25%, 50%, and 75% indicated low, medium, and high statistical heterogeneity respectively. Where statistical combination of reported data was considered inappropriate, such data was reported narratively.

2.1. Definitions

For the purpose of this review, annoyance was defined as a constellation of psychosocial and/or psychological symptoms — "feelings of being bothered, exasperation at being interrupted by noise, and symptoms such as headache, fatigue and irritability" (Anonymous, 1977). Sleep disturbance was defined as any interruption of an individual's normal sleep–wake pattern (Cormier, 1990). A change in an individual's quality of life was measured based on their own perceptions, with regard to their own goals, expectations, standards and concerns (WHO, 1997).

3. Results

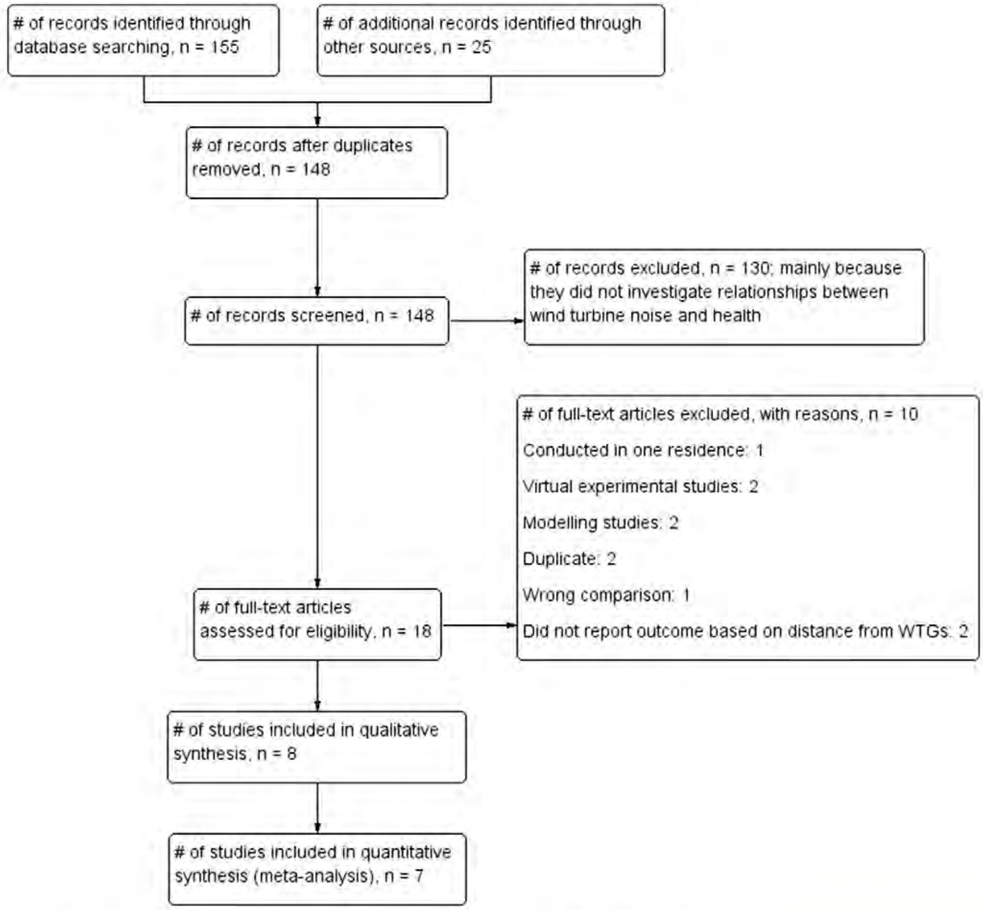
Our electronic searches returned 148 non-duplicate citations, out of which 18 potentially eligible articles were identified (Fig. 1). One article (Ambrose et al., 2012) was excluded because the study was conducted in only one residential apartment and another two (Maffei et al., 2013; Van Renterghem et al., 2013) because they were virtual experimental studies conducted in subjects not residing within the vicinity of WTGs. Two articles (Verheijen et al., 2011; Pedersen and Larsman, 2008) were excluded because they were modelling studies, the latter of which used results from two studies already included in the review. One article was excluded because it explored the effects of road traffic noise using data from a study included in the review (Pedersen et al., 2010) and another two because they did not distinguish subjects by distance from WTGs or SPLs (Harry, 2007; Morris, 2012). Two articles (Nissenbaum et al., 2011; Pedersen et al., 2009) were excluded because more complete versions of their reports were included in the review. Thus eight studies (Bakker et al., 2012; Krogh et al., 2011; Magari et al., 2014; Nissenbaum et al., 2012; Pawlaczyk-Łuszczyńska et al., 2014; Pedersen and Persson Waye, 2004, 2007; Shepherd et al., 2011) with a total of 2433 participants were included in the review. The key details of the studies are shown in Tables 1, 2a and 2b.

All included studies were of cross-sectional design (Table 1). Seven studies reported appropriate recruitment and sampling strategies, and all used objective and validated measures to compute outcome variables. The studies also used appropriate statistical methods to compare groups, but only half (50%) adequately reported sample size calculations. All studies reported adequate statistical analysis, and baseline demographics for participants in the high and low exposure groups were generally similar. The response rate for questionnaires ranged from 37% to 93%.

Annoyance was measured on a 5-point scale (ranging from did not notice to very annoyed) using questionnaires that enquired about attitudes towards wind turbines; one study (Pawlaczyk-Łuszczyńska et al., 2014) used a 6-point scale that included "extremely annoyed" variable after "very annoyed". In all the studies, annoyance from exposure to WTG noise implied being rather annoyed, very annoyed or extremely annoyed. Sleep disturbance (defined in the studies as interruption of normal sleep patterns) was assessed from the general questionnaire administered in seven studies (Bakker et al., 2012; Krogh et al., 2011; Magari et al., 2014; Pawlaczyk-Łuszczyńska et al., 2014; Pedersen and Persson Waye, 2004, 2007; Shepherd et al., 2011), and measured by Pittsburgh Sleep Quality Index (PSQI) in the eighth (Nissenbaum et al., 2012) — this same study assessed daytime sleepiness using the Epworth Sleepiness Scale (ESS). Quality of life was measured in three studies by general health questionnaire (GHQ) (Bakker et al., 2012; Pawlaczyk-Łuszczyńska et al., 2014), short form 36 (SF-36v2) (Nissenbaum et al., 2012), and health-related quality of life (HRQOL) (Shepherd et al., 2011). Two studies used unspecified masked questionnaires that addressed health and general well-being (Pedersen and Persson Waye, 2004, 2007); these questionnaires were described as validated. One study (Krogh et al., 2011) did not use a validated questionnaire to assess quality of life and another (Magari et al., 2014) did not report quality of life as an outcome.

The study locations ranged from rural to semi-rural and metropolitan built-up areas (Table 2a), with varying population densities and terrain. The distance of homes from WTGs varied between 0 and 8 km, and the number of WTGs in the individual studies ranged from 16 to 1846. The emission levels for the WTGs in the studies were measured using A-weighted scales (a filtering method aimed at mimicking responses to sound by the human ear) with 8 m/s downwind, and power generated from the turbines ranged between 0.15 and 2300 kW.

The mean age of the respondents across all the studies was 46 to 58 years (Table 2b). One study (Krogh et al., 2011) did not report the socio-economic status of respondents, while another (Bakker et al.,



The Flow Diagram has been adapted from the online version of the PRISMA statement, 2009. Available from: http:// www.prisma-statement.org/statement.htm

Fig. 1. Flow diagram showing the process for inclusion of studies examining the relationship between wind turbine noise and health.

2012) reported a significantly higher proportion of respondent who received higher education in the high SPL group compared with the low SPL group ($p < 0.001$). The remaining studies did not report significant differences in the baseline demographics of respondents. All the respondents in two studies (Magari et al., 2014; Nissenbaum et al., 2012) had financial benefits from WTGs (Table 2b). Reported background noises

Table 1
Reporting quality of studies exploring the association between turbine noise, sleep and quality of life.

Study ID Country of study	Study design	Appropriate recruitment strategy?	Appropriate sampling technique?	Response rate	Representative sample?	Relevant outcome measures?[a]	Power calculation?	Appropriate statistical analysis?	Evidence of bias?
Bakker et al., 2012 The Netherlands	Cross-sectional	Yes — questionnaire sent to houses	Yes	37%	Yes	Yes	Yes	Yes	No
Krogh et al., 2011 Canada	Cross-sectional	Yes — postal & hand-delivered questionnaire	Unclear	88.9%	Yes	Yes	Unclear	Yes	No
Magari et al., 2014 USA	Cross-sectional	Yes — administered in person by two field personnel	Yes	92.9%	Yes	Yes	Unclear	Yes	No
Nissenbaum et al., 2012 USA	Cross-sectional	Yes — telephone and door to door	Yes	40%	Yes	Yes	Unclear	Yes	No
Pawlaczyk-Łuszczyńska et al., 2014 Poland	Cross-sectional	Yes — postal questionnaire	Yes	71%	Yes	Yes	Yes	Yes	No
Pedersen and Persson Waye, 2004 Sweden	Cross-sectional	Yes — questionnaire sent to houses	Yes	68.4%	Yes	Yes	Yes	Yes	No
Pedersen and Persson Waye, 2007 Sweden	Cross-sectional	Yes — postal questionnaire	Yes	57.6%	Yes	Yes	Yes	Yes	No
Shepherd et al., 2011 New Zealand	Cross sectional	Yes — postal	Yes	33%	Yes	Yes	Unclear	Yes	No

[a] All the outcomes measured were subjective, except for Pedersen and Persson Waye (2007) which measured visual perception using visual angle of WTGs from homes.

Table 2a
Main characteristics of studies investigating the association between wind turbine noise, sleep and quality of life.

Study ID	Study location & site topography	Number of participants	SPLs & distance from WTGs	Power & number of WTGs	Outcomes	Tools used to measure outcomes
Bakker et al. (2012)	1. Rural area (with no major road within 500 m from the closest wind turbine) 2. Rural area with a major road within 500 m from the closest wind turbine 3. More densely populated built up area Flat terrain	725	21–54 dB (average: 35 dB) 0–2.5 km	≥500 kW (0.5 MW); 1846	Annoyance, sleep disturbance, psychological stress	Annoyance: 5-point ordinal scale & 2 Likert scales. Sleep disturbance: Frequency
Krogh et al. (2011)	5 WTG areas with anecdotal reports of adverse health effects	109	0.35–2.4 km	1.65 MW: 5 WTG project areas	Sleep disturbance	WindVOiCe Survey Questionnaire
Magari et al. (2014)	1. Rural area 2. 5 receptor locations within wind turbine park; two locations outside the park as comparator	62	0.4–4 km	1.5 MW; 84	Annoyance, health effects	Validated general questionnaire
Nissenbaum et al. (2012)	2 rural areas — 'low-lying, tree-covered island.' Flat terrain	79	32–57 dB 0.4–6.6 km	1.5 MW; 31	Sleep quality, mental health	Sleep disturbance: PSQI & ESS QOL: (SF-36v2)
Pawlaczyk-Łuszczyńska et al. (2014)	1. 3 populated areas in Central & Northwest Poland 2 Flat terrain 3. Mainly agricultural, but railroads and/or roads also present	156	30–50 dB 0.24–2.5 km	0.15, 1.5 & 2 MW; total number of wind turbines 108	Annoyance, mental health	Annoyance: 5-point ordinal scale Sleep and QOL: GHQ
Pedersen and Persson Waye (2004)	5 wind turbine areas; flat terrain	351	<30 to >40 dB 0.15–1.2 km	14 WTGs: 600–650 kW; 2 WTGs: 150 & 500 kW	Noise perception, annoyance, sleep disturbance	Validated general questionnaire: Annoyance: unipolar annoyance scale Sleep disturbance: presence or absence
Pedersen and Persson Waye (2007)	7 wind turbine areas; different landscapes in terrain and urbanisation (flat and 'complex'–rocky or altitude); suburban and rural	754	31.4–38.2 dB (mean: 33.4). 0.6–1 km (mean: 0.78 km)	>500 kW; 478	Perception, annoyance, sleep quality, quality of life	Validated general questionnaire Annoyance: unipolar annoyance scale Sleep disturbance: presence or absence
Shepherd et al. (2011)	2 semi-rural coastal areas differentiated by their proximity to wind turbines; hilly terrain	197	20–50 dB <2 to 8 km	2300 kW; 66	Annoyance, sleep disturbance, quality of life (health)	Questionnaire with subcomponents: Annoyance: 7-item scale Sleep: 7-item scale QOL: HRQOL

Abbreviations: SPLs: sound pressure levels; WTGs: wind turbine generators; dB: decibels; km: kilometres; kW: kilowatts; MW: megawatts; PSQI: Pittsburgh Sleep Quality Index; ESS: Epworth Sleepiness Scale; QOL: quality of life; GHQ: general health questionnaire; HRQOL: health-related quality of life.

included road traffic noise, noises from birds and household pets, and other machinery.

One study (Pedersen and Persson Waye, 2004) was funded by a grant from a research foundation, while four (Bakker et al., 2012; Magari et al., 2014; Pawlaczyk-Łuszczyńska et al., 2014; Pedersen and Persson Waye, 2007) were funded by government grants. The authors in two studies (Nissenbaum et al., 2012; Shepherd et al., 2011) failed to declare their sources of funding. The authors in all studies were affiliated with public institutions, except in two studies (Magari et al., 2014; Nissenbaum et al., 2012) where authors were affiliated to public health consultancy firms. One study (Krogh et al., 2011) was not funded by any entity.

3.1. Relationship between wind turbine noise and annoyance

Two studies (Krogh et al., 2011; Nissenbaum et al., 2012) did not report annoyance as an outcome. Meta-analysis of the remaining six studies ($n = 2364$; Fig. 2) revealed a significant increase in the odds of being rather annoyed, annoyed or very annoyed by wind turbine noise (OR: 4.08; 95% CI: 2.37 to 7.04; $I^2 = 63\%$; $p < 0.00001$). Subgroup analyses by SPLs or distance from WTG did not change the direction of the results (Fig. 2). Sensitivity analysis of three studies with larger sample sizes ($n = 1793$) revealed that the odds of being annoyed by wind turbine noise is significantly increased with higher SPLs (OR: 6.94; 95% CI: 4.36 to 11.03; $I^2 = 10\%$; $p < 0.00001$). Meta-analysis of four studies with higher respondent rates ($n = 1313$) revealed that the odds of being annoyed by living close to wind turbines is statistically significant (OR: 3.00; 95% CI: 1.87 to 4.80; $I^2 = 0\%$; $p < 0.00001$).

3.2. Relationship between wind turbine noise and sleep disturbance

Two studies (Nissenbaum et al., 2012; Shepherd et al., 2011) did not provide suitable data for statistical pooling. One of these (Nissenbaum et al., 2012) reported the "near group" as having significantly worse sleep scores for both PSQI ($p = 0.046$) and ESS ($p = 0.03$); and two subjects in the "near group" were diagnosed with insomnia compared to none in the "far group". In the second study (Shepherd et al., 2011), participants with greater exposure to WTG noise reported significantly worse sleep scores ($p = 0.0006$). For the remaining six studies which provided suitable data, three (Bakker et al., 2012; Pedersen and Persson Waye, 2004, 2007) used low SPL values of <30 dB as controls, while two (Krogh et al., 2011; Magari et al., 2014) compared groups based on the distances of respondents' from WTGs. Meta-analysis revealed a significant increase in the odds of reporting sleep disturbances with greater exposure to noise from WTGs (OR 2.94; 95% CI: 1.98 to 4.37; $I^2 = 0\%$; $p < 0.00001$; Fig. 3). Subgroup analysis by SPLs or distance did not result in a change in the direction of the results. A similar result was observed when five studies with higher respondents' rates ($n = 810$) were meta-analysed (OR: 2.76; 95% CI: 1.65 to 4.62; $I^2 = 0\%$; $p = 0.0001$). Sensitivity analyses of studies with larger sample sizes

Table 2b
Demographic characteristics of respondents and influence of moderating factors in the included studies.

Study ID	Mean age	Average duration at home	Socio-economic status	Background noises and their influence on outcome	Visual perception of WTGs and influence on outcome	Financial relationship with WTG and influence on outcome
Bakker et al. (2012)	51 years	Not reported; economic benefits had no statistically significant impact on perception of the sound.	Proportion of respondents with higher education was significantly higher with those living in high SPLs ($p < 0.001$)	Road traffic; aircraft; railways; industry & shunt yards Exposure to WTG sound did not lead to noise annoyance amongst respondents who lived in areas classified as noisy and reported that they could hear the sound. Sound exposure predicted noise annoyance ($r = 0.54$) amongst respondents who reported that they could hear WTG sound and lived in areas classified as quiet	73% of respondents in rural areas and 54% in built-up areas could see at least one WTG from their dwellings The probability of being annoyed by WTG sound was higher if they were visible ($p < 0.001$)	Of 100 persons who benefitted from WTG, 76 were in high SPL group. The proportion of benefiting respondents who were rather or very annoyed by WTG sound was 4 times lower compared to the non-benefiters (12 versus 3%; $p < 0.05$), despite the fact that respondents who benefited economically were exposed to higher levels of WTG sound and noticed the WTG sound more often
Krogh et al. (2011)	52 years	Not reported	Not reported	Not reported	Not reported	Not reported
Magari et al. (2014)	51 years	18 years	Similar for residents	Amongst participants annoyed by WTG noise, 60% were affected daily or a few times weekly by noise, 92% by television or radio interference, and 54% by shadows or reflections None of the indoor or outdoor SPL measurements significantly correlated with other environmental factors — noise, pollution, and landscape littering	On average 19 WTGs were visible General annoyance was significantly correlated with opinion of altered landscape due to WTG ($p < 0.0001$)	All residents benefitted from WTG: substantial property tax reduction; free trash removal Respondents who directly benefitted from WTGs were not less annoyed than other respondents. 90% of participants were satisfied or very satisfied with their environment
Nissenbaum et al. (2012)	57.5 years	14 to 21 years in near group 24 to 30 years in far group	No significant differences	Not reported	WTGs were visible to a majority of respondents The visual impact of WTG on those living closest to turbines was greater compared with those living further away	All residents benefit financially: reduced electricity costs and/or increased tax revenues Fear of reducing property value led to downplaying of adverse health effects
Pawlaczyk-Łuszczyńska et al. (2014)	46 years	Not reported	Comparable between groups	Mainly agricultural terrain with low traffic intensity railways, roads. Did not analyse the impact of terrain and urbanisation on annoyance related to WTG noise. There was high positive correlation between as well as between the respondents' sensitivity to noise and sensitivity to landscape littering ($p < 0.0000001$)	97% of respondents could see 1 or more WTGs from their dwelling, backyard or garden. There was high positive correlation between general attitude towards WTGs and attitude to their visual impact ($p < 0.0000001$)	2.6% benefitted from WTG: type of benefit unspecified
Pedersen and Persson Waye (2004)	48 years	Not reported	No statistically significant differences between groups	Road traffic, rail traffic, neighbours. No significant differences in variables related to noise sensitivity, attitude, or health between the different sound categories At lower sound categories, no respondents were disturbed in their sleep by WTG noise, but 16% of the 128 respondents living at SPLs >35 dB reported sleep disturbance due to WTG noise	WTGs were visible from "many" directions. Respondents' attitude to the visual impact of WTGs on the landscape scenery influenced noise annoyance ($p < 0.001$). No impact of visual perception on sleep disturbance	95% did not own or share a WTG
Pedersen and Persson Waye (2007)	51 years	14 to 16 years in near group 15 to 16 years in far group	Similar for residents	The rural dwellers were the respondents' group with the highest proportion of noise sensitivity (56–59%) There was a significant increase in the odds of annoyance from WTGs in rural areas (quiet) compared with suburban areas (noisy), OR 1.8. [1.25 to 2.51]	The highest proportion of respondents who could see at least 1 WTG was rural (88–91%) Perception of annoyance correlated with SPLs ($p < 0.001$) Both the objective variable "vertical visual angle" and the subjective report of visibility of wind turbines increased the odds of being annoyed: 1.2	Not reported

(continued on next page)

Table 2b (*continued*)

Study ID	Mean age	Average duration at home	Socio-economic status	Background noises and their influence on outcome	Visual perception of WTGs and influence on outcome	Financial relationship with WTG and influence on outcome
					(95% CI: 1.03 to 1.42), and 10.9 (95% CI: 1.46 to 81.92) respectively	
Shepherd et al. (2011)	Range: 18–71 years	Not reported	Matched between groups	No differences between groups for traffic ($p = 0.154$) or neighbourhood ($p = 0.144$) noise annoyance	Not reported specifically due to masking of the study intent	Not reported

(n = 838) revealed a significant increase in the odds of sleep disturbances with higher SPLs (OR: 3.24; 95% CI: 2.03 to 5.18; $I^2 = 0\%$; $p < 0.00001$).

Another study (Pedersen and Persson Waye, 2004) reported no statistically significant correlations between sleep quality and sensitivity to WTG noise. One study (Pawlaczyk-Łuszczyńska et al., 2014) reported a significant relationship between the frequency of annoyance and sleep disturbance ($p < 0.05$).

3.3. Relationship between wind turbine noise and quality of life (QOL)

Because of discrepancies in the methods used to assess QOL across studies, a meta-analysis was not considered appropriate. One study (Bakker et al., 2012) reported significant correlations between wind turbine noise and psychological distress in quiet ($p < 0.05$), and both noisy and quiet areas ($p < 0.01$). Another (Nissenbaum et al., 2012) reported that participants in the high noise exposure group had significantly lower QOL (lower GHQ scores) compared with the low exposure group ($p = 0.002$), and a third (Pawlaczyk-Łuszczyńska et al., 2014) reported a weak but significant correlation between wind turbine noise and mental health based on the responses on the GHQ ($p < 0.00625$) — in the same study, a significantly greater proportion of respondents in the "near group" reported that WTG noise has impacted negatively on their health ($p < 0.05$). Another study (Pedersen and Persson Waye, 2007) reported that SPLs were not correlated with general wellbeing of study participants, but annoyed respondents felt significantly more tired ($p = 0.05$) and tense ($p < 0.05$) in the mornings. In one study (Shepherd et al., 2011), the high SPL group had lower HRQOL and environmental QOL scores compared with the lower SPL group ($p = 0.017$ and 0.018 respectively).

One study (Krogh et al., 2011) reported a significant relationship between proximity related WTG noise and excessive tiredness ($p = 0.03$) (the residents in the groups closer to the WTGs reported a higher percentage of excessive tiredness). This same study showed a trend towards increased risk of headache with closer proximity to WTGs ($p = 0.1$). Another study (Nissenbaum et al., 2012) reported a near significant increase in the proportion of respondents receiving new psychotropic prescriptions (after WTG installation) in the "near group" compared with the "far group" (24% vs 0.07 $p = 0.06$). While 90% of participants in one study (Magari et al., 2014) reported being either satisfied or being very satisfied with their environment, the "near group" respondents in another study (Shepherd et al., 2011) were significantly less satisfied compared with the "far group" ($p = 0.03$).

3.4. Influence of background noise and settings on outcomes

In two studies (Bakker et al., 2012; Pedersen and Persson Waye, 2007), episodes of annoyance at a given WTG noise level were significantly higher in quiet areas compared with areas classified as noisy. A third study (Pedersen and Persson Waye, 2004) reported no significant

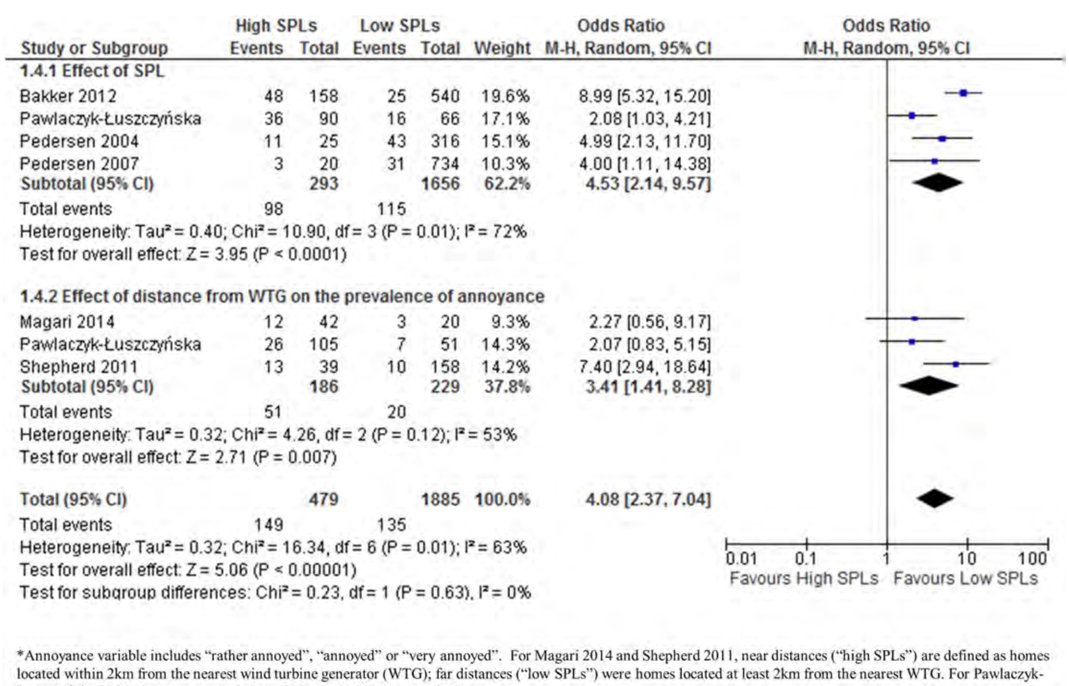


Fig. 2. Relationship between wind turbine noise and annoyance.* *Annoyance variable includes "rather annoyed", "annoyed" or "very annoyed". For Magari et al. (2014) and Shepherd et al. (2011), near distances ("high SPLS") are defined as homes located within 2 km from the nearest wind turbine generator (WTG); far distances ("low SPLS") were homes located at least 2 km from the nearest WTG. For Pawlaczyk-Łuszczyńska et al. (2014), these corresponded to <800 m and >800 m respectively.

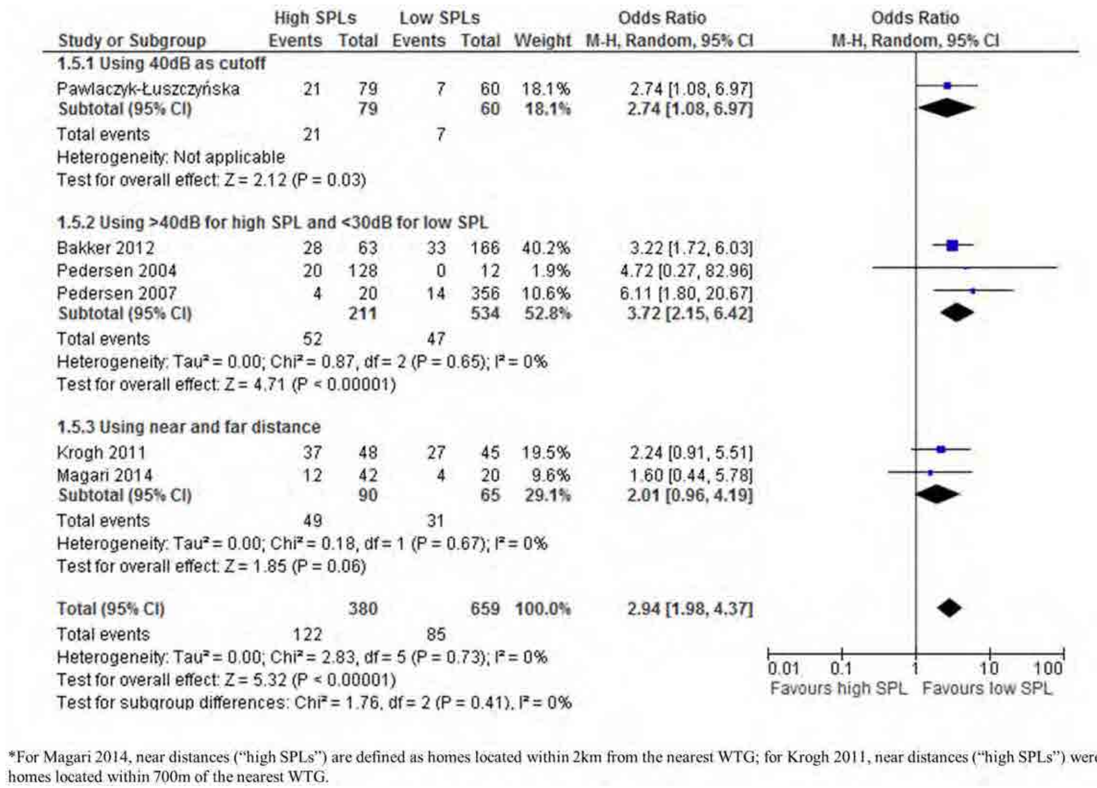


Fig. 3. Relationship between wind turbine noise and sleep.* *For Magari et al. (2014), near distances ("high SPLS") are defined as homes located within 2 km from the nearest WTG; for Krogh et al. (2011), near distances ("high SPLS") were homes located within 700 m of the nearest WTG.

difference between groups for different sound categories; however, there was a trend towards increased sleep disturbances with higher SPLs. A fourth study (Shepherd et al., 2011) reported no differences between groups for traffic ($p = 0.15$) or neighbourhood ($p = 0.14$) noise annoyance (Table 2b). One study (Pawlaczyk-Łuszczyńska et al., 2014) did not analyse the impact of other environmental noise on outcomes.

3.5. Effect of visual perception on outcomes

Six studies reported data on the relationship between visual perception of WTG and its influence on outcomes (Table 2b). Five of these (Bakker et al., 2012; Magari et al., 2014; Pawlaczyk-Łuszczyńska et al., 2014; Pedersen and Persson Waye, 2004, 2007) reported a significant positive correlation between visual perception of WTGs and the episodes of annoyance; one of these studies (Pedersen and Persson Waye, 2007) also reported a significant correlation when an objective variable (visual angle) was used to explore the relationship. The sixth study (Nissenbaum et al., 2012) reported that visual impact of WTG on those living closest to turbines was greater compared with those living further away, but did not report whether this was significant. The authors of one study (Shepherd et al., 2011) did not explore the effect of visual perception on outcomes because they wanted to mask the study intent.

3.6. Influence of economic benefit from WTG on outcome

The influence of economic benefit on outcome was inconsistent across the three studies that explored the relationship. One study (Bakker et al., 2012) reported a significantly lower rate of annoyance amongst respondents who benefitted economically from WTGs compared with respondents who had no benefit ($p < 0.001$), while another study (Magari et al., 2014) reported no significant difference in outcomes between groups. Respondents in the third study (Nissenbaum et al., 2012) indicated that the fear of reducing property value led to downplaying of adverse health effects. Two studies (Pawlaczyk-Łuszczyńska et al., 2014; Pedersen and Persson Waye, 2004) in which ≤5% of participants had financial benefits from WTGs did not report whether financial incentives resulted in differences in outcome rates.

4. Discussion

Our results provide evidence that living in areas with WTGs appears to result in "annoyance", and may also be associated with sleep disturbances and decreased quality of life. The results of included studies also suggest that visual perception of WTGs is correlated with increased episodes of annoyance, and the reported adverse effects from WTGs are more prominent in quiet areas compared with noisy ones. The results of our meta-analysis corroborate the findings of a previous meta-analysis of three studies which reported that wind turbine noise is significantly associated with annoyance (Janssen et al., 2011). However, our pooled data contained twice as many studies compared with that report. Our results contradict the findings of another review that concluded that there was no consistent relationship between WTG noise and adverse health effect (Merlin et al., 2013). In contrast to that report, we statistically combined data, and we included evidence from two new studies that were not available for that review. The results of our meta-analysis also support the findings of a more recent systematic review which concluded that exposure to WTG noise increases the risk of annoyance and self-reported sleep disturbance (Schmidt and Klokker, 2014). In comparison with that report, we meta-analysed study data, and also included one study which was not available in that report. Our meta-analyses results should be interpreted with caution due to the variation in outcome measures, and moderate heterogeneity observed in some of the analyses.

The results of our meta-analysis suggest that exposure to WTG noise can elicit annoyance. However, the moderate to large heterogeneity observed in the subgroup analysis limits the firmness of any conclusions that can be drawn from the meta-analytic results. Some authors have suggested that the perception of rhythmic sound pressure by the inner ear could result in negative health outcomes (Enbom and Enbom, 2013; Gohlke et al., 2008; Todd et al., 2008), but this has been refuted by others (Knopper and Ollson, 2011). In addition, other investigators have concluded that it is impossible to distinguish between noises generated by WTGs from that caused by wind itself (Bilski, 2012). Until better tools to assess the impact of WTGs are developed, the relationship between WTG noise and annoyance will remain controversial.

Our meta-analytic results indicate that living close to WTGs increases the odds of experiencing sleep disturbances. Results of studies which did not provide adequate data for statistical pooling were also consistent with this finding. The evidence from the included studies also suggests that sleep disturbance is positively correlated with annoyance and this supports the findings from research conducted in other types of settings (Aasvang et al., 2007; van den Berg et al., 2014; Lee et al., 2011).

We observed a relationship between noise generated from WTGs and reduction in QOL in a majority of the included studies, and this corroborates with previous research reports (Basner et al., 2014; Stansfeld and Matheson, 2003). Pathways showing inter-relationships between annoyance, sleep disturbance and QOL have been modelled (Bakker et al., 2012). However, sleep disturbance has also been shown to independently correlate with a poorer QOL (Lee et al., 2009), and the results of the studies included in our review showed a trend towards a reduction in QOL with increased frequency of sleep disturbances.

It appears that background noise from other environmental sources may influence attitude towards WTGs. The evidence from the studies in our review suggests that the reported adverse effects were more prominent in quiet areas compared with noisy ones. However, residents in quiet areas had a greater proportion of individuals with noise sensitivity and this attitude could have played a role in their responses. Because A-weighted scales (used by most WTGs) totally ignore sound frequencies below 20 Hz, the use of G-weighted scales (specifically designed for infrasound) for measurement of WTG noise has been suggested (Farboud et al., 2013); however, the G-weighted scale has been demonstrated to fluctuate significantly at low frequencies (Bilski, 2012). Other authors have reported that noise from WTGs are too low to cause any harm at distances over 305 m (Knopper and Ollson, 2011; O'Neal et al., 2011). A universally agreed method for measuring sound emissions from WTGs will help clarify these uncertainties.

The results of our review indicate that visual interference could determine attitudes to WTG. There was a greater likelihood of annoyance or less satisfaction if respondents could either see WTGs from their residence, or if they thought WTGs distorted their landscape. This finding supports the conclusions of other authors who reported that visual interference from WTGs may actually be responsible for the annoyance, rather than the noise generated by the wind turbines (Jeffery et al., 2014). Based on this finding, we are less certain if the noise from WTGs themselves actually results in the annoyance, sleep disturbances or reduced quality of life observed in our systematic review and meta-analysis; this issue warrants further investigation.

It is unclear to what extent economic ties with WTGs influenced participants' responses. The inconsistency in the relationship reported across studies makes it difficult to ascertain whether benefitting financially from WTGs affects attitude. Therefore, we are unable to draw conclusions about this relationship based on present evidence.

5. Strengths and limitations

The strengths of this systematic review and meta-analysis are the use of a robust search strategy to identify relevant studies, and our success with obtaining additional data through contact with investigators of studies that we included in the review. The overall quality of the evidence from the included studies was moderate. In addition, heterogeneity was reduced in most of our sensitivity and subgroup analyses, and the results of these analyses were also consistent with overall analyses. However, we recognize some limitations. The small number of included studies prevented us from performing a funnel plot to test for publication bias. It could be argued that publication bias may have occurred in either direction, given the different financial and social implications of WTG and their placement. It is also possible that participants' responses could have been biased; especially in settings where anecdotal reports of adverse effects from WTGs have been documented (Krogh et al., 2011; Magari et al., 2014; Nissenbaum et al., 2012), or in situations where administered questionnaires did not mask the topic of interest (Bakker et al., 2012; Pawlaczyk-Łuszczyńska et al., 2014; Pedersen and Persson Waye, 2004, 2007). It is difficult to gauge the extent to which residual background noise or financial benefits influenced the responses received from study participants. The variations in topography, design, number and power of WTGs, and variation in outcome measures limit the conclusions that could be drawn from our analyses. Finally, apart from one study (Pedersen and Persson Waye, 2007) which used an objective method (visual angle) to assess the relationship between visual perception and annoyance, the response variables measured in the included studies are all subjective and do not establish causality for the relationships examined.

5.1. Implications for research and policy

Independently funded studies exploring the relationships of wind turbines on human health are warranted; in particular, objective outcome measures that separate auditory and visual effects of WTGs should be developed. Experimental and observational studies investigating the relationship between noise exposure at WTGs and health effects should be conducted. Such studies should also explore whether benefitting economically from WTGs influences attitudes. In addition, research aimed at determining the minimum distance of homes from wind turbines at which there will be no risk of interference with health is advocated.

Further, greater monitoring of the sound emission levels from WTGs, especially those located in quiet rural communities, is advocated. A balance between individual and community preferences should be struck when making decisions about where to site WTGs. This will help to ensure the maximisation of the climatic, provider and consumer benefits from future constructions of WTGs.

6. Conclusion

The evidence from cross-sectional studies suggests that exposure to wind turbine noise may be associated with increased frequency of annoyance and sleep problems. Evidence also suggests that living in proximity to WTGs could be associated with changes in the quality of life. Individual attitudes could influence the type of response to noise from WTGs.

Authors' contribution

IJO and JOS were involved with protocol design, data extraction, data-analysis and interpretation, and co-drafting of the manuscript. MJT was involved with data-analysis and interpretation, and co-drafting of the manuscript. CJH was involved with protocol design, data analysis and interpretation, and co-drafting of the manuscript.

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Competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2015.04.014.

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EXHIBIT
17

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REVIEW PAPER

Health Effects Related to Wind Turbine Sound, Including Low-Frequency Sound and Infrasound

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Abstract A narrative review of observational and experimental studies was conducted to assess the association between exposure to wind turbine sound and its components and health effects in the general population. Literature databases Scopus, Medline and Embase and additional bibliographic sources such as reference sections of key publications and journal databases were systematically searched for peer-reviewed studies published from 2009 to 2017. For the period until early 2015 only reviews were included, while for the period between January 2015 and January 2017 all relevant publications were screened. Ten reviews and 22 studies met the inclusion criteria. Most studies examined subjective annoyance as the primary outcome, indicating an association between exposure levels and the percentage highly annoyed. Sound from wind turbines leads to a higher percentage of highly annoyed when compared to other sound sources. Annoyance due to aspects, like shadow flicker, the visual (in) appropriateness in the landscape and blinking lights, can add to the noise annoyance. There is no evidence of a specific effect of the low-frequency component nor of infrasound. There are indications that the rhythmic pressure pulses on a building can lead to additional annoyance indoors. Personal characteristics such as noise sensitivity, privacy issues and social acceptance, benefits and attitudes, the local situation and the conditions of planning a wind farm also play a role in reported annoyance. Less data are available to evaluate the effects of wind turbines on sleep and long-term health effects. Sleep disturbance as well as other health effects in the vicinity of wind turbines was found to be related to annoyance, rather than directly to exposure.

Keywords Health effects · Wind turbine sound · Infrasound · Low-frequency noise · Observational studies · Experimental studies

1 Introduction

Globally, the use of sustainable sources of energy such as biomass, water power, solar and wind energy is increasing in order to reduce the use of fossil fuel. Worldwide targets are set for an increase in sustainable energy. As a result, it can be expected that the number of wind farms will keep growing in the years to come and more people will have them in their immediate living environment. Most people have a positive attitude towards alternative energy sources; for example, in the Netherlands in 2006 90% of the population was positive about solar energy and 79%[1] was positive about wind energy. However, although the benefits at national and global level are recognized, viz. a reduction in atmospheric carbon dioxide concentration, at a local level people often oppose wind farm plans. The awareness of the consequences of a wind farm can lead to intense, and sometimes emotional discussions about the need for wind energy, the suitability of the area, the visual and aesthetic aspects and noise-related issues

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are not uncommon. Health effects of living in the vicinity of the turbines are often part of the discussion. The association between wind turbines and human responses is a complex one, and many factors play a role in the public debate. At the local level attention is often focused on the potentially negative health effects of living near a wind turbine.

This paper addresses the state of the art regarding health effects related to wind turbine sound and is based on a manuscript prepared at the request of the Noise and NIR Division of the Swiss Federal Office for the Environment (Bundesamt für Umwelt). Although several excellent reviews on this topic have been published, we think it is worthwhile to publish this narrative review because several large studies have been completed after publication of the most recent meta-analysis [1]. Also, this review addresses the effects to living in the vicinity of wind turbines (WT's) in a broader physical and social context and includes the evidence for possible health effects of the low-frequency and infrasound components. And finally, we made an effort to write a text that is accessible for a broader audience.

In this text we use the word 'sound' when it refers to sound in a neutral sense. The sound of WT's is not always perceived as negative as the word 'noise' (meaning: unwanted sound) would suggest. The term WT noise is quite common but in our opinion only correct when it refers to negative effects, such as in 'noise annoyance'. When it does, we may also use the word 'noise'.

In line with the definition of health as 'a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity' of the World Health Organization (WHO) [2], noise annoyance and sleep disturbance are considered here as health effects [3] [2] [4].

Because this review aims at a broad audience, it might be useful to explain briefly WT sound itself. We therefore start in Sects. 1.1 to 1.3 with an explanation of the sound produced by and heard from a wind turbine and what sound levels occur in practice. After a description of methods used in this review in Sects. 2 and 3 first summarizes the evidence from existing reviews. This is followed by a more detailed description of studies not covered in these reviews. In both parts the key issue is how sound from a wind turbine can affect people, especially neighbouring residents, and in what way and to what degree other factors are important to take into account. This is repeated in Sect. 4 for sound at (very) low frequencies that allegedly can affect people in other ways than 'normal' sound does. Here we use the term 'normal' sound casually when it is easily recognizable as sound and can be heard; this does not include infrasound or low levels of other sound that are normally considered to be inaudible.

Our conclusions from reading and interpreting all the scientific information are summarized in Sect. 5 that concludes the main text.

1.1 Sound Production and Character

An overview of wind turbine sound sources can be found in a number of publications such as [5–8]. For the tall, modern turbines most sound comes from flowing air in contact with the wind turbine blades: aerodynamical sound. The most important contributions are related to the atmospheric turbulence hitting the blades (inflow turbulence sound) and air flowing at the blade surface (trailing edge sound).

- Turbulence at the rear or trailing edge of a blade is generated because the air flow at the blade surface develops into a turbulent layer. The frequency with the highest (audible) sound energy content is usually in the range of a few hundred Hz up to around 1000–2000 Hz. At the blade tips conditions are somewhat different due to air flowing towards the tip, but this tip noise is very similar to trailing edge noise and usually not distinguished as a relevant separate source.
- Inflow turbulence is generated because the blade cuts through turbulent eddies that are present in the inflowing air (wind). This sound has a maximum sound level at around 10 Hz.
- Thickness sound results from the displacement of air by a moving blade and is insignificant for sound production when the air flows smoothly around the blade. However, rapid changes in forces on the blade result in sudden sideways movements of the blade and sound pulses in the infrasound region. This leads to the typical wind turbine sound 'signature' of sound level peaks at frequencies between about 1–10 Hz. These peaks cannot be heard, but can be seen in measurements.

Inflow turbulence sound is important in the low- and middle-frequency range, overlapping with trailing edge sound at medium and higher frequencies. As both are highly speed dependent, sound production is high where the speed is high and highest near the fast rotating tips of the blades. Wind turbine sound can sometimes be tonal, i.e. one can hear a specific pitch. This can be mechanical sound from the gear box and other devices in the turbine which was a relevant source for early turbines. Another possible source is an irregularity on a blade, but this is apparently rare and can be mended.

When the sound penetrates into a dwelling, the building construction will attenuate the higher frequencies better than the lower frequencies. As a result, indoor levels will be lower and the sound inside is of a lower pitch, as higher frequencies

[2] Although high annoyance is not classified as a disease in the International Classification of Disease (ICD-9; ICD-10), it does affect the well-being of many people and therefore may be considered to be a health effect falling within the WHO definition of health.

are more reduced than low frequencies. This is true for every sound coming from outside. Wind turbine sound changes over time. An important feature is the variation of the sound at the rhythm of the rotating blades. This variation in synchrony with the blade passing frequency is also called the amplitude modulation (AM) of the sound [6,9–12].

1.2 Human Hearing

Most environmental sounds with a level of 40 dBA will approximately have the same loudness for human hearing because the A-weighting (that is implied by the A in dBA) is based on the loudness curve of 40 phon (which equals 40 dB at 1000 Hz). Such a low to moderate loudness is comparable with actual wind turbine sound levels at many residences near wind farms. Therefore, A-weighting should give a (nearly) correct estimate of the loudness of a sound. With hearing tests this was confirmed in the Japanese wind turbine sound study [13]. A-weighting is less correct at lower sound levels; application of A-weighting to low levels (roughly < 30 dBA) may allow for more low-frequency sound. Of course, this concerns sound levels that are already low and usually will comply with limits. It is because of the combination of our hearing capacities at different frequencies and the sound level of the different wind turbine sources that trailing edge sound is the most dominant sound when outside and not too far from a wind turbine. The sound will shift to lower frequencies at larger distances or indoors, and then inflow turbulent sound can be more important.

When a sound is 'subaudible', the level of that sound is below the hearing threshold and thus below the level it can be audible. Usually the 'normal' threshold (hearing threshold of young adults without hearing problems, according to the international standard ISO 326) is used. As there is a variation between individuals, the normal threshold is the hearing threshold separating the 50% best hearing from the 50% that hear less well. For an individual often that normal hearing threshold is taken as an indication, but for that person of course the individual hearing threshold is relevant. Hearing acuity may differ considerably between persons. Hearing generally deteriorates with age, but this is typically less so at lower frequencies when compared to higher frequencies.

1.3 Sound Levels in Practice

For a modern turbine, the maximum sound power level is in the range between 100 and 110 dBA. 'Sound power' is the total amount of sound radiated from a source. For a listener on the ground close to a turbine, the outdoor sound level will not be more than about 55 dBA. At residential locations this is often less and in most studies there are few people, if any, exposed to an average sound level of over 45 dBA. For a wind turbine, maximum sound levels are not much higher than average sound levels. For two turbine types in a temperate climate, it was shown that the sound level from these two types at high power is 1–3 dB above the sound level averaged over a long time [14].

Measurements on many types of modern wind turbines show that most sound energy is radiated at low and infrasound frequencies and less at higher frequencies (approximately 100–2000 Hz). However, because of the lower sensitivity of human hearing at low frequencies, audibility is greater at the higher frequencies. In the last decades wind turbines have become bigger and onshore wind turbines now can have several megawatts (MW) electric power. 2 MW turbines produce 9–10 dB more sound power when compared to 200 kW turbines [15,16]. Over time the amount of low-frequency sound (10–160 Hz) increases at nearly the same rate as the total sound level. Depending on what the reference situation is, this is somewhat less according to one author [15], somewhat more according to the other [16].

1.4 Aspects Other than Sound

Apart from sound, visual aspects, safety and vibrations related to wind turbines may also have an impact on the environment and the people living in it. Economic benefit, intrusion in privacy and acceptance of the wind turbines and other sources of disturbance are relevant to understand levels of annoyance. Also, personal and contextual aspects can determine the level of annoyance due to wind turbines.

2 Method

2.1 Data Sources and Search

This paper summarizes the present knowledge available about the association between wind turbine sound and health. It is based on several literature searches and reviews recently performed in the Netherlands [17,18] and updated with literature until February 2017, using the same method. Some papers from the most recent conference on Wind Turbine Noise (May 2017) have also been added to the overview in Sect. 4.

For this review a systematic literature search was performed at three moments in time (2000–2012; 2012–2015; and 2015–2017) using the same protocol. Observational as well as experimental studies described in the peer review literature in the period between 2009 and 2017 were included. Language was restricted to German, English, French and Dutch. The databases Scopus, Medline and Embase (note: only 2015–2017) were searched because these studies do not appear in the available reviews yet and they are of high value as they build on earlier evidence. The search strategy is described in Table 1.

Table 1 Key search terms and search profile

1	(Wind turbine* or wind farm* or windmill* or wind park* or wind power or wind energy).ti. (550)
2	Turbine noise*.tw. and wind/ (33)
3	(Power plants/ or energy-generating sources/ or electric power supplies/) and wind/ (187)
4	(Low frequency noise* or low frequency sound* or infrasound or infrasonic noise* or infrasonic sounds or infrasonic frequencies or low frequency threshold or (noise* adj4 low frequenc*)).ti. (500)
5	1 or 2 or 3 or 4 (1113)
6	(Wind turbine* or wind farm* or windmill* or wind park* or wind power or wind energy).ab. (803)
7	(Low frequency noise* or low frequency sound* or infrasound or infrasonic noise* or infrasonic sounds or infrasonic frequencies or low frequency threshold or (noise* adj4 low frequenc*)).ab. (1487)
8	Noise*.ti. (26930)
9	(6 or 7) and 8 (498)
10	(Impact or perception* or perceive* or health* or well-being or "quality of life" or syndrome*).ti. (1456358)
11	(Annoyance or annoying or annoyed or aversion or stress or complaints or distress or disturbance or adversely affected or concerns or worries or noise problems or noise perception or noise reception or noise sensitivity or (sensitivity adj3 noise) or sound pressure level* or sleep disturbance* or sleep quality or cognitive performance or emotions or anxiet* or attitude*).tw. (1260490)
12	(Social barrier* or social acceptance or popular opinion* or public resistance or (living adj4 vicinity) or (living adj4 proximity) or (residing adj4 vicinity) or (residing adj4 proximity) or living close or "living near" or residents or neighbors or neighbours).tw. (105942)
13	(Soundscape or landscape or visual annoyance or visual interference or visual perception or visual impact or visual preferences or visual assessment or visual effects or perceptual attribute*).tw. (41227)
14	(Effects adj4 population) or dose-response relationship* or exposure-response relationship* or dose response or exposure response or human response or health effects or health aspects or health outcome*).tw. (136924)
15	(Flicker or reflection).ti. (10980)
16	Environmental exposure/ or noise/ae or environmental pollution/ae (79725)
17	Loudness perception/ or psychoacoustics/ or auditory perception/ or auditory threshold/ or sensory thresholds/ or visual perception/ or motion perception/ (130572)
18	Sleep disorders/ or emotions/ or anger/ or anxienty/ or quality of life/ or epilepsy/ or attitude/ or affect/ or pressure/ or aesthetics/ or social environment/ or risk factors/ (1232239)
19	(Physiopathology or adverse effects).fs. (3235762)
Language: English or Dutch or French or German	
Search period: 2009–2017	
Duplicates removed	
Exclude animals/not humans	

We aimed to include low-frequency sound and infrasound in this review, but there are less publications and reviews specifically addressing this part of the spectrum. Also, the (alleged or studied) effects of infrasound and low-frequency sound are different from the effects of 'normal' sound. As a consequence, this topic is reviewed separately and is based on all relevant publications from the literature search (Fig. 1).

2.2 Inclusion Criteria

Only studies were included in which it was mentioned in the title, abstract or summary that the association was studied between the sound or noise of wind turbines and a reaction or effect concerning health or well-being. Also, studies addressing participation during the building process were accepted for review. This implied that the association between exposure to wind turbine (low-frequency) sound and annoyance, health, well-being or activity disturbance in the adult population was studied.

For a first selection the following criteria were used. Inclusion: papers address human health effects, perception, opinion, concern in relation to wind turbines. Exclusion: papers address non-human effects such as ecosystem effects, animals, papers solely about technical aspects of the wind turbines, papers regarding health effects of sound but not related to wind turbines. This resulted in total in 202 possi-

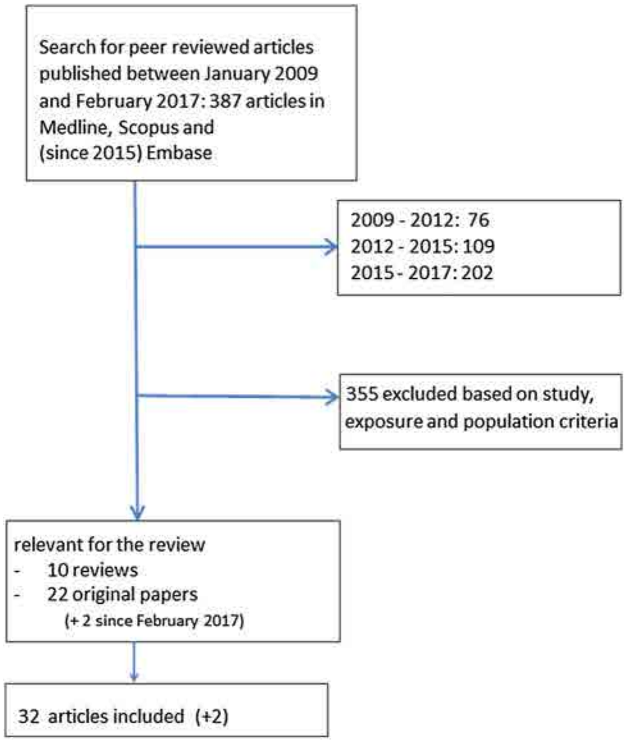

Fig. 1 Flowchart of selection process

bly relevant studies for the period between January 2015 and February 2017.

The papers for the period from January 2015 to February 2017 were grouped in seven categories: review, health effects, case studies, offshore, low-frequency sound/infrasound, visual aspects, social and not relevant. All reviews and health effects studies were included for full paper examination. All low-frequency sound/infrasound studies were examined for inclusion in the separate review. Offshore studies were a priori excluded; papers from the other categories were reconsidered after reading the abstracts.

Lastly, after full examination of the reviews and low-frequency sound/infrasound and health effect papers by the two authors, a final decision was made about inclusion in this review.

2.3 Procedure and Study Quality Assessment

This review is primarily based on results from epidemiological studies at population level and smaller-scale laboratory experiments.

The results have been divided into three sections. The difference in material between both periods (up to and since 2015) resulted in two sections: first we review the reviews (Sect. 3.1), and then we review original studies most of which are from the second period (3.2). The effects of infrasound and low-frequency sound are summarized in a third part (Sect. 4).

The main results are summarized per outcome. For the key studies, the study design and outcomes are discussed in more detail. For this review primarily scientific publications are used, from both peer-reviewed journals and conference proceedings. In some cases results are discussed which were described in non-scientific ('grey') literature. Also, some publications are mentioned that are often used in the debate (discourse) about the risks of living in the vicinity of wind turbines.

As usual, all material from the selected literature has been read and analysed, but not necessarily included as reference, e.g. because the study was less relevant than originally thought or in case of doubling with other references (e.g. a conference paper and an article from the same authors and study). A meta-analysis on (part of) the data was not considered in the time frame of this assignment.

3 Results

Annoyance and sleep disturbance are the most frequently studied health effects of wind turbine sound as is also the case for sound from other sources. After a short explanation of the health effects addressed in the literature, the overall conclusions from key reviews are summarized. Then the main findings for annoyance, sleep disturbance and other health effects are described in more detail, sometimes referring to the underlying publications. The influence of personal, situational and contextual factors on these effects is also included. Then in Sect. 3.2 the most recent original studies (2015–2017) are described separately in more detail while following the same structure.

Effects that are mentioned as specific effects of infrasound and/or low-frequency sound are treated in Sect. 4.

3.1 Evidence Until Early 2017: Reviews

People can experience annoyance or irritation, anger or disturbance from wind turbine sound, or when they feel that their environmental quality and quality of life deteriorates due to the siting of wind turbines near their homes.

The number of publications on wind turbine sound and its health effects has increased considerably in the past 10 years, including peer-reviewed articles, conference papers and policy documents (Table 2).

A remarkable number of nineteen reviews were published in the period between 2009 and 2017. These include systematic reviews as well as policy preparing reviews. Some reviews were dismissed after reading the full text, since they were highly anecdotal, no health impact was estimated, incomplete or only concerned occupational exposure, etc.

Table 2 Reviews (2009–2017) selected for this paper

First author year and reference	Studies included					Meta-analysis
	Number of studies evaluated	Number of participants	Time range	Exposure	Outcomes	
Knopper, (2011) [21]	15 studies	Na	2003 and 2011	Aspects of wind turbines broadly	Physiological and self-reported health effects, annoyance, stress, sleep disturbance, insomnia, anxiety	No
Harrison, (2015) [27]	Review of reviews	Na	2015	Low-frequency noise, levels < 100 dB SPL	Wind turbine syndrome. Vertigo, nausea and nystagmus, aural fullness, hyperacusis, and tinnitus	No
Ellenbogen (MPED), (2012) [22,23]	4 studies (peer-reviewed and 4 non-peer-reviewed	Na	2011	Aspects of wind turbines broadly: noise, shadow flicker, visual aspects, ice throw	Annoyance, sleep, health effects (self-reported, diagnosed)	No
Merlin, (2013) [19]	7 studies	2309 (79–754)	1981–2012	Infrasound/noise, electromagnetic interference, shadow flicker, blade glint	Adverse health effects (broad)	Yes
SHC, (2013) [20]	Na			Noise (including low-frequency noise, infrasound and vibrations) shadow flicker electromagnetic fields	Adverse health effects (broad)	No
Schmidt, (2014) [24]	36 studies	300–3000	2014	A-weighted sound exposure, < 30 dB >, infrasound, LFN, distance	Health, annoyance, tinnitus, vertigo, epilepsy, headache	No
MacCunney, (2014) [25]	20/14 studies	Na	2014	Distance, exposure, LFN infrasound	Sleep, cardiovascular, health, symptom, condition, disease	No
Knopper, (2014) [26]	60 studies	Na	2014	Noise, environmental change(s), wind, farm(s), infrasound, wind turbine(s), LFN, EMF, neighbourhood change	Annoyance, sleep disturbance, epilepsy, stress, health effect (wind turbine, syndrome	No, due to methodological, heterogeneity
Council of Canadian Academies, (2015) [28]	38 studies	Na	2009–2014	WT noise: a weighted SPL, infrasound, low-frequency sound and amplitude modulation	Annoyance sleep disturbance, tress, tension, health-related quality of life, vibroacoustic disease, cardiovascular system, endocrine system, immune system, musculoskeletal system, nervous system (general), nervous system (auditory), psychological health, respiratory system	No
Onakpoya, (2016) [1]	8 studies	2433	2000–2014	> and < 40 dB, distance	Annoyance and sleep disturbance	Yes

The remaining ten recent and leading reviews and policy documents (described in 11 manuscripts: [1,19–28] draw comparable conclusions about the health effects of wind turbine sound: in general, an association is found between annoyance and the level of wind turbine sound. Also, an association between sound level and sleep disturbance is considered plausible, even though a direct relation is uncertain because of the limited number of studies with sometimes contradictory results. Perceived stress is related to chronic annoyance or to the feeling that environmental quality and quality of life has diminished due to the placement of wind turbines, and there is sufficient evidence that stress can negatively affect people's health and well-being in people living in the vicinity of wind turbines [20].

Next to sound, vibration, shadow flicker, warning lights and other visual aspects have been examined in the reviews. There are no studies available yet about the long-term health effects. Such longitudinal studies (studies comparing the situation at different moments in time) might be useful to gain more insight in the causal pathways of the different factors. However, they can still only examine the strength of temporal associations across a range of relevant variables and to establish causal relations will remain problematic in this area.

Most recently, Onakpoya et al. [1] reanalysed the data from eight cross sectional studies, selected on strict quality requirements and including a total of 2433 participants. Effects considered were annoyance, sleep disturbance and quality of life. Evidence supports the earlier conclusion that there is an association between exposure to wind turbine sound and an increased frequency of annoyance and sleep problems, after adjustment for key variables as visual aspects, attitudes and background sound levels. The strength of evidence was the most convincing for annoyance, followed by sleep disturbance, when comparing participants at exposure levels below and above 40 dB. The findings are in line with Schmidt and Klokker [24] and Janssen et al. [29]. In contrast to these authors, Merlin et al. [19] consider annoyance a response to wind turbines and not a (health) effect as such.

Personal and contextual factors can influence annoyance. There is consensus in the literature that visual aspects, attitudes towards wind turbines in the landscape and towards the people responsible for wind farms, the process around planning and construction and economic interest can all in their own way affect levels of annoyance. However, actual evidence for this is still limited.

The next sections will describe the state of the art in more detail per health effect. Note that the description is limited to the effects of wind turbine sound in the 'normal' frequency range. Findings from studies, addressing suggested specific impacts of the low-frequency component and infrasound distinct from 'normal' sound are summarized separately in Sect. 4.

3.1.1 Noise Annoyance

In many countries the assessment of the sound of wind turbines is based on average, A-weighted sound levels (see Sect. 1.2). It is generally accepted that annoyance from wind turbines occurs at lower levels than is the case for traffic or industrial sound. Based on Dutch and Swedish data, an exposure–effect relation was derived between calculated sound exposure levels expressed in Lden (day–evening–night level) and the percentage highly annoyed, for indoor as well as outdoor exposures. Later research in Japan and Poland have confirmed these results and obtained similar results [30,31]. The relation between wind turbine sound and annoyance can be compared with those for road, rail and aircraft sound. This comparison is presented in Fig. 2 where the 'aircraft Europe' data are from the European HYENA study [32], the wind turbine data are from Janssen et al. [29], and the other data are from Miedema and Vos [33] for industrial sound and from Miedema and Oudshoorn [34] for air, road and rail transportation sound. The more recent HYENA study has shown that at a number of big European airports noise annoyance has increased when compared to the older data from Miedema and Oudshoorn [34]. Figure 2 shows that sound from wind turbines leads to a higher percentage of highly annoyed people when compared to other sound sources. The relation resembles that of air traffic sound, but near airports there are higher sound levels and a correspondingly higher percentage of highly annoyed. The relations for transport sound in Fig. 2 have been derived for large numbers of persons from many countries, but the actual percentage for a specific place or situation can be very different, for wind turbines as well as other sources.

Some think that it is too early to define exposure–effect relations for wind turbines [20,35]. According to them, the influence of context (like residential factors, trust in

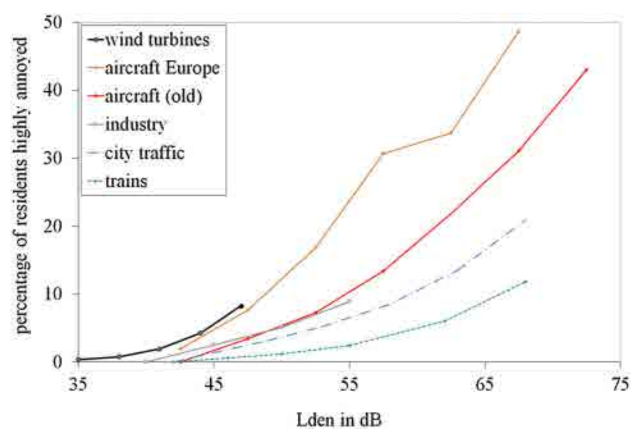

Fig. 2 Comparison of the percentage highly annoyed residents from sound of wind turbines, transportation and industry (approach adapted from Janssen et al. [51]); see text for explanation of legend

authorities and the planning process, situational factors) and personal factors (such as noise sensitivity and attitude) is so strong that the exposure–effect relation can only (or at best) give an indication of the percentage of highly annoyed at the local level [22,23].This is not unique to wind turbines, but is to some degree—also true for other sound sources and in part explains why in specific places or situations the actual percentage of annoyed persons can differ from the relations in Fig. 2. Michaud et al. [36] compared the results from five studies and found there was a 7.5 dB variation in wind turbine sound levels that led to the same percentage of annoyed persons.

What makes wind turbine sound so annoying?

In a Dutch survey [37] 75% of the respondents indicated that the terms ‘swishing/lashing’ gave the best description of wind turbine sound, irrespective of their being annoyed or not [37]. Laboratory studies have consistently shown that the periodic variation in the sound of wind turbines adds to the annoyance. In the study of Persson Waye and Öhrström [38] it was found that wind turbine sounds described as ‘swishing’, ‘lapping’ or ‘whistling’ were more annoying while the least annoying sounds were described as ‘grinding’ and ‘low frequency’ [38]. In the UK research was performed near three dwellings where people complained about wind turbine sound. Rather than the low-frequency component of the sound amplitude modulation or the rhythmic character was the most conspicuous aspect of the sound [39]. In a later UK study Large and Stigwood [40] concluded that amplitude modulation is an important aspect of the intrusiveness of wind turbine sound. More recently Yoon et al. [12] stated that there is a strong possibility that amplitude modulation is the main reason why wind turbine sound is easily detectable and relatively annoying.

Whether the type of environment affects the levels of annoyance is not yet clear. It can be assumed that people in rural areas are more likely to hear and see wind turbines than in more built-up urban areas with more buildings and a less open view. However, Dutch research showed that the percentage of highly annoyed people was equally high in rural and urban areas [37] although the correlation with the wind turbine sound level was less strong in the built-up area [41]. An important moderator was the existence of a busy road nearby, reducing the percentage annoyed by wind turbine sound annoyance in rural areas only. In a Swedish study it was found that residents in rural areas reported more annoyance in rural areas than in urban environments, possibly due to their expectation that the rural area would be quiet [42]. In a recent study Qu et al. [43] found that the level of annoyance from wind turbine sound in urban and suburban areas was less than reported in the Swedish, Dutch, Polish and Canadian studies in rural areas.

3.1.2 Sleep Disturbance

Good sleep is essential for physical and mental health. Sound is one of the factors that can disturb sleep or affect the quality of sleep. Several biological reactions to night time sound from different sources have been described in the literature: increased heart rate, waking up, difficulty in falling asleep and more body movements (motility) during sleep [4]. The night noise guidelines of the WHO are not specifically aimed at noise from wind turbines, but cover a range of (other) noise sources. It is conceivable that the relatively small but frequently occurring sound peaks just above the threshold for sleep disturbance due to the rhythmic character of wind turbine sound cause sleep disturbance [44]. A Dutch study found that wind turbine sound did not affect self-reported sleep onset latency but did negatively influence the ability to keep sleeping [37,41]. An increase in sound level above 45 dBA increased the probability of awakening. This was not the case for people who obtained economic benefit from the wind turbines, but this might also have been an age effect (co-owners of the turbines were younger). These findings of the study in the Netherlands are in line with the conclusions which the WHO drew from the review of scientific literature the relation between transport sound and sleep [4]. According to the WHO, sleep disturbance can occur at an average sound level at the facade at night (Lnight) of 40 dB and higher [4].

A direct association between wind turbine sound and sleep disturbance can only be determined when there is a measurable reaction to the sound. Such an immediate influence is only plausible when the sound level is sufficiently high and as yet has not been convincingly shown for wind turbine sound [23,45]. An indirect effect has been shown between self-reported sleep disturbance and annoyance from wind turbine sound, but not between sleep disturbance and the sound levels per se [41]. Research has shown that also for other sound sources there is a high correlation between self-reported sleep disturbance and annoyance from noise [46].

Several more recent studies show an association between quality of life and sleep disturbance and the distance of a dwelling to a wind turbine [47,48]. Differences in perceived quality of life were associated with annoyance and self-reported sleep disturbance in residents. These results are highly comparable with those found for air and road traffic, e.g. see [49].

3.1.3 Other Health Effects Due to Sound

In an Australian report [50] the number of people living in the vicinity of wind turbines with serious health complaints was estimated to be 10–15%. However, according to literature reviews on the health effects of wind turbines [1,19,20,23–25,28] there is no evidence for health effects caused by wind turbines in people living in the vicinity of wind turbines, other than annoyance and self-reported sleep disturbance and the latter is inconclusive. There was, however, a clear correlation between annoyance and self-reported sleep disturbance in one study [41]. Based on existing field studies, there is insufficient evidence that living near a wind turbine is the direct cause of health effects such as mental health problems, headaches, pain, stiffness or diseases such as diabetes, cardiovascular disease, tinnitus and hearing damage.

3.1.4 Influence of Situational and Personal Factors

Research in the past decade has shed some light on the question why some people are more disturbed by wind turbines than others. Next to physical aspects, personal and contextual aspects influence the level of annoyance. Often these aspects are referred to as non-acoustic factors, complementary to the acoustic factors (the 'decibels'). Because the term non-acoustic refers to a broad range of aspects, and as a result is very unspecific, we prefer the term personal and contextual factors [51]. They can be subdivided in the following categories (with some exemplary aspects in brackets):

- Situational factors (visual aspects frequency of sound events, meteorological circumstances, other sound sources, distance to amenities and attractiveness of the area).
- Demographic and socio-economic factors (age, gender, income, level of education);
- Personal factors (fear or worry in relation to source, noise sensitivity, economic benefit from the source);
- Social factors (expectation, attitudes towards producers or government, media coverage);

There is a lot of variation in the aspects studied and also the strength of the evidence varies strongly. Without pretending to be exhaustive, those aspects documented in the reviews on wind turbine sound up to 2015 are discussed in more detail below.

3.1.4.1 Visual Aspects

Modern wind turbines are visible from a considerable distance because they rise high and change the landscape. Due to the movement of their rotor blades, wind turbines are more salient in the landscape than objects that do not move. The rotating blades draw our attention and can cause variations in light intensity when the blades block or reflect sunlight. The visual and auditory aspects have been shown to be highly interrelated [19,36,52] and are therefore hard to unravel with respect to their effects. Annoyance from visual aspects may add to or even reinforce annoyance from noise (and vice versa). Noise and visual annoyance are strongly related as was also described above. It has been suggested [20] that people who see the wind turbines from their homes are more worried about the health effect of continuous exposure and as a consequence also report more annoyance [20].

3.1.4.2 Economic Aspects

Economic aspects can also affect annoyance from wind turbines. In a study of Pedersen et al. [52] in the Netherlands, some 14% of the respondents benefited from one or more wind turbines, in particular enterprising farmers who lived in general closer to the turbines and were exposed to higher sound levels than the remaining respondents. The percentage of annoyed persons in this group was low to very low, despite the higher exposure and the use of the same terms to describe the typical characteristics of wind turbine sound. In the study this group was described as 'healthy farmers': on average they were younger, more often male and had a higher level of education when compared to those not having economic benefits and reported less problems with health and sleep. However, it might not only be the benefit, but differences in attitude and perception as well as having more control over the placement of the turbines that might play a role [37].

3.1.4.3 Noise Sensitivity

Being noise sensitive refers to an internal state determined by physiological, psychological, attitudinal aspect, lifestyle and activities of a person that increases the reactivity to sound in general. Noise sensitivity has a strong genetic component (i.e. hereditary), but can also be a consequence of a disease (e.g. migraine) or trauma. Also, serious anxiety disorders can go together with an increased sensitivity to sound and possibly lead to a feeling of panic [53]. Only a few studies have addressed this issue in relation to wind turbine sound. An early example is the study of Shepherd et al. [47] in New Zealand, in which two groups were compared (a 'turbine group' versus a control group). Noise sensitivity was measured with a single question informing whether people considered themselves as noise sensitive. In the turbine group a strong association was found between noise sensitivity and annoyance and a weak association in the control group. This is indicative of an interaction effect of exposure and sensitivity on annoyance. This has also been documented for other sound sources [54]. According to a case report from Thorne [50], a relatively high proportion of residents near two wind farms in Australia were noise sensitive. Self-selection into a 'quiet area' by noise sensitive people can be a plausible explanation.

3.1.4.4 Social Aspects

For the social acceptance of wind turbine projects by a local community, the Belgian Superior Health Council [20] stated it is crucial how the community evaluates the consequences for their future quality of life. The communication and relation between the key parties (residents, municipality and project developer) are very important. Disturbance by wind turbines is a complex problem, in which the objective (physical) exposure and personal factors play a role, but also policy, psychology, communication and a feeling of justice.

When planning and participation are experienced as unjust or inadequate, public support will soon deteriorate, also among people who were originally neutral or in favour of the wind farm [55]. When residents feel they have been insufficiently heard, they feel powerless and experience a lack of control over their own environmental quality and quality of life. Worry or concern can be reduced by an open and honest procedure in which residents can contribute to the decisions in a positive way [56]. Already in the early phase of wind energy, research from Wolsink [57] and later from Breukers [58] showed that collaboration with emphasis on local topics was more successful than a policy aimed at as much wind energy as possible and a non-participatory approach.

Pedersen et al. [52] found that people who perceive the wind turbines as intruding and a threat to their privacy (motion, sound, visual) reported more annoyance. When people feel attached to their environment (‘place attachment’), the wind farm can form a threat to that location and can create resistance [59]. Also, a feeling of helplessness and procedural injustice can develop when people feel they have no real say in the planning process. Potentially, this plays a role especially in rural areas where people choose to live because of tranquillity; for them the wind park can form an important threat (visual and auditory). Based on renewable energy projects in the UK, Walker and Devine-Wright [60] concluded that the more people participated in project development, the higher was the public support for renewable energy in general.

3.2 Evidence Since 2015 Based on New Studies

In the period between January 2015 and 2017, 22 relevant publications were identified in peer-reviewed literature. These are 10 on field studies [36,61–69], 7 on experiments [12,70–75], 3 on a prospective cohort study [76–78], 1 panel study [79] and 1 qualitative analysis of interviews and discourse [80]. After the systematic literature search, two relevant papers from the most recent International Wind Turbine Noise Conference (Rotterdam 2017) were included [43,81].

Two major studies were (partly) reported in this period and not included in the reviews, one in Canada [16,61–65] and one in Japan [66,67]. The study from Health Canada [36,61–65] was performed with 1238 adult residents living at varying distances from wind turbines. A-weighted sound levels outdoors were calculated as well as C-weighted levels, and additional measurements were made at a number of locations. A strong point of the study is the high response rate of 79%. The results were presented in six publications, addressing effects on sleep, stress, quality of life, noise annoyance and health effects and a separate paper on the effect of shadow flicker on annoyance. Also, two papers were published describing the assessment of sound levels near wind turbines and near receivers [82,83]. The Japanese study by Kakeyama et al. [66,67] pertains a field study with structured face-to-face interviews at 34 study sites and 16 control sites. Wind turbine sound levels were estimated based on previous measurements at some sites and expressed in LAeq. Outcomes studied were sleep deprivation, sleep disturbance and physical and mental health symptoms (Table 3).

The next sections describe the state of the art in more detail per health effect as in 3.1. Note again that the description is limited to the effects of wind turbine sound in the ‘normal’ frequency range. Findings from studies addressing suggested specific impacts of the low-frequency component and infrasound distinct from ‘normal’ sound are summarized separately in Sect. 4.

3.2.1 Noise Annoyance

In one of his papers about the Health Canada study, Michaud et al. [61] describe the findings on annoyance, self-reported health and medication use. In line with earlier findings the study confirms that the percentage of highly annoyed increased significantly with increasing wind turbine sound levels. The effect was highest for annoyance with visual aspects of wind turbines, followed by blinking lights, shadow flicker, sound and vibrations.

An Iranian study of Abasssi et al. [68] included 53 workers divided in three job groups with repairing, security and administration tasks. The exposure level to wind turbine sound of employees at each job group was measured as an 8-h equivalent sound level as is usual in working conditions. Outcome measures included annoyance, sleep, psychological distress and health complaints. Noise sensitivity, age, job stress and shift work were accounted for. Annoyance was associated with measured sound levels but lower than found in residential studies. The other health outcomes did not show a significant association. It is not clear how this relates to residential conditions as the situations are quite different and different factors are involved.

In the period 2015–2017 several laboratory studies have addressed the effects of wind turbine sound and annoyance. In a listening test among 60 people, after a pilot in 12 people, an association was found by Schäffer et al. [70] between road traffic and wind turbine sound level or variations in sound level due to amplitude modulation and annoyance. Attitude towards wind turbines and noise sensitivity were important confounders, and the frequency of the amplitude modulation (higher for the wind turbine sound) seemed to play an important role.

The relative contribution of the typical characteristics of wind turbine sound, and particularly the rhythmic character or amplitude modulation (AM) was studied in several exper-

Table 3 Overview of the studies published after January 2015 and selected for this review

First author, year and reference	Studies included						
	Country	Number of participants	Design	Quality	Exposure	Outcomes	Effect
Michaud, (2016a) [61]	Canada	1238	Survey	objective and subjective measures	A waited SPL outdoors estimated + C-weighted	Annoyance, sleep disturbance, stress or psychological	The prevalence of self-reporting to be either 'very' or 'extremely' (i.e. highly) annoyed with several wind turbine, features increased significantly with increasing A-weighted levels
Michaud, (2016b) [62]	Canada	1238	Mixed	Objective and subjective measures	SPL 31–48 dB estimated + measurements on location	Sleep (actimeter), subjective sleep indicators	No effect on any of the sleep indicators
Michaud, (2016c) [63]	Canada	1238	Survey	Objective and subjective measures	A waited SPL outdoors estimated + C-weighted	Perceived stress scale (PSS) scores, hair cortisol concentrations, resting blood pressure and heart rate	The findings do not support an association between exposure to WTN up to 46 dBA and elevated self-reported and objectively defined measures of stress
Michaud, (2016d) [36]	Canada	1238	Survey	Objective and subjective measures	A waited SPL outdoors estimated + C-weighted	Noise annoyance, wind turbine perceptions, (including concern for physical safety) and a whole range of personal and situational aspects	Annoyance determined by other wind turbine-related, annoyances, personal benefit, noise sensitivity, physical safety concerns, property ownership and province: the community tolerance level (CTL) to WTN is 11 and 26 dB less than to other sources
Jalali, (2016a) [76]	Canada	T1-43, T2-31	Prospective cohort Before after	Objective and subjective measures		Annoyance, Qol subjective health, mental health	Significant effect on mental health and annoyance and symptoms. Interaction with negative attitude, worry about housing prize and visual complaints
Jalali, (2016b) [77]	Canada	16/2 nights	Prospective cohort Before after	Objective and subjective measures	Distance only	Sleep indicators with polysomnographic	No major change in sleep after placement of WT's
Jalali, (2016c) [78]	Canada		Prospective cohort Before after	Objective and subjective measures	Distance only	Pittsburg sleep quality, Epworth Sleepiness Scale and the Insomnia Severity Index	WT placement was associated with increased poor sleep quality, daytime sleepiness and rates of insomnia (expressed in th score on the PSQI and the ESS and the ISI. There was a strong association with negative attitude, worry about property values and WT visibility

Table 3 continued

First author, year and reference	Studies included						
	Country	Number of participants	Design	Quality	Exposure	Outcomes	Effect
Schäffer, (2016) [70]	Germany and Switzerland	60	Laboratory study	Test in j 12 pp of noise stimuli	WT $<$ 55 versus traffic outdoor levels $>$ 40 normal fluctuations due to weather conditions	Annoyance (short term) modifying effect of noise characteristics	Difference found but (much) smaller than Janssen and Michaud), AM next to noise level
Feder, (2015) [64]	Canada	1238	Field study	Objective and subjective measures	22–11 km and estimates based on ISO9613-1 and ISO9613-for each dwelling, dBA and dBC	WHO Qol annoyance, symptoms, sleep quality, perceived stress, life, style behaviours and prevalent chronic disease	No effects on Qol subscales below 46 dB
Chrichton, (2015) [71]	New Zealand	60	Laboratory study	Students/no control group	Up to 43 dB NZ standard for WT infra sound	Annoyance	Effect only in negative expectation group, interaction with NS
Blanes-Vidal, (2016) [69]	Denmark/USA	454	Cross sectional	Na	Distance to WT and number of turbines	Ideopathic symptoms	Effects on fatigue, difficulty concentrating, headache all disappeared after adjustment for noise exposure and odour from other sources
Ionannnidou, (2016) [72]	Denmark	19	Laboratory study	Na	Amplitude modulation elements 60 dBA 30 s M (approach van den Berg)	Annoyance	Check
Abassi, (2015) [68]	Iran	53	Field study	Na	8-h equivalent sound level (LAeq, 8 h) based on ISO 9612:2009	Annoyance, sleep psychological distress, health complaints	Annoyance associated with measured levels but lower than found in residential studies possibly due to economic benefits
Tonin, (2016) [74]	Australia	72	Laboratory study	More men	Infrasound exposure double blind (sham noise)	Annoyance, symptoms	Effects mediated by high/low expectancy
Hafke-Dys, (2016) [73]	Poland	21	Laboratory study	Control condition without modulation	Broadband and narrowband noise. With modulations typical, for WT (3, 6 and 9 dB) based on Renteghem	Annoyance	Interaction between noise type (broadband) and AM on annoyance. WT noise is perceived as less annoying when AM freq. is $<$ 4 Hz
Yoon, (2016) [12]	Korea	24	Laboratory study	Control group	Amplitude modulation	Perceived loudness	Combined effect of noise levels and AM on noise perception

Table 3 continued

First author, year and reference	Studies included						
	Country	Number of participants	Design	Quality	Exposure	Outcomes	Effect
Botterill, (2016) [80]	Australia	Na	Interviews and discourse analysis	Na	Na	Topics mentioned most often in the discourse	Health and property values came forward as main topics
Kageyama, (2016) [66,67]	Japan	1079	Face-to-face structured interviews	Control sites! (16) versus 34 exp. sites	LAeq estimated based on some measurement sites, median 36–40 and 35 at control sites	Insomnia, physical and mental health, sensitivity to noise and visual annoyance	Odds ratio (OR) of insomnia was significantly higher when the noise exposure level exceeded 40 dB, self-reported sensitivity and visual annoyance independently associated with insomnia. OR of poor health only significant for, noise sensitivity and visual annoyance
Maffei, (2015) [75]	Italy	40	Listening, experiments	Exp versus control	Sound recordings of about 5 min were made at five distances	Noise recognition	Recognition is congruent with the increase of the distance and the decrease of the values of sound, equivalent levels and loudness
Krekel, (2016) [79]	France/Germany	30	Panel data	Na	(i) The exact geographical coordinates, (ii) the exact construction, dates and (iii) information on the size of the installation	Satisfaction with life	Geographical distribution of well-being merged with WT locations. Well-being data merged with
Voicescu, (2016) [65]	Canada	1238	Survey	Objective and subjective measures	Shadow flicker (SF) combined with noise estimates expressed in maximum minutes per day (SFm), modelled and based on distance	Annoyance, health complaints including dizziness	Annoyance associated with SF annoyance to other wind turbine-related features, concern for physical safety and noise sensitivity. Reported dizziness was also retained in the final model (all significant)

Table 3 continued

First author, year and reference	Studies included						
	Country	Number of participants	Design	Quality	Exposure	Outcomes	Effect
Yano, (2015) [30]	Japan	1079	Face-to-face interview	Control group (332) in areas with no wind turbines	Extra/interpolated from measured night time noise level ($L_{\mathrm{Aeq},n}$); distance for visual exposure	Noise annoyance, visual disturbance, perception of shadow flicker (SF)	$L_{\mathrm{Aeq},n}$ and distance significantly related to noise annoyance; distance more strongly associated with noise annoyance than level. Most annoyance reported at night-time. Visual annoyance not significantly related to distance, SF indoor and SF outdoor significantly related to distance. SF outdoor more prominent in mountainous area (compared to flat). Interaction between noise annoyance and visual annoyance/SF outdoor, not with visibility and SF indoors
Qu, (2017) [43]	England + Scotland	357	Survey in (sub)urban areas	No attribution to wind turbines in control group (96)	Calculated (maximum?) A-weighted wind turbine sound pressure level (SPL) on most exposed facade	Awareness of and annoyance with wind turbine noise, self-reported sleep disturbance, prevalence of specific health problems, general health, subjective well-being	SPL positively associated with noise annoyance. SPL not associated with sleep, but degree of noise annoyance significantly increased possibility of sleep disturbance. Visibility of wind turbine from both window and garden significantly increased odds of less deep sleep. In case group, annoyance with wind turbine noise significantly influenced prevalence of health problems: psychological problems significantly and positively associated with being annoyed by wind turbine noise, but not with SPL itself. Positive associations were found between SPL and adverse health problems, including nausea and dizziness. Dizziness and ear discomfort related to SPL in control group

iments. Ionannidou et al. [72] report on a study among 19 volunteers in which the effect of changes over time in the amplitude modulation of wind turbine sound on annoyance was investigated. The changes could either be the frequency of the modulation, the depth (or strength) of the modulation or a change in depth over time. The study confirms earlier results that AM leads to a higher annoyance rating. A higher modulation frequency (from 0.5 to 2 Hz) also resulted in a higher rating, but the effect was not significant. There was also a higher annoyance rating when the modulation depth increased intermittently, but again this was not significant. Because of the limited statistical power of these tests (because of the low number of participants and the limited time), it was recommended to investigate the variations in AM for a longer period and in a field setting.

A study from Hafke-Dys et al. [73] among 21 volunteers again concerned the effect of amplitude modulation on annoyance. In this study sounds with several modulation conditions were compared to a non-modulation condition. The test sounds used were (1) sound from moving cars, passing at a rate of 1–4 per second; (2) broadband sound with the same spectrum as wind turbines and (3) narrowband sound that could be modulated at 1, 2 and 4 Hz. All three types of sound had modulation depths typical for wind turbines at 3, 6 and 9 dB similar to Van Renterghem et al. [84], or zero (no modulation). Results showed that AM did increase annoyance in the case of broadband sound and passing cars, but not for the narrow band sound. The modulated sound was more annoying with increasing modulation frequency, in agreement with an expected highest sensitivity for modulated sounds at 4 Hz. Large, modern wind turbines modulate their sound at a frequency close to 1 Hz. The effect of AM on annoyance was less for the broadband sound than for passing cars. The main difference between these two sounds was the spectral content, with the broadband sound having more low-frequency sound than the passing cars. The authors conclude that this result supports the Japanese study [13] in which it was demonstrated 'that low frequency components are not the most significant problem when it comes to the annoyance perception of wind turbine noise'.

Yoon et al. [12] studied the reaction to modulation of wind turbine sound in 12 people. Findings show again that there is an association between AM and level of annoyance. The authors conclude that there is a strong possibility that amplitude modulation is the main cause of two typical properties of wind turbine sound: that it is easily detectable and highly annoying at relatively lower sound levels than other noise sources. They add that this does not mean that these properties can be fully explained by the amplitude modulation.

Crichton and Petrie [71] studied 60 volunteers at exposure levels up to 43 dBA (the New Zealand standard limit) in combination with infrasound (9 Hz, 50 dB). In one group, the participants were shown a video about the health risk of wind turbine infrasound, and in the second group a video on health benefits was shown. An effect on annoyance was found only in the group expecting to be negatively affected, and in this group noise sensitivity increased the likelihood of being annoyed. In the group expecting a positive effect, there was far less annoyance and almost no influence from noise sensitivity.

In a later publication from the Japanese study, it was found that within 860 m from a wind farm 10% of the residents were annoyed by shadow flicker while within 780 m 10% of the residents were highly annoyed by wind turbine sound [81]. The authors concluded that a minimum distance (or 'setback') between residences and wind farms should be considered from an aural and visual point of view.

3.2.2 Sleep Disturbance

Michaud et al. [62] reported on sleep disturbance from a field study involving 742 of the 1238 respondents (as described under 3.2) wearing an actimeter, to measure relevant sleep indicators during 3–7 consecutive nights after the interviews. Outdoor wind turbine sound levels were calculated following international standards. Neither self-reported sleep quality, diagnosed sleep disorders nor objective measures such as sleep onset latency, awakenings and sleep efficiency showed an immediate association with exposure levels up to 46 dB after adjustment for relevant confounders such as age, caffeine use, body mass index (BMI) and health condition. This partly contrasts with earlier findings on subjective sleep measures [47]. No study addressed objective sleep measures in relation to wind turbines before. However, it should be mentioned that the method of actigraphy is limited as compared to more elaborate polysomnographic measures as were employed by Jalali et al. [76] and described below. In the Health Canada study having to close the window in order to guarantee an undisturbed sleep had by far the strongest influence on annoyance [61]. This could be a reason that no relation between wind turbine sound level and sleep disturbance was found: if persons disturbed at night by wind turbine sound would close their bedroom window, the result could be that they are less disturbed at night by the sound as such, although they could be annoyed because they had to close the window. The results do not directly support or negate this explanation. However, those closing their bedroom windows was eight times more likely to be annoyed. At higher wind turbine sound levels, people more often gave wind turbines as a reason for closing the bedroom window [61].

Kakeyama et al. [66,67] showed a significant association between sound levels above 40 dB and sleeping problems (insomnia). These findings are in contrast with those reported by Michaud et al. [62] who did not observe an immediate association between sound exposure levels up to 46 dBA and subjective and objective indicators for sleep. The earlier findings of Bakker [41] regarding subjective sleep indicators showed that sleep disturbance seemed to be related to sound level only when no others factors were included. When annoyance with wind turbine sound was included, then sleep disturbance was related to that annoyance and not anymore to sound level. Earlier, Pedersen and Persson [42] also concluded on an association between annoyance and sleep disturbance rather than a direct effect of sound level.

Jalali et al. [77] measured sleep disturbance in a group of 16 people for 2 consecutive nights using a polysomnographic method including a range of sleep and physiological parameters such as sleep onset, duration, movement during sleep, awakening, EEG activity. Sound measurements over the whole frequency range (0.5–20,000 Hz) were performed in the bedroom as well as outdoor, while accounting for weather conditions, wind speed and temperature. Factors that were taken into account were attitude, sensitivity, visibility, distance within 1000 m and windows open versus closed. Results showed no major changes in the sleep of participants who had new wind turbines in their community. There were no significant changes in the average indoor (31 dBA) and outdoor sound levels (40–45 dBA before, 38–42 dBA after) before and after the wind turbines became operational. None of the participants reported waking up to close their windows because of the outside noise. The lack of an effect might be explained by the limited measurements (two nights) or the low indoor sound levels that almost equalled the threshold value for sleep disturbance of 30 dBA.

In another paper Jalali et al. [78] report on the association between measured wind turbine sound levels and subjective sleep quality as measured with the Pittsburgh sleep quality index. Results show only an indirect association with attitude towards the wind turbines and concern about reduced housing values and the visibility of the turbine from the properties. The results confirm the strong psychological component and individual differences in sleep disturbance from wind turbine sound.

3.2.3 Other Health Effects Due to Sound

From the Canadian study Michaud et al. [61] concluded that, except for annoyance, the results do not support an association between exposure to wind turbine sound up to 46 dBA and the evaluated health-related end points, such as mental health problems, headaches, pain, stiffness, or diseases such as diabetes, cardiovascular disease, tinnitus and hearing damage. Michaud et al. [63] also studied the association between wind turbine sound level and objective stress indicators (cortisol, heart rate) and perceived stress (PPS index). These stress indicators were weakly associated with each other, but analysis showed no significant association between exposure to wind turbine sound (up to 46 dBA) and self-reported or objective measures of stress. The authors remarked that there was also no association between stress indicators and noise annoyance, which does not support the hypothesis that stress can be a consequence of chronic annoyance. The only wind turbine-related variable that had an influence on stress was high annoyance with the blinking lights on top of the wind turbines [63]. McCunney et al. [25] found an explanation for a lack of significant associations in the fact that sound levels from wind turbines do not reach levels which could cause such direct effects.

Results for quality of life (Qol) [64], measured using the WHO Qol index and including physical, environmental, social quality and satisfaction with health, showed no relation with sound levels (at levels up to 46 dB). This is in contrast with findings reported earlier by Shepherd et al. [47] and Nissenbaum et al. [48]. However, the results of these studies are hard to compare because the exposure levels are not the same and because different instruments were used to measure perceived quality of life

Tonin et al. [74] studied 72 volunteers in a laboratory setting for a double-blind test similar to that of Crichton et al. [71] but used infrasound at a higher level (91 dB). Before the listening test, participants were influenced to a high expectancy of negative effects from infrasound with a video of a wind farm affected couple, or a low expectancy of negative effects with a video of an academic explaining why infrasound is not a problem. Then normal wind turbine sound was presented via a headset to all participants with the inclusion of the infrasound or no infrasound for a period of 23 min. The infrasound had no statistically significant effect on the symptoms reported by participants, but the concern they had about the effect of infrasound had a statistically significant influence on the symptoms reported.

A survey in Denmark [69] among 454 citizens living in rural areas at different distances to wind turbine farms with a varying numbers of wind turbines studied the effect on nonspecific symptoms. The study included idiopathic symptoms (i.e. not related to a specific disease) as effects and distance to the wind farm and the number of turbines as a measure of exposure. The originally positive association of distance with fatigue, headaches and concentration problems all disappeared after adjustment for exposure to sound and odour from other sources.

Jalali et al. [76] report on a prospective cohort (i.e. before–after) study with 43 participants who completed a questionnaire in spring 2014 and again a year later. Exposure to a wind farm was only measured in terms of distance. Residents who were annoyed by the sound or sight of turbines, or who had a negative attitude towards them or were concerned about property devaluation, after 1 year experienced lower mental health and life quality and reported more symptoms than residents who were not annoyed and had positive attitudes towards turbines. The response rate for this study was low (only 22%), and 12 people (of 43 that is approximately 25%) were not in the second round. Another weak point is the lack of a control group.

Against the background of the increasing number of wind farms in Germany, Krekel et al. [79] investigated the effect of the presence of wind turbines on residential well-being by combining household data from the German Socio-Economic Panel with a dataset on more than 20,000 wind turbines for the time period between 2000 and 2012. The key effect studied was life satisfaction. Results showed that the construction of one or more wind turbines in the neighbourhood of households had a significant negative effect on life satisfaction. This effect was limited in both distance and time.

More recent the first results were published of a new British study that was held near wind turbines in densely populated, suburban areas [43]. In this study part of the participants received a questionnaire that included explicit questions on the impacts of the local wind turbines on well-being, and the remaining part received a variant with no such questions. When including all participants, there was less annoyance from wind turbine sound in this study compared to what was found in earlier (Swedish, Dutch, Polish and Canadian) studies in rural areas. For the first group (with questions concerning local wind turbines), the sound levels were not significantly related to health problems and this group reported less health problems and better general health; this was opposite to the relationship found in the other, variant group.

3.2.4 Influence of Situational and Personal Factors

3.2.4.1 Visual Aspects

The paper of Voicescu et al. [65] on the Canadian data set (see Sect. 3.2) studied the effect of shadow flicker, expressed as the maximum duration in minutes per day, in combination with sound levels and distance, on annoyance and health complaints including dizziness. As shadow flicker exposure increased, the percentage of highly annoyed increased from 4% at short duration of shadow flicker ($<$ 10 min) to 21% at 30 min of shadow flicker. Variables associated with the percentage highly annoyed due to shadow flicker included concern for physical safety and noise sensitivity. Reported dizziness was also found to be significantly associated with shadow flicker.

3.2.4.2 Economic Aspects

In the study of Michaud et al. [16] personal (economic) benefit was associated with less annoyance, in a significant but modest way, when excluding factors that were likely to be a reaction (such as annoyance) to the wind turbine operation. The association between personal benefit from a wind turbine was also found in the Netherlands [85]. In the Japanese study from Kageyama et al. [66,67], this relationship was not found to be significant. However, it might not only be the benefit, but differences in attitude and perception as well as having more control over the placement of the turbines that might play a role [37].

3.2.4.3 Noise Sensitivity

Recent studies of Michaud et al. [36] and Kageyama et al. [66,67], both from 2016, confirm the independent role noise sensitivity has on reaction to wind turbines (see also Sect. 3.1.4.3). The influence of noise sensitivity on noise annoyance was reported earlier by many other researchers [42,59,86–88]. In all these studies, being highly noise sensitive was related to more annoyance. Similarly, the odds of reporting poor QoL and dissatisfaction with health were higher among those who were highly noise sensitive. However, after adjustment for current health status and work situation (unemployment) the influence of noise sensitivity became marginal. Fear and concern about the potential harm of wind turbines was an important predictor of annoyance as has been reported earlier for other noise sources [89–92].

In the Canadian study length of exposure seemed to be an important situational factor and led to up to 4 times higher levels of annoyance for people living more than 1 year in the vicinity of a wind turbine. This indicates sensitization to the sound rather than adaptation or habituation as is often assumed. The moderate effect of wind turbine sound level on annoyance and the range of (other) factors that predict the level of annoyance imply that efforts aimed at mitigating the community response to WTN will profit from considering other factors associated with annoyance. In the Japanese study [66,67] poor subjective health was not related to wind turbine sound levels, but again noise sensitivity and visual annoyance were significant predictors for the effects studied. Both noise sensitivity and visual annoyance seem, according to them, to be indicators of a certain vulnerability to environmental stimuli or changes in environmental factors.

Maffei et al. [75] studied 40 people subdivided in an experimental and control group (familiar for a long time with wind turbine sound versus not familiar). The study included a listening test to sound recorded at a wind farm of 34 wind turbines including background sound (wind in vegetation), or only background sound. Sound recordings of about 5-min duration were made at five distances (150, 200, 250, 300 and 1500 m) from the wind farm. For each distance 65 soundtracks were used. The aim was to detect wind turbine sound at varying distances. For both groups of participants, familiar and unfamiliar, there was no difference in recognition of wind turbine sound at distances of 300 m or less and detection was easiest at distances up to 250 m. At 1500 m those familiar with wind turbine sound could detect the sound better, but they also reported more often ‘false alarms’. Noise sensitivity was an important factor.

3.2.4.4 Social Aspects

According to Chapman et al. [93] and Crichton et al. [94], there is a strong psychogenic component in the relation between wind turbine sound and health complaints. This is not unique for wind turbine sound but has been documented for other sources as well, see e.g. [89,95,96]. In both studies [93,94] attention was given to expectations on the level of annoyance and the level of awareness (‘notice’) of the characteristics and prominent sounds of wind turbines [84]. The influence of these factors has been found in many studies regarding the effects of other sound sources [97]. In more recent years many researchers have investigated the social acceptance of wind projects in a number of countries by local communities and many stress the relevance of a fair planning process and local involvement [98–101]. The influence of injustice and fair planning process are confirmed in the most recent studies. Jalali [76] e.g. showed that concern about decreases in property values was associated with mental health problems.

Finally, Botterill and Cockfield [80] studied the discourse about wind turbines in submissions to public inquiries and in a small number of detailed interviews, and topics addressed in the discourse. Health and property values were found to be the most prominent topics discussed in the inquiries with regard to wind turbines in the submissions (and aesthetics/landscape arguments less often), but in the interviews these were never mentioned.

4 Health Effects of Low-Frequency Sound and Infrasound

In the non-scientific literature, which can be found on the internet, a range of health effects is attributed to the presence of wind turbines. Infrasound is described as an important cause of these effects, also when the infrasound levels must be very low or are unknown. In this section the question is whether infrasound or low-frequency sound deserves special consideration with respect to the effects of wind turbine sound. There is some discrepancy when comparing conclusions from the majority of scientific publications to conclusions in popular publications. Also, some scientific publications suggest possible impacts that are not generally supported. The findings regarding low-frequency sound and infrasound are not easy to interpret. It may be confusing that the frequency of the rhythmic changes in sound due to amplitude modulation is the same as the frequency of an infrasound component. Also, some authors conclude that low-frequency sound and infrasound play a role in the reactions to wind turbine sound that is different from the effects of ‘normal’ sound [16,102] which is contested by many others. In general, however, there is little definite evidence on specific health effects of low-frequency sound when compared to health effects from ‘normal’ sound [103].

First, we will consider the audibility of infrasound and low-frequency sound and then possible health effects not involving audibility. Because we are, in the case of low-frequency sound and infrasound, dealing with other health effects, the paragraphs are structured different than was the case in the previous section.

4.1 Audibility of Infrasound and Low-Frequency Sound

Audible low-frequency sound is all around us, e.g. in road and air traffic. Audible infrasound is less ubiquitous, but can be heard from big machines and storms. In most publications on wind turbine sound, there is agreement that infrasound and low-frequency sound are both present in wind turbine sound. Generally, it is acknowledged that wind turbine infrasound is inaudible as infrasound levels are low with respect to human sensitivity [16,19,25,104,105].

Even close to a wind turbine, most authors argue that infrasound is not a problem with modern wind turbines. This can be shown from measurement results at 10 and 20 Hz. At the (infrasound) frequency of 10 Hz the A-weighted sound power level is typically 60 dB lower than the total sound level in dBA [15]. At a receiver with a total sound level of 45 dBA this means that the 10 Hz sound level is about minus 15 dBA or, in physical terms (not A-weighted), 55 dB. This is far below the hearing threshold at that frequency, which for normal-hearing persons is about 95 dB. A sound of 55 dB at 10 Hz would also be inaudible for the few persons that have been reported with a much lower hearing threshold (close to 80 dB). At 20 Hz, the upper frequency limit of infrasound, the result, again at a receiver total sound level of 45 dBA, would be a physical level of wind turbine sound of 50–55 dB which is much lower than the normal hearing threshold at that frequency of 80 dB [106].

As a part of a Japanese study on wind turbine low-frequency sound, persons in a laboratory were subjected to wind turbine sound where very low frequencies were filtered out over different frequency ranges [13]. When infrasound frequencies were filtered out, the study persons did not note different sensations. Above about 30 Hz they began to notice a difference between the filtered and original sound.

Leventhall [107] states that the human body produces infrasound internally (through blood flow, heartbeat and breathing, etc.) and this would mask infrasound from outside sources when this sound is below the hearing threshold.

In contrast to infrasound, there is general agreement that low-frequency sound is part of the audible sound of wind turbines and therefore contributes to the effects caused by wind turbine sound. The loudest part of the sound as radiated by a turbine is in the mid-frequency range (250–1600 Hz) [15,16]. This shifts to lower frequencies when the sound travels through the atmosphere and enters a building because absorption by the atmosphere and a building facade reduces low frequencies less than higher frequencies. However, studying the effects of the low frequencies separately from the higher frequencies is not easy as both frequency ranges automatically go together: wind turbines all have very much the same sound composition. In a Canadian study on wind turbines, the sound levels at the facades of dwellings were calculated as both A- and C-weighted sound levels, but this proved not to be an advantage as the two were so closely linked that there was no added value in using both [82]. A limit in A-weighted decibels (where the A-weighting mimics human hearing at moderate sound levels) thus automatically limits the low-frequency part of the sound [105].

Bolin et al. [108] calculated and compared wind turbine and road traffic sound over a broad frequency range (0–2000 Hz) at sound levels considered acceptable in planning guidelines (40 dB L_{Aeq} for wind turbine sound and 55 dB L_{Aeq} for road traffic sound). Compared to road traffic sound, wind turbine sound had lower levels at low frequencies. Thus, at levels often found in urban residential areas, low-frequency sound from wind turbines is less loud than from road traffic sound. Recent measurements in dwellings and residential areas show that similar levels of infrasound occur, when comparing wind turbine sound with sound from traffic or household appliances [109].

4.2 Effect of Lower Frequencies

McCunney et al. [25] mention that both infrasound and low-frequency sound have been suggested to pose possibly unique health hazards associated with wind turbine operations. From their review of the literature, including results from field measurements of wind turbine-related sound and experimental studies in which people have been purposely exposed to infrasound, they conclude that there is no scientific evidence to support the hypothesis that wind turbine infrasound and low-frequency sound has effects that other sources of infra/low-frequency sound do not have.

4.3 Subaudible Effects

Several authors have linked infrasound and low-frequency sound from wind turbines to health effects experienced by residents, assuming that infrasound can have physiological effects at levels below the (normal) hearing threshold [110–112]. This was supported by Salt and Kaltenbach [113] who argued that normal hearing is the result of inner hair cells in the inner ear producing electric signals to the brain in response to sound received by the ear. However, infrasound and low-frequency sound (up to 100 Hz) can also lead to signals from the outer hair cells (OHC) and the threshold for this is lower than for the inner hair cells. This means that inaudible levels of infrasound and low-frequency sound can still evoke a response [113]. The OHC threshold is 60 dB at 10 Hz and 48 dB at 20 Hz. Comparing this to actual sound levels (see Sect. 4.1) shows that infrasound levels from wind turbines could just exceed this OHC threshold when their total outdoor sound level is 45 dBA. It is unlikely that the OHC threshold can be exceeded indoors, where levels are lower, except at a high sound level that may occur very close to a wind turbine. Salt and Kaltenbach [113] conclude from this that it is 'scientifically possible' that infrasound from wind turbines thus could affect people living nearby. However, it is not clear to what reactions these signals would lead or if they could be detrimental when just exceeding the OHC threshold. If such inaudible sound could have effects, it is not clear why this has never been observed with everyday sources (other than wind turbines) that produce infrasound and low-frequency sound such as strong winds, road and air traffic, or with physiological sounds from heartbeat, blood flow, etc.

Farboud et al. [114] conclude that physiological effects from infrasound and low-frequency sound need to be better understood; it is impossible to state conclusively that exposure to wind turbine sound does not cause the symptoms described by authors such as Salt and Hullar or Pierpont.

Leventhall [107] argues that infrasound at low level is not known to have an effect. Normal pressure variations inside the body (from heart beat and breathing) cause infrasound levels in the inner ear that are greater than the levels from wind turbines. From exposure to high levels of infrasound, such as in rocket launches and associated laboratory studies or from natural infrasound sources, there is no evidence that infrasound at levels of 120–130 dB causes physical damage to humans, although the exposure may be unpleasant [107].

Stead et al. [115] come to a similar conclusion when considering the regular pressure changes at the ear when a person is walking at a steady pace. The up and down movement of the head implies a slight change in atmospheric pressure that corresponds to pressure 'sound' levels in the order of 75 dB. The pressure changes in the rhythm of the walking frequency are similar in frequency (close to 1 Hz), and level to the pressure changes from infrasound at rotation frequencies measured at houses near wind farms.

4.4 Vestibular Effects

According to Pierpont the (infra)sound of wind turbines can cause visceral vibratory vestibular disease (VVVD), affecting the vestibular system from which we derive our sense of balance. She characterized this new disease with the following symptoms: 'a feeling of internal pulsation, quivering or jitteriness, and it is accompanied by nervousness, anxiety, fear, a compulsion to flee or check the environment for safety, nausea, chest tightness, and tachycardia' [111], stating that infrasound and low-frequency sound were causing this 'wind turbine syndrome'. Pierpont's research was based on complaints from 38 people from 10 families who lived within 300–1500 m from one or more turbines in the USA or Great Britain, Italy, Ireland and Canada. In several publications (e.g. [22,25]), it was pointed out that Pierpont's selection procedure was to find people who suffer the most, and it was not made clear that it was indeed the presence of the wind turbine(s) that caused these symptoms. Although the complaints may be genuine, it is possible that very sensitive people were selected and/or media coverage had led to physical symptoms attributed to environmental exposures as has been demonstrated for wind turbines [93] and other environmental exposures [116]. Van den Berg [44] noted that the symptoms of VVVD are mentioned in the Diagnostic and Statistical Manual of Mental Disorders (DSM) as stress symptoms in three disorders: an adjustment disorder, a panic disorder and a generalized anxiety disorder. The wind turbine syndrome may thus not be a new phenomenon, but an expression of stress that people have and which could have a relation to their concern or annoyance with respect to a (planned) wind farm.

In his examination of the wind turbine syndrome, Harrison [27] argued that at a level of 40–50 dBA no component of wind turbine sound approaches levels high enough to activate the vestibular system. The threshold for this is about 110 dB for people without hearing ailments. In people with a hearing ailment, particularly the 'superior (semicircular) canal dehiscence syndrome' (SCDS), this threshold is lower and can be 85 dB. Such levels are only reported very close to wind turbines. Reports show that 1–5% of the adult population may have (possibly undiagnosed) SCDS.

Schomer et al. [117] studied residents of three homes where residents generally did not hear the wind turbines in their area, but they did report symptoms comparable to motion sickness. Schomer et al. suggest that this could result from sound affecting the vestibular sensory cells and in their opinion wind turbine infrasound could generate a pressure that they compare with an acceleration exceeding the U.S. Navy's criteria for motion sickness. This has been investigated by Nussbaum and Reinis much earlier [118]. They exposed 60 subjects to a tone of 8 Hz and 130 dB with high distortion (high-level harmonics at multiples of 8 Hz) or low distortion (harmonics at lower level). Dizziness and nausea were primarily associated with the low distortion exposure, i.e. a relatively high infrasound content. In contrast, headache and fatigue were primarily associated with the high distortion exposure, with a relatively low infrasound content. Nussbaum and Reinis [118] hypothesized that the effects of the purer infrasound could be explained as acoustically induced motion sickness. However, this was concluded from exposure levels (130 dB) much higher than wind turbines can cause.

4.5 Vibroacoustic Disease

According to Alves-Pereira and Castelo Branco [112], the infrasound and low-frequency sound of a wind turbine can cause vibroacoustic disease (VAD), an affliction identified by a thickening of the mitral valve (one of the valves in the heart) and the pericardium (a sac containing the heart). The most important data regarding VAD are derived from a study among aircraft technicians who were professionally exposed to high levels of low-frequency sound [119]. VAD is controversial as a syndrome or disease. Results of animal studies have only been obtained in studies using low-frequency sound levels which are found in industrial settings. No studies are known that use a properly selected control group. And finally, the way the disease was diagnosed has been criticized because of a lack of precision [120]

After investigating a family with two wind turbines at 322 and 642 m from their dwelling, Alves-Pereira and Castelo Branco [112] concluded that VAD occurred and was caused by low-frequency sound. The measured sound levels were substantially lower (20 dB or more) than levels at which VAD was thought to occur by Marciniak et al. [119] and the levels were below the normal hearing threshold for a considerable range of frequencies in this range. In their review of evidence on VAD Chapman et al. [93] concluded that in the scientific community VAD was only supported by the group who coined the term and there is no evidence that vibroacoustic disease is associated with or caused by wind turbines.

4.6 Effect of Vibrations

Vibrations from wind turbines can lead to ground vibrations and these can be measured with sensitive vibrations sensors. In several studies vibrations have been measured at large distances, but this was because these vibrations could affect the performance of seismic stations that detect nuclear tests. These vibrations are too weak to be detected or to affect humans, even for people living close to wind turbines [98].

In measurements at three dwellings, Cooper et al. [104] found surges in ground vibration near wind turbines that were associated with wind gusts, outside as well as inside one of the three houses. Vibration levels were weak (less than from people moving around), but measurable. According to Cooper, two residents were clearly more sensitive than the other four; the sensations experienced by the residents seemed to be more related to a reaction to the operation of the wind turbines than to the sound or vibration of the wind turbines. This echoes earlier findings from Kelley [121] who investigated complaints, from two residences, that were thought to be associated with strong low-frequency sound pulses from the experimental downwind MOD-1 wind turbine. The low-frequency sound pulses were generated when a turbine blade passed the wind wake behind the mast. The residents perceived 'audible and other sensations, including vibration and sensed pressure changes'. Although the wind turbine sound at frequencies below about 30 Hz was below the normal hearing threshold, this sound was believed to be causing the annoyance complaints. The sound levels were within a range of sound levels and frequencies cited in a report from Stephens et al. [122] for situations where (sub-audible) industrial sound within this range was believed to be the source of the complaints. This could be explained by the response of a building to the sound outside: the distribution of sound pressure in the building can be the result of structure-borne sound, standing waves and resonances due to the configuration of a room, closet and/or hallway. The rhythmic character of wind turbine sound could have an added effect because of the periodic pressure pulses; if these coincide with a structural resonance of the building the indoor level can be higher than expected from just reduction by the facade. These structural vibrations can lead to sound at higher frequencies which are audible. Several authors have pointed out that the rhythmic character itself (technically, amplitude modulation) is more relevant to human perception than low-frequency sound or infrasound (see *What makes wind turbine sound so annoying?* in Sect. 3.1.1). However, the appreciation of the sound may depend on a combination of the frequency and strength of the modulation and the balance of low- and higher-frequency components [123].

5 Discussion and Conclusions

5.1 Primary Findings

This review summarizes the findings of ten previous reviews on the effect of wind turbines on health and the role of personal, situational and physical factors other than sound. In addition, the results from 22 papers that were published later (after early 2015) were reviewed. The results will be presented here with an indication of a possible change over time when comparing evidence before and since 2015.

Results confirm the earlier evidence that living in areas with wind turbines is associated with an increased percentage of highly annoyed residents. Earlier findings of a possible association with perceived and measured sleep disturbances are not confirmed in the latest studies, nor does recent evidence support the notion of a possibly decreased quality of life in relation to exposure to wind turbine sound. Also, the findings of recent studies do not support a relation between subjective and objective stress indicators and exposure to wind turbine sound. Earlier findings on personal, situational and contextual factors (such as visual aspects, attitude, benefits, perceived injustice and fair planning process) are confirmed in the most recent studies. Available scientific research does not provide a definite answer about the question whether wind turbine sound can cause health effects which are different from those of other sound sources. However, wind turbines do stand out because of their rhythmic character, both visually and aurally. Several new laboratory studies have in particular addressed the role of amplitude modulation (AM). Results are inconclusive regarding the effect of amplitude modulation on annoyance. A common conclusion seems to be that AM appears to aggravate existing annoyance, but does not lead to annoyance in persons who benefit from or have a positive attitude towards wind turbines. Recent reviews of McCunney et al. [25] and Harrisson [27] conclude that there is no scientific evidence to support the hypothesis that wind turbine infrasound and low-frequency sound have effects that other sources do not have. In general, evidence on specific health effects of low-frequency sound is limited. As the CCA [28] worded it: knowledge gaps remain with regard to the influence of specific sound characteristics, such as amplitude modulation, low-frequency content or visual aspects of wind turbines, which are difficult to study in isolation.

The recent studies largely support earlier scientific findings but have improved the state of the art with thorough research and adding objective measures to self-reported effects. Exposure characterization has been improved considerably by including local sound measurements in field studies, and the recent AM studies have improved the knowledge base considerably.

5.2 Discussion

5.2.1 Physical, Social and Personal Factors Add

There are many models or schemes that show how people react to sound. However, much of the public debate about wind turbines and sound is at the planning stage when wind turbines are not yet present. Michaud et al. [63] proposed a model that incorporates the influence of (media) information and expectations as well as actual wind turbine sound exposure. In Fig. 3 we present a simplified model based on the one from Michaud et al. [63]. It shows that plans for wind turbines or actual wind turbines can lead to disturbances and concern, but a number of factors can influence the effect of the (planned) turbines (see 'Michaud model' for these factors). Personal factors include attitude, expectations, noise sensitivity. Situational factors include other possible impacts such as visibility or shadow flicker, other sound sources, type of area. Contextual factors include participation, the decision-making process, the siting procedure, procedural justice.

The model illustrates that next to wind turbine sound itself, several other features are relevant for residents living in the vicinity of wind turbines. These include physical and personal aspects, and the particular circumstances around decision-making and siting of a wind farm as well as commu-

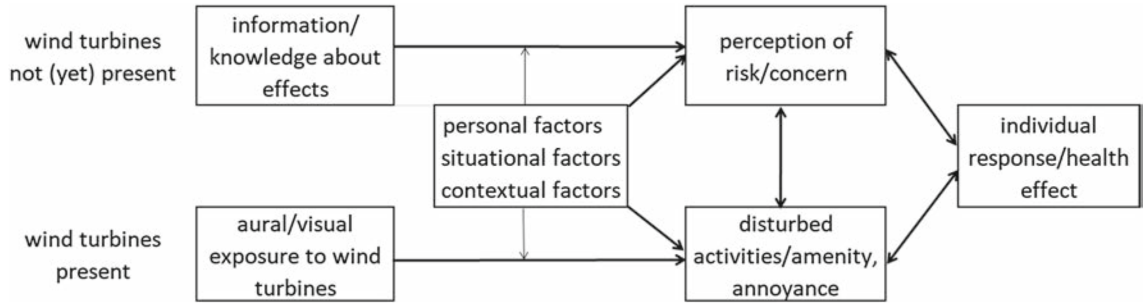

Fig. 3 A graphic summary model for the relationship between exposure to wind turbines and individual response (after Michaud et al. [63])

nication and the relation between different people involved in the process. There is consensus that visual aspects play a key role in reactions to wind turbines and this includes the (mis-)match with the landscape, shadow casting and blinking lights. Shadow casting from wind turbines is described as annoying for people and also the movement of the rotor blades themselves can be experienced as disturbing. Light reflection/flicker from the blades and vibrations play a minor role in modern turbines as far as the effect on residents is concerned. It has been shown that people who benefit from and/or have a positive attitude towards wind turbines in their environment in general report less annoyance. People who perceive wind turbines as intruding into their privacy and detrimental to the quality of their living environment in general report more annoyance. Perceived (procedural) injustice has been found to be related with the feeling of intrusion and lack of control/helplessness. Most studies confirm the role of noise sensitivity in the reaction to wind turbines, independent of the sound level or sound characteristics. Attitude and media coverage are just a few elements of the complex process of policy and decision-making for siting wind turbines. Most recent studies conclude that social acceptance of wind projects is highly dependent on a fair planning process and local involvement. The latest evidence seems to confirm the role of these factors described in earlier reviews and studies.

5.2.2 Evidence on Adverse Effects of Wind Turbine Sound

Noise annoyance is the main health effect associated with the exposure to sound from an operational wind turbine. At equal sound levels, sound from wind turbines is experienced as more annoying than that of traffic sources [19,29]. From epidemiological and laboratory studies, the typical character of wind turbine sound comes forward as one of the key issues. Particularly, the rhythmic character of the sound (technically, amplitude modulation or AM), described as a swishing or wooshing sound, is experienced as annoying. Residential wind turbine sound levels themselves are modest when compared to those from other sources such as road or industrial sound. However, recent laboratory studies [12,71,72] are inconclusive regarding the effect of amplitude modulation on annoyance. One conclusion is that 'there is a strong possibility that amplitude modulation is the main cause of the properties of wind turbine noise', in which properties refer to sounds that are easily detectable and highly annoying at relatively low sound levels [12]. Another dismisses amplitude modulation as a negative factor per se because it is highly related to attitude [72]. A common factor is that AM appears to aggravate existing annoyance, but does not lead to annoyance for persons positive about or benefiting from wind turbines. The general exposure–effect relation for annoyance from wind turbine sound includes all aspects that influence annoyance and thus averages over all local situations and non-acoustic factors. The relation can therefore only form an indication of the annoyance levels to be expected in a local situation.

New evidence regarding the effect of night time wind turbine sound exposure on sleep suggests no direct effect, but remains inconclusive. The current results do not allow a definite conclusion regarding both subjective and objective sleep indicators [62]. However, studies do find a relationship between self-reported sleep disturbance and annoyance from wind turbines [41] and between self-reported sleep disturbance and perceived quality of life [47,48].

For other health effects, there is insufficient evidence for a direct relation with wind turbine sound levels.

Based on noise research in general, we can conclude that chronic annoyance from wind turbines and the feeling that the quality of the living environment has deteriorated or will do so in the future, and can have a negative impact on well-being and health in people living in the vicinity of wind turbines. This is similar to the effect of other stressors [19]. The moderate effect of the level of wind turbine sound on annoyance and considering the range of factors that influence the levels of annoyance implies that reducing the impact of wind turbine sound will profit from considering other factors associated with annoyance. The influence of these factors is not necessarily unique for wind turbines. The fact that residents can respond very differently to a sound shows that annoyance from a sound is not inextricably bound up with that sound.

5.2.3 Evidence on Adverse Effects of Low-Frequency Sound and Infrasound

There is substantial knowledge about the physical aspects of low-frequency sound. Low-frequency sound can be heard daily from road and air traffic and many other sources. Less is known about infrasound and certainly the perception of infrasound. Infrasound can sometimes be heard, e.g. from big machines and storms, but is not as common as low-frequency or 'normal' sound. However, with sensitive equipment infrasound, as well as vibrations, can be measured at large distances. Infrasound and low-frequency sound are present in wind turbine sound. Low-frequency sound is included in most studies as part of the normal sound range. In contrast, infrasound is in most studies considered as inaudible as the level of infrasound is low with respect to human sensitivity. Studies of the perception of wind turbine infrasound support this. Infrasound and low-frequency sound from wind turbines have been suggested to pose unique health hazards. There is little scientific evidence to support this. The levels of infrasound involved are comparable to the level of internal body sounds and pressure variations at the ear while walking. Infrasound from wind turbines is not loud enough to influence the sense of balance (i.e. activate the vestibular system), except perhaps for persons with a specific hearing condition (SCDS). Effects such as dizziness and nausea, or motion sickness, could be an effect of infrasound, but are expected at much higher levels than wind turbines produce in residential situations. Vibroacoustic disease and the wind turbine syndrome are controversial and scientifically not supported. At the present levels of wind turbine sound, the alleged occurrence of vibroacoustic disease (VAD) or the disease (VVVD) causing the wind turbine syndrome (WTS) is unproven and unlikely. However, the symptoms associated with WTS are symptoms found in relation to stress.

The rhythmic character of wind turbine sound is caused by a succession of sound pulses produced by the blade rotations. From early research it was concluded that this may lead to structural vibrations of a house and wind turbines thus may be perceived indirectly inside a house and hence lead to annoyance. This possibility needs further investigation.

5.3 Strengths and Limitations

The strengths of this review are the use of a robust search strategy to identify relevant studies, its broad approach in terms of both the range of outcomes and noise characteristics considered and the special consideration of the role of low-frequency sound and infrasound. We also tried to make the available knowledge accessible for a broader audience by avoiding technical terms as much as possible. We added to earlier reviews by reviewing the latest studies which are of high quality and have shown how the state of knowledge developed over time. However, we recognize limitations as well. Although the literature search was performed systematically, the review is primarily a narrative one and in this sense will repeat in a less rigid manner the conclusions of previous reviews. Although the studies were systematically selected and structured, in our wording and interpretation we follow a 'story line' inherent to a narrative review. The text reflects our view, based on an extensive amount of knowledge of (reactions to) wind turbine sound and environmental sound in general.

5.4 Methodological Considerations and Implications for Future Research

Again, or we might say still, we can conclude that the earlier identified lack of methodological and statistical strength of wind turbine studies by CCA [28] still holds. With a few exceptions in general, the sample size of most studies is limited, and with regard to both the exposure and outcomes, there is room for improvement.

5.5 Final Conclusion

Systematic reviews published since 2009 including some recent and high quality ones, and new evidence not yet reviewed suggest that exposure to wind turbine sound is associated with higher odds for annoyance. The proximity of a wind turbine or wind farm has not conclusively been proven to negatively affect stress responses, quality of life, sleep quality (subjective and objective) nor other health complaints. A reason for this may be that individual traits and attitudes, visual aspects as well as the process of wind farm planning and decision-making are highly likely to influence the response to sound from wind turbines. Larger-scale studies at locations with varying circumstances and with a before after component (prospective cohort) are recommended for the future. Ideally measured sound levels over the whole frequency range and routinely collected registry health data should be used in conjunction with more subjective data.

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EXHIBIT
18

RESEARCH ARTICLE

Health Effects Related to Wind Turbine Noise Exposure: A Systematic Review

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Abstract

Background: Wind turbine noise exposure and suspected health-related effects thereof have attracted substantial attention. Various symptoms such as sleep-related problems, headache, tinnitus and vertigo have been described by subjects suspected of having been exposed to wind turbine noise.

Objective: This review was conducted systematically with the purpose of identifying any reported associations between wind turbine noise exposure and suspected health-related effects.

Data Sources: A search of the scientific literature concerning the health-related effects of wind turbine noise was conducted on PubMed, Web of Science, Google Scholar and various other Internet sources.

Study Eligibility Criteria: All studies investigating suspected health-related outcomes associated with wind turbine noise exposure were included.

Results: Wind turbines emit noise, including low-frequency noise, which decreases incrementally with increases in distance from the wind turbines. Likewise, evidence of a dose-response relationship between wind turbine noise linked to noise annoyance, sleep disturbance and possibly even psychological distress was present in the literature. Currently, there is no further existing statistically-significant evidence indicating any association between wind turbine noise exposure and tinnitus, hearing loss, vertigo or headache.

Limitations: Selection bias and information bias of differing magnitudes were found to be present in all current studies investigating wind turbine noise exposure and adverse health effects. Only articles published in English, German or Scandinavian languages were reviewed.

Conclusions: Exposure to wind turbines does seem to increase the risk of annoyance and self-reported sleep disturbance in a dose-response relationship.

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There appears, though, to be a tolerable level of around L_{Aeq} of 35 dB. Of the many other claimed health effects of wind turbine noise exposure reported in the literature, however, no conclusive evidence could be found. Future studies should focus on investigations aimed at objectively demonstrating whether or not measureable health-related outcomes can be proven to fluctuate depending on exposure to wind turbines.

Introduction

In recent years suspected health-related effects of exposure to wind turbine noise have attracted much public attention. Whether or not this exposure can result in an array of described symptoms and disorders has been widely debated. It has been reported that noise from wind turbines can lead to such symptoms as dizziness, nausea, the sensation of ear pressure, tinnitus, hearing loss, sleeping disorders, headache and other symptoms. Additionally, the term ''Wind Turbine Syndrome'' has been coined to describe the association of these symptoms to wind turbine noise exposure [1–6]. However, the level of scientific evidence in wind turbine research, evaluated by several comprehensive reviews, is poor, as most of the research used to reach the conclusions found in these studies has been based on mere case reports and other similar studies [7–11]. It has also been argued that most of the symptoms supposedly related to wind turbine noise exposure could be psychosomatic ones stemming from a fear of wind turbines rather than any real adverse health effects [12]. Furthermore, reports in the scientific literature which have tried to establish a causal relationship between wind turbine noise and adverse health effects have tended to initiate heated debates between the authors and their readers, with critics often claiming that there was an insufficient amount of high quality evidence of a direct-dose response relationship between the noise exposure and the symptoms [9, 13, 14].

In order to shed light on the question of causation, researches frequently seek a statistically significant dose-response relationship. Statistically significant relationships between exposure and symptoms may not be shown to be causal without knowing if there is a dose-response relationship. The aim of the present study is to systematically analyse the literature and conclude if there is any evidence to support these theories of adverse health effects caused by exposure to wind turbines.

Guidelines, Recommendations and Requirements for wind turbine noise

Noise from wind turbines is generated to a lesser degree by the rotory hub; however, virtually all other wind turbine noise is generated by the downward movement of the rotating blades which result in the characteristic audible swishing pulses [15–17]. During the night these swishing pulses can become more dominant, and pulses from several wind turbines in the same vicinity can propagate in phase and lead to increased pulse sounds with increased sound pressure levels of 5 dB [18]. This amplitude modulation of the sound can also become more prominent under certain meteorological conditions [19]. Furthermore, noise from wind turbines will increase with any increase in the ambient wind speed [20, 21]. This amplitude modulating sound is often considered to be the most annoying aspect of wind turbine noise, and this has led to suggestions of incorporating the level of amplitude modulation as a measurement parameter for setting regulations for these noise measurements [22–24].

Noise is often measured as A-weighted equivalent sound pressure levels (L_{Aeq}) during a certain period of time. To then calculate L_{den}, 10 dB is added to the A-weighted equivalent sound pressure levels (L_{Aeq}) during the night and 5 dB is added to these noise levels during evening periods. If L_{Aeq} is constant throughout the day and night, L_{den} can be calculated by the addition of 6.4 dB to the measured L_{Aeq} [25]. L_{den} is measured at a height of 10 meters, and it is dependent on the wind speed, the landscape and the turbine type [25]. In several countries wind turbine noise has been limited to a maximum allowable level of L_{Aeq} at 35–44 dB, depending on the given wind speed and the special noise sensitivity in areas with low levels of background noise [9, 21, 26–28]. In Denmark, for example, the maximum level - L_{max}, corresponding to a L_{Aeq} of 42–44 dB or 37–39 dB in noise sensitive areas, is dependent on the wind speed (8 or 6 m/s respectively) [29]. In general noise levels in residential areas are calculated from noise prediction models; however, these noise prediction models have often been found to over-predict wind turbine noise levels at the point of the receivers [30].

Infrasound is considered to be sound of frequencies below 20 Hz, and low-frequency sound is considered to be sound between 20–200 Hz. Infrasound originates from many different sources in the environment including compressors, ventilation and traffic noise [31]. It has been demonstrated that wind turbines can cause low-frequency sound exposure of above 20 dB in the homes of close neighbours [32]. Most countries do not have regulations regarding infrasound and low-frequency noise from wind turbines, with the exception of Denmark where low-frequency sound in the 10–160 Hz range is limited to an A-weighted level (L_{pALF}) of 20 dB [29].

Methods

The supporting PRISMA checklist is available as supporting information; See Checklist S1 .

The objective of the present study was to analyze the literature systematically, and to determine if there was any statistical evidence of adverse health effects from exposure to wind turbine noises. The literature reviewed here included literature from both peer-reviewed scientific sources as well as internet sources which were not necessarily peer-reviewed. All types of studies investigating any relationship between wind turbine noise exposure and health-effect outcomes were included in the systematic review. Furthermore, with the purpose of aiding in the analysis and interpretation of the findings of the systematic review, a separate review of issues related to wind turbine exposure was also conducted. Focus was given in particular to finding additional technical information with respect to the size and character of wind turbine noise, as well as information regarding documented community opinions of wind turbines.

A PubMed search was conducted using the search string: wind turbines OR wind turbine OR wind farm OR wind farms. Additionally, a Web of Science search was conducted using the search string: (wind turbines OR wind turbine OR wind farm OR wind farms) AND (health OR noise OR annoyance OR tinnitus OR vertigo OR epilepsy OR headache) (Figure 1). Both database searches were performed again for a final time on the 9th of June 2014, and included all relevant reports published up until that time. No limits in language were used in the database searches.

Duplicates of articles were removed, and the titles and abstracts of all records were screened. Articles were then selected for full-text review, dependent upon whether the content of the article concerned wind turbines and related health effects on humans. Of the articles selected for full-text review, reported health effects included noise annoyance and psychological aspects related to the opinions of communities regarding wind turbine noise, as well as specific studies exploring noise exposure from wind turbines. Only articles in English, German and Scandinavian languages were selected for full-text review. Articles containing specific environmental issues and problems related to biology and wild life, as well as more technical articles regarding wind turbine mechanics, were not selected for full-text review.

Additionally, Google Scholar (http://scholar.google.dk/) was searched with the same search string previously used for the Web of Science search (See Figure 1). Articles from all years were retrieved in the initial search, while all patents and citations were excluded. (Google Scholar is a search engine that shows the 1000 most relevant web-resources). Several additional searches were also performed with limitations set to articles from 2014, 2013–2014 and 2010–2014. Based on these searches, publications were selected for full-text review based on the same criteria as described above. The final search was performed on the 9th of June 2014. Following this selection procedure, duplicates of previously retrieved articles were removed.

Google Scholar may not necessarily retrieve all relevant sources of, in particular, non-peer reviewed sources, and it was also evident from searches in Google Scholar that several additional websites contained a large number of relevant publications. Therefore, publications listed at the following websites: https://www.wind-watch.org/, http://www.windturbinesyndrome.com/and http://waubrafoundation.org.au/were also searched and screened by using the same selection procedure as described above. Publications were only retrieved for full-

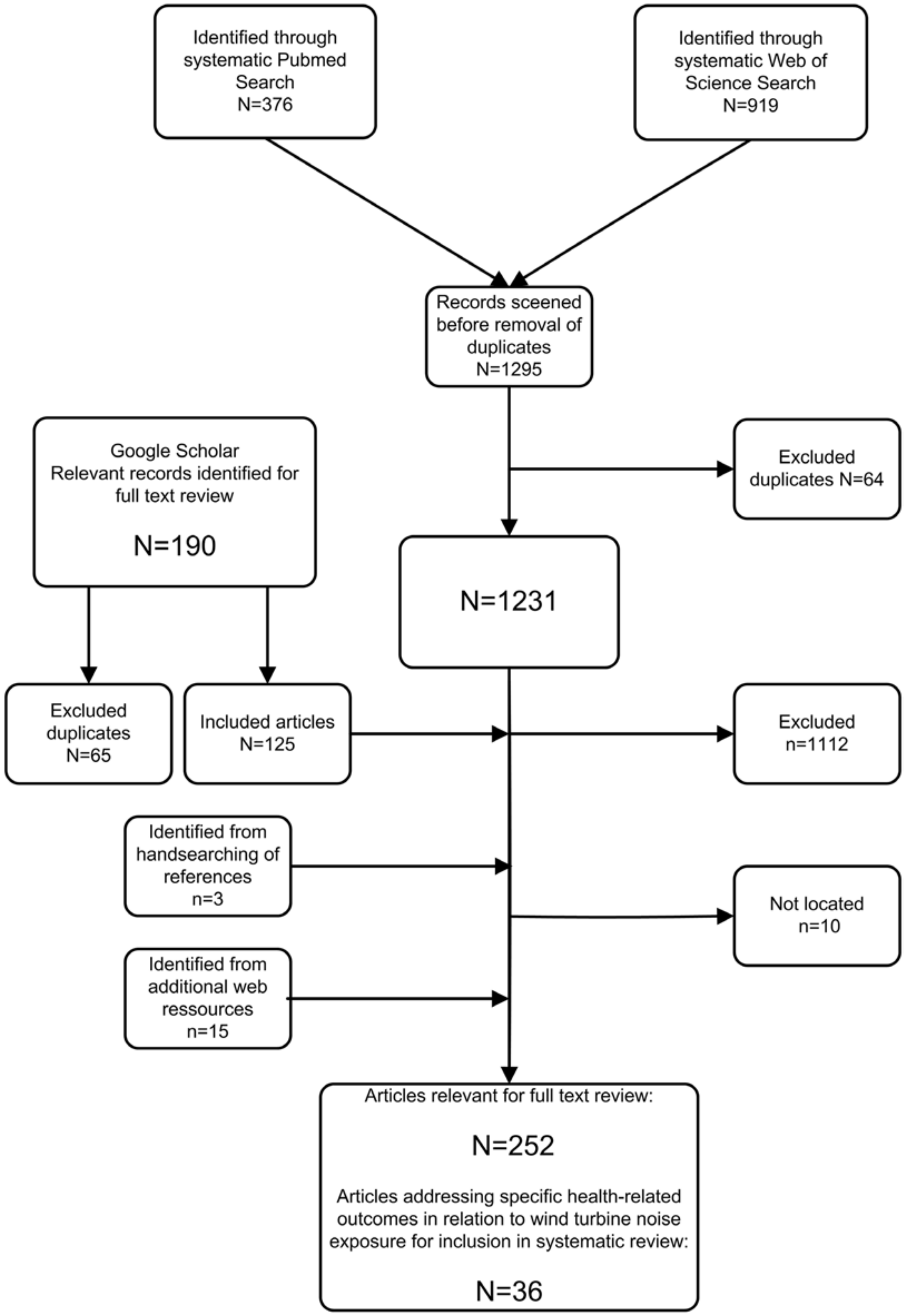

Figure 1. Search strategy for relevant publications.

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text review, however, if they were not already retrieved in the previous searches with PubMed, Web of Science and Google Scholar.

The reference lists of selected publications were also searched for additional articles pertaining to health-related issues believed to be related to wind turbine noise.

All articles investigating the association between wind turbine noise exposure and any suspected health-related outcomes were then identified from among the articles selected for full-text review, and these identified articles were included in the systematic review. Originally the systematic review had only attempted to investigate and, if possible, provide evidence for any association between wind turbine noise exposure and health-related outcomes such as noise annoyance, sleep disturbance, any kind of psychological distress including mental and concentration problems, tinnitus, vertigo, headache and epilepsy, as these symptoms had been reported in case reports as resulting from wind turbine exposure. The data extraction was, however, not limited to these variables. Other health-related outcomes could be included in the review as well, should these variables later be identified as important during the review process. Thus, information regarding any evidence of health-related effects associated with wind turbine noise exposure was extracted from the included articles by one reviewer and confirmed by the second reviewer. Disagreements were resolved by discussion of the selected articles. Duplicate publications from the same study population were included in the study to present additional evidence for health-related effects related to wind turbine noise, if this evidence was not previously reported in other publications. It was also specified when several publications reported data from identical study populations. Extracted information from different studies addressing similar health-related outcomes related to wind turbine exposure were summarized in tables where study differences in terms of study populations and the exposure assessment were described. It was stated when a specific association between wind turbine noise exposure and a health-related outcome was found to exist.

No limiting criteria regarding the quality of the research was used initially in the selection process of the articles for the systematic review of health-related effects in relation to wind turbine noise exposure. Any potential risk of bias identified in the selected studies was assessed afterwards and reported specifically as a part of the quality assessment of the included studies in the systematic review.

Results

Literature searches from PubMed and the Web of Science identified 1231 publications after the removal of duplicates (Figure 1). Only articles related to wind turbines and health-related effects were selected for further full text review, and, for this reason, 1112 publications were excluded.

In total 119 publications from the Web of Science and PubMed databases and additional 125 publications identified from Google Scholar were selected for further evaluation (Figure 1) after excluding duplicates. Fifteen publications were added from Internet sources regarding wind turbines. Additionally, three publications were included after reviewing the reference lists of the selected publications, and 10 of the selected publications could not be retrieved. Thus, a total of 252 unique publications were included in the full-text review. Thirty-five publications investigating health-related outcomes of exposure to wind turbines were identified from the systematic literature search to be included in the systematic review [1, 33–66]. In addition, one article that calculated the expected annoyance of sound exposure to wind turbines based on previous results from Janssen et al. 2011, was also included [33, 67]. Thus, 36 publications fulfilled the inclusion criteria and were included in the systematic review. Two publications by Janssen et al. (2009, 2010), two by Pedersen et al. (2006, 2008), and one publication by Nissenbaum et al. (2011) were published in conference proceedings. The results in these publications were identical to the meta-analysis published by Janssen et al. 2011, and to the studies from Sweden and the Netherlands published by Pedersen et al. (2007, 2009) and to the study from the U.S.A. published by Nissenbaum et al. (2012). Thus, only Janssen et al. 2011, Pedersen et al. 2007 and 2009 and Nissenbaum et al. 2012 were used in the systematic review [33, 37, 39, 40, 58–62]. Likewise, only Pawlaczyk-Luszczynska et al. 2014 was used for this review since Pawlaczyk-Luszczynska et al. 2013 reported identical results in a conference proceeding [46, 63]. As such, 30 publications, after the exclusion of the aforementioned six conference publications, were identified as specifically investigating health-related outcomes of exposure to wind turbine noise.

Four of these 30 publications were identified as case series [1, 64–66]. Case series studies report adverse health effects which are hypothesized to be a result of exposure to wind turbines. Case studies in general may be affected by selection and information bias which may also be true for the selected case studies in this review. This means, that these case studies may be biased and, as such, contribute fairly week evidence towards forming any conclusions about causation. The studies can, however, be hypothesis-generating in terms of a causal relationship.

The remaining 26 publications that investigated a relationship between exposure to wind turbine noise and adverse health effects were cross-sectional studies. These studies used a stratified approach where subjects with low or no exposure were compared to subjects with high exposure to wind turbine noise [36–56, 67]. One of these studies with a limited sample size (11 exposed, 10 unexposed) used longitudinal health data related to wind turbine noise exposure [57]. Three of these studies were meta-analyses of previous cross-sectional studies [33–35]. With such cross-sectional studies it is thereby possible to assess a dose-response relationship between exposure to wind turbine noise and adverse health effects. Selection bias and information bias, however, will likely occur. Cross-sectional studies can, therefore, not be used to determine any specific causal relationships.

Thus, the evidence presented in this systematic review had to rely on case-series reports and cross-sectional studies. Meta-analyses could increase the sample size, but the level of evidence was still dependent on the original cross-sectional studies included in the meta-analysis.

None of the included studies investigated the relationship of health effects and exposure to low-frequency noise or infrasound; however, infrasound and low-frequency noise emission from wind turbines were measured and studied in a number of the publications retrieved from the 252 articles initially selected [2, 32, 68–77].

Health effects related to infrasound and low-frequency sound exposure from wind turbines

Infrasound

While no study conducted so far has examined the potential adverse health effects related to specific infrasound exposure, this subject has been widely debated as a possible explanation for suspected health effects of wind turbine noise exposure even when the infrasound is not audible [1, 37, 42, 45, 46, 52, 53, 66]. Infrasound in general may be audible at high sound pressure levels; however, infrasound from wind turbines is subaudible unless one is very close to the wind turbine rotor [68, 72, 78]. Wind turbine infrasound levels for frequencies of up to 20 Hz were measured between 122–128 dB near wind turbines using G-weighting as recommended for the measurement of infrasound [32]. At further distances, however, between 85–360 meters from other wind turbines, G-weighted sound pressure levels were measured between 61–75 dB [32, 69]. In addition, measurements taken from large wind turbines above 2 MW at distances ranging between 68–1000 meters gave an infrasound exposure of between 59–107 dB(G), as summarized in a review by Jakobsen [70]. Smaller wind turbines below 2 MW measured at 80–500 meters distance were recorded as giving an infrasound exposure of 56–84 dB(G) [70]. Similar infrasound exposures were measured at 350 meters from a gas-fired power station (74 dB(G)), at 70 meters from major roads (76 dB(G)), at 25 meters from the waterline at the beach (75 dB(G)) as well as at 8 kilometres inland from the coast (57 dB(G)) [69]. Even when the infrasound exposure from wind turbines is not audible outdoors, infrasound in the 5–8 Hz range can still lead to a rattling of doors and windows which is audible indoors and can be an annoyance to those living in close proximity to wind turbines [73].

Wind turbines do emit infrasound, but it remains unknown if exposure to infrasound from wind turbines can lead to adverse health effects. It has also been hypothesised that infrasound may contribute to the amplitude-modulated nature of wind turbine noise which can then contribute to the perception of this noise [79, 80].

Some physiological changes have, however, been demonstrated in humans exposed to infrasound as shown in one functional MRI study where 110 dB infrasound at a 12 Hz tone activated areas of the primary auditory cortex in the brain [81]. Infrasound at 6 Hz and 130 dB was also able to affect Distortion Product Otoacustic Emissions (DPOAE) in humans [82]. The exposure in these studies was above 100 dB(G) and may be audible to some individuals. Of further note, it has been demonstrated in a double-blinded study that patients with Meniere's disease experience significant relief or even curative effects by using a Meniett pressure device which applies pressure of sinusoidal pulses of 6 Hz [83].

Some evidence suggests that even inaudible sound may affect the delicate structure of the ear and the vestibular organ. A recent review of several animal studies demonstrated that small physiological changes could be detected in the cochlear outer hair cells when these animals were exposed to infrasound. The outer hair cells of the cochlea were more sensitive to infrasound compared to the inner hair cells [84]. There exists as yet no human data comparable to that of these animal studies, so it is therefore still unclear if such theoretical affections of the inner ear structures can explain why some individuals have symptoms like tinnitus, vertigo and Meniere's disease [4].

Exposure to inaudible infrasound from wind turbines has also led to speculations that adverse health effects resulting from this exposure are perhaps psychological in nature [12]. In two recent randomized and controlled psychological experiments 54 and 60 subjects respectively were randomized into groups with either positive or negative expectations towards wind turbine noise and then informed separately about either the potential benefits or the supposed harmful effects and symptoms related to wind turbines and infrasound exposure. The subjects were shown either positive or negative videos about wind turbines and related health effects prior to the experiments. These studies demonstrated that the subjects randomized to the groups with negative expectations reported significantly more symptoms both when exposed to infrasound ($p<0.01$) and to sham infrasound (no sound) ($p<0.01$), as well as after exposure to audible wind turbine noise compared to the baseline ($p<0.001$) [85, 86]. Thus, these experiments support the hypothesis that a subset of the population conditioned to dislike wind turbines may be more sensitive to adverse effects after infrasound exposure itself or wind turbine noise in general [85, 86]. It should be noted that discrete sound exposure periods in a listening room may not be comparable to wind farm noise; however, positive or negative expectations towards wind turbine noise or any other noise would seem to affect self-reported health outcomes. Such psychological expectations may influence the opinion of a subset of the population who will then fear the potential health effects of wind turbines [8]. Furthermore, there can be a general resistance in the population towards a nearby planned location of wind turbines close to residential areas. This phenomenon has been termed "Not In My Back Yard (NIMBY)", and it relates to the resistance often seen when a wind farm project or any other project (e.g. airports, highways, chemical plants) is planned near a residential area, regardless of whether or not that project is actually harmful or just perceived to be so [87, 88].

Thus, it remains unknown if exposure to infrasound from wind turbines does cause adverse health effects or if these potential health effects are the results of psychological mechanisms. Moreover, no studies so far have specifically examined the relationship between G-weighted sound pressure levels of infrasound with wind turbine noise exposure and health effects, and, likewise, no studies have demonstrated an influence of infrasound on specific vestibular diseases.

Low-frequencies

Wind turbines have been shown to produce a relatively large amount of noise in the low-frequency spectrum [32, 89]. Wind turbine low-frequency noise can be more intense compared to other well-known sources of low-frequency noise such as road traffic noise and aircraft noise [89]. Furthermore, the low-frequency noise can increase with an increase in turbine size [32]. In fact, this noise is not particularly different when compared to other known sources of low-frequency noise from road traffic noise and industry [29].

Sound pressure levels of nine wind turbines (2.3–3.6 MW) were measured in Denmark, and the distances which equalled L_{Aeq} of 35 dB were calculated. The distances were found be between 629–1227 meters from the rotor of the wind turbine. At this distance the level of the infrasound was 54–59 dB(G) and the low-frequency noise was between 26.7–29.1 dB(A). The highest octave band was found to be 250 Hz, and this means that low frequencies play an important role regarding the noise measured in neighbouring areas of wind turbines. Half of the measured room/wind turbine combinations actually demonstrated that the low-frequency limit of 20 dB set by Danish legislation was exceeded [32]. Furthermore, noise generated by wind turbines can lead to ground vibrations [68, 71]. These ground vibrations are, however, small since walking or running 50 meters from the measurement point, elicited larger outdoor vibrations than a wind turbine located 90 meters away [68]. However, the perception of sound and sensation of airborne vibrations from i.e. wind turbines has been demonstrated to be higher indoor compared to outdoor and the vibrations indoor were detected as recurrent low-frequency pulses which are likely to be more annoying compared to a more constant noise [2, 71, 90].

Vibrations from low-frequency sounds are reported to be the cause of vibro-acoustic disease (VAD) [91]. VAD is reported to happen when long-time exposure to low-frequency sounds occurs [92, 93]. However, VAD has not yet generally been accepted as a clinical disease by the medical community as reviewed by Chapman and St George [91].

Relationship between noise annoyance and sound exposure

Noise annoyance is not directly studied as a primary outcome in most of the case studies; however, it is evident from these studies that many subjects complain about noise from wind turbines [1, 64, 66].

Several reasons can explain why wind turbine noise probably causes more annoyance than other sound sources. Wind turbines are often placed in areas where background noise levels are low. People living in these areas may have sought out tranquillity and have likely accustomed themselves to the silence, which may influence their annoyance level regarding unwanted sounds in their environment [5, 94]. Furthermore, any changes in their surroundings or their

Table 1. Relation between annoyance and sound exposure to wind turbines.

Studies	N	Dose- response-relationship	Effects	Other factors influencing annoyance
Jansen et al. [33] 2011 (meta analysis of Pedersen et al. 2004,2007,2009 [38–40].	1820	Yes	Highly exposed subjects more annoyed compared to less exposed subjects.	Noise sensitive subjects (↑)Visible wind turbines (↑)Age (↑)Economic benefits (↓)
Pedersen 2011 [35]. (A subpopulation of same study populations as Jansen et al. 2011 [33]).	1755	Yes	Highly exposed subjects more annoyed compared to less exposed subjects.	Economic benefits (↓) – analyses were adjusted for economic benefits, but only in analyses with data from Pedersen et al. 2009.
Pedersen and Larsman 2008 [34] (meta-analysis of Pedersen et al. 2004 and 2007 [38, 39].	1095	Yes	Highly exposed subjects more annoyed compared to less exposed subjects. Effect was independent on terrain.	Negative evaluation of wind turbines (↑)Visual attitude towards wind turbines for subjects who could see the wind turbines and to a lower degree for subjects who could not see the wind turbines (↑)Increased vertical visual angel is correlated to wind turbine noise and annoyance (↑)
Pedersen et al. 2009Bakker et al. 2012 [36, 40, 41].	725	Yes	Highly exposed subjects more annoyed compared to less exposed subjects.	Noise sensitive subjects (↑)Visible wind turbines (↑)Economic benefit (↓)Build-up area opposed to rural area without main road (↑)Rural area with main road (↓)
Pedersen et al. 2004 [38, 41, 47].	341	Yes	Highly exposed subjects more annoyed compared to less exposed subjects.	Noise sensitive subjects (↑)Negative attitude to visible wind turbines (↑)Negative attitude to wind turbines in general (↑)
Pedersen et al 2007 [39, 41, 47].	754	Yes	Highly exposed subjects more annoyed compared to less exposed subjects.	Noise sensitive subjects (↑)Attitude to visible wind turbines (↑)Attitude to wind turbines in general (↑)
Pawlaczyk-Luszczynska et al. 2014 [46].	156	Yes	Highly exposed subjects more annoyed compared to less exposed subjects.	Noise sensitive subjects (↑)Attitude to visible wind turbines (↑)Attitude to wind turbines in general (↑)Sensitivity to landscape littering (↑)Negative self-assessment of physical health (↑)Wind turbines were found to be the most annoying sound source.

Table 1. Cont.

Studies	N	Dose- response-relationship	Effects	Other factors influencing annoyance
Aslund et al. 2013 [67]. Based on calculations from Pedersen et al. 2009 and Bakker et al. 2012 and Jansen et al. 2011 [33, 36, 40].	8123 theoretically exposed subjects. 522 are participating receptors.	Yes (Dose-response relationship derived from other studies).	Highly exposed subjects close to wind turbines calculated to be more frequently annoyed and very annoyed.	Participating residents in wind farm projects (↑)Annoyance outdoor calculated to be higher than annoyance indoor.
Shepherd et al. 2011 [42].	39 subjects. 158 controls.	Not related to sound – related to distance.	Annoyance not directly compared between subjects and controls.	Annoyance decreased perceived general health as well as physical, social and environmental quality of life scores for the control group only. Subjects reported, however, lower environmental quality of life scores compared to controls.
Kuwano et al. 2013 [43].	747 subjects. 332 controls.	Not related to sound.	Proportion of annoyed subjects higher in wind turbine exposed subjects	All kinds of noise sources increased annoyance in both groups. Subjects in the wind turbine group found wind turbines as the most annoying sound source.
Yano et al. 2013 [44].	747 subjects.	Yes	Highly exposed subjects more annoyed compared to less exposed subjects.	No difference in dose-response curves between cold and warm areas. Living near the sea (↓). (Waves may mask wind turbine sounds). Noise sensitivity (↑)Landscape disturbing (↑)Environmental interest (↑)
Morris 2012 [50, 51].	93 households.	Not related to sound.	56% of households are annoyed during night time within 0–5 km. from the wind turbines compared to 40% of households living within 0–10 km from wind turbines.	No influencing factors were investigated.
Schafer 2013 [54].	23 households.	Not related to sound.	66% of subjects affected by noise at night.	No influencing factors were investigated.
Schneider 2012 [55, 56].	23 households, 25 household in follow-up.	Not related to sound.	85.7%/ (87.7% in follow-up study) were disturbed from day time noise. 100% from night time noise in follow-up.	No influencing factors were investigated.
Thorne 2012 [52].	25	Not related to sound, but sound levels measured.	91% were annoyed indoor.	No influencing factors except living near wind turbines were investigated.

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environment will probably introduce a level of annoyance in the case of at least some individuals [5, 8].

As shown in Table 1, which summarizes studies on annoyance and wind turbine noise, a dose- response effect of noise exposure and noise annoyance has been demonstrated. Two studies (754+351 subjects) were conducted in Sweden, one study in the Netherlands (725 subjects), one study in Poland (156 subjects) and one study in Japan (747 subjects) with different questionnaires assessing noise annoyance used than those in the aforementioned studies from Sweden, the Netherlands and Poland [38–40, 46]. All five studies demonstrated a significant relationship between A-weighted sound exposure and wind turbines and annoyance [38–40, 44, 46]. All studies were cross-sectional studies, and they used a questionnaire-based survey which was combined with either direct sound measurements or estimated sound emission levels outside the subjects' dwellings [38–40, 44, 46]. All studies asked for subjective answers regarding the degree of annoyance towards different sound sources to mask the true purpose of the questionnaire [38–40, 44, 46]. In general, the selection of geographical areas in which to conduct these studies was quite large, encompassing several different areas, thus helping to limit selection bias. In the study from Japan, for example, a control group of 332 subjects not exposed to wind turbines was also included for comparison. While wind turbine noise was found to be the most annoying sound source in the exposed group, traffic noise was perceived as the most annoying sound in the control group [43].

Additionally four studies ranging from 23 to 93 households were conducted near four different specific wind farms in Australia (Table 1) [50–52, 54–56]. These studies reported that 40 to 91% of households were annoyed. Response rates between 23 to 40% were reported in only two of the studies [50, 51, 55, 56].

The studies from Sweden and the Netherlands were used in a meta-analysis where L_{den} was calculated from the measured L_{Aeq} reported in the original studies [33]. To calculate L_{den} an average correction factor of 4.7 dB was used as earlier suggested by van den Berg (2008) to account for differences in wind conditions and different terrains in the different studies. By calculation of L_{den} this study could compare the degree of annoyance in relation to L_{den} and this value could be compared to other well-known sources of environmental noise such as road traffic noise and noise from airports. The meta-analysis showed that noise from wind turbines was perceived as more annoying compared to noise from road traffic, airports and trains at similar values of L_{den} [33]. Age, general noise sensitivity and visual disturbance by wind turbines were positively associated with annoyance whereas economic benefit was significantly negatively associated with annoyance. The data from the two Swedish studies were also combined in an additional analysis and it was demonstrated that noise annoyance from wind turbines was significantly correlated to swishing, whistling, resounding and pulsating sounds from wind turbines [34]. Furthermore, a model for the dose-response relationship between sound exposure and the risk of high annoyance due to sound exposure to wind turbines was established [33]. The degree of annoyance has in general been reported to be between 10–45% of the population if the sound exposure was above 40 dB(A) but less than 10% of the population will be annoyed if the sound exposure is below 35 dB(A) [38–40]. In a planned wind farm project where the noise exposure was calculated based on the results from the meta-analysis by Janssen et al., 17 to 18% of the 8123 recipients living within a distance of 1 km from the wind turbines were expected to be rather or very annoyed when outdoors [33, 67]. On the other hand, it was demonstrated in a field study from the United States that the degree of annoyance was only 4% in a population living within a distance of approximately 600 meters to wind turbines [95].

Experimentally it has been shown that wind turbine noise does not differ substantially from traffic noise when the wind turbine noise is not known of in advance [96]. However, wind turbine noise is poorly masked by road traffic noise unless the exposure to wind turbine noise is at an intermediate level (35–40 dB(A)) [97, 98]. Wind turbine noise has distinctive features which allow for detecting that type of noise from amongst other sound sources at low signal-to-noise ratios. This means that focussing on the sound can increase noise annoyance [96]. It has been shown that wind turbine noise can be masked with natural background noise. In order to mask the sound completely the background noise needs to exceed the noise from the wind turbines with 8–12 dB [99]. An increase of background noise with 8–12 dB is not practical, but the perceived loudness of noise and annoyance from wind turbines is reduced if the background noise is at the same level or higher than the wind turbine noise [99, 100].

It was calculated that 330 dwellings in the Netherlands were exposed to wind turbine noise exceeding L_{den} by as much as 50 dB and that 440.000 inhabitants were exposed to L_{den} above 29 dB. Of these 440.000 inhabitants, 1500 were expected to be severely annoyed [89]. The estimation of this noise exposure at different dwellings may, however, have been altered by atmospheric changes, so it was further calculated that the sound exposure could be up to 5 dB lower and 10 dB higher than predicted under neutral conditions. It is generally believed that noise limits for wind turbines should be set at a level where fewer than 10% of exposed people are annoyed. A limit of 45 dB in the Netherlands has been estimated to annoy 5.2% of the exposed inhabitants [89].

Relation between wind turbine noise exposure and sleep disturbance

Table 2 summarizes studies investigating the relationship between noise exposure to wind turbines and sleep disturbance. Reports from case studies indicated that many subjects living near wind turbines complained of sleep disturbance [1, 64–66]. These results were supported by the finding of a dose-response relationship between self-reported sleep disturbance and A-weighted noise exposure in three out of four larger epidemiological studies from Sweden, the Netherlands and Poland [35, 36, 46]. Furthermore, a disturbed sleep was also found to be higher among exposed subjects compared to unexposed control subjects in three studies from Japan (754 subjects, 332 controls), the U.S.A. (38 subjects, 41 controls) and New Zealand (39 subjects, 158 controls) [37, 42, 43]. The Pittsburg Sleep Quality

Table 2. Relation between sound exposure to wind turbines and sleep disturbance.

Study	N	Dose- response-relationship	Effects	Other factors influencing sleep
Nissenbaum et. al. 2012 [37].	38 subjects near wind turbines.41 controls far from wind turbines.	Not related to sound but sleep scores related to distance.	Subjects near wind turbines had worse sleep (Pittsburg Sleep Quality Index and Epworth Sleepiness Scale score) compared to subjects far from wind turbines.	
Bakker et al. 2012 [36].	725	Yes	Highly exposed subjects reported more frequent sleep disturbances.	Sleep disturbance higher in urban areas where subjects were disturbed by traffic noises, people leaving the disco, animals.
Pedersen et al. 2011 [35].	1755	Yes/No	Highly exposed subjects reported more disturbed sleep in 2 out of 3 studies.	Pedersen et al. 2004 and 2009 did report an association between sound exposures and sleep disturbance. Pedersen et al. 2007 did not find an association.
Pawlaczyk-Luszczynska et al. 2014 [46].	156	Yes	Highly exposed subjects suffered significantly more of insomnia ($p<0.05$).	Negative self-assessment of physical health (↑) Wind turbines were found to be the most annoying sound source.
Kuwano et al. 2013 [43].	747 subjects.332 controls.	Not related to sound – related to distance.	Proportion of subjects with affected sleep was slightly higher in wind turbine exposed subjects.	All kinds of noise sources increased sleep disturbance in both groups. Subjects in the wind turbine group found wind turbines as the most disturbing sound source.
Shepherd et al. 2011 [42].	39 subjects.158 controls.	Not related to sound – related to distance.	Perceived sleep quality poorer in subjects (wind turbine exposed) compared to controls (not exposed).	Worse sleep with increased noise sensitivity in wind turbine exposed. General health, physical and psychosocial health increased with better perceived sleep quality.
Krogh et al. 2011 [49].	102 subjects with health problems.	Not related to sound.	Sleep disturbance more frequently reported, but not significantly ($p=0.08$) different in subjects living close to wind turbines compared to subjects living further away.	Excessive tiredness was reported significantly increased ($p=0.03$) in subjects living within 350–673 meters from wind turbines compared to subjects living between 700–2400 meters from wind turbines.
Lane 2013 [57].	11 exposed.10 unexposed.	Increased awakenings were related to sound levels above 45 dB(A).	Slightly but not significantly worse sleep parameters in the exposed group measured with actigraph.	Reasons of awakening were not related to wind turbine noise. Use of the bath-room by a child or partner were the most commonly reported sources of awakening. No correlation between distance to wind turbines and sleep efficiency were found. Overall uneven correlation between subjective and objective sleep parameters.
Paller 2014 [45].	396	Not related to sound but sleep scores related to distance.	Subjects near wind turbines had worse sleep (Pittsburg Sleep Quality Index) ($p<0.01$) compared to subjects far from wind turbines.	Analyses were controlled for age, gender and county.
Harry 2007 [66].	42	Not related to sound.	More than 70% of cases reported impaired sleep.	No control group. Cases are just reported to live near wind turbines.
Iser 2004 [65].	19	Not related to sound.	8/19=42% reported disturbed sleep.	No control group. Cases were just living near wind turbines.
Morris 2012 [50, 51].	93	Not related to sound.	39% of households had disturbed sleep within 0–5 km. from the wind turbines compared to 29% of households living within 0–10 km from wind turbines.	No influencing factors were investigated.
Wind Concerns Ontario [64].	112	Not related to sound.	48% reported sleep disturbance.	No influencing factors except living near wind turbines were investigated.
Schafer 2013 [54].	23 households.	Not related to sound.	51% of subjects affected by sleep disturbance.	No influencing factors except living near wind turbines were investigated.

Table 2. Cont.

Study	N	Dose- response-relationship	Effects	Other factors influencing sleep
Schneider 2012 [55, 56].	23 households. 25 households in follow-up.	Not related to sound.	78.5% had disturbed sleep. 100% had disturbed sleep in follow-up study.	No influencing factors except living near wind turbines were investigated.
Thorne 2012 [52].	25	Not related to sound, but sound levels measured.	92% noted a change in sleep patterns.	No influencing factors except living near wind turbines were investigated.
Pierpont 2009 [1].	38 subjects from 10 families.	Not related to sound.	86% reported disturbed sleep.	No influencing factors except living near wind turbines were investigated.
Phipps [53].	614 households.	Related to distance.	Disturbed sleep was reported by 42, frequently disturbed sleep by 21 and 5 were affected most of the time.	No influencing factors except living near wind turbines were investigated.

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Index (PSQI) was used as an outcome measurement in the American study and in studies, from Australia (25 subjects) and Canada (396 subjects) [37, 45, 52]. The Australian study showed lower PSQI in the wind turbine group compared to known population values [52]. The studies from the U.S.A. and New Zealand both demonstrated a significant relationship between PSQI results and the distance to the wind turbines. Selection bias is a concern in these studies, however, as only a few selected wind farms were included in the studies, and the study from Canada had a response rate of only 8% [37, 42, 45]. Surveys of single wind farms in Australia, including 23–93 households within 0–10 km from the wind farms, investigated sleep disturbance along with the noise annoyance reported above. Twenty-nine to ninety-two percent of exposed households reported disturbed sleep in these studies (Table 2) [50–52, 54–56]. A larger survey from New Zealand (614 subjects) found only 42 subjects with disturbed sleep, but this study only investigated subjects living within 2–10 km to the wind farm. A study from Canada collected self-reported sleep disturbance complaints amongst other health-related outcomes. The data was collected from an Internet survey where subjects reported health data. This study found a significant relationship between the distance to wind turbines and undue tiredness ($p<0.03$). However, disturbed sleep ($p<0.08$) showed only a borderline significance in relation to the distance from the wind turbines [49].

Whereas most studies collected only subjective information about sleep disturbance, some studies attempted to also collect objective longitudinal sleep data over several nights. By using an Actigraph, sleep was monitored and related to noise measurements in the sleeping room. The study had a limited sample size; however, and no difference in objective sleep quality in relation to the noise exposure was observed in the 11 subjects exposed to wind turbines compared to the 10 unexposed subjects.

Noise from various environmental factors can affect sleep if the noise is pronounced at night [101].

Noise annoyance, self-reported sleep disturbance and psychological stress were all related to increasing sound pressure levels of wind turbines [35, 36, 42]. The impact of wind turbine noise was stronger for people living in rural areas with less background noise from other environmental factors. Sleep disturbance was only seen at high exposure levels above 45 dB(A), and sleep disturbance was significantly related to annoyance [36]. It was not possible, however, to conclude that sleep disturbance was caused directly by wind turbine noise, as other environmental noise sources could have played a role as well [36]. On the other hand, noise annoyance was not significantly correlated to sleep disturbance within a distance of two kilometers from the wind turbines, as had been reported in the study from New Zealand. Sleep, and ones physical and environmental quality of life were, however, affected in the wind turbine exposed group as reported above, and the authors suggested that both sleep disturbance and noise annoyance could have caused the observed degradation of health-related quality of life in the wind turbine exposed group [42]. Sleep disturbance was only weakly associated to A-weighted sound pressure levels in the first Swedish study and in the Dutch study if in- and outdoor noise annoyance were also included in the models. This demonstrates a correlation between noise annoyance and sleep disturbance and that noise annoyance may be a mediator of sleep disturbance or that sleep disturbance may induce annoyance [35].

Relation between wind turbine noise and other health parameters

Table 3 summarizes the findings from studies investigating the association between wind turbine noise and psychological distress. Psychological symptoms such as memory and concentration problems, anxiety and stress were frequently reported in case series of subjects exposed to wind turbine noise [1, 64–66]. Furthermore, noise annoyance was significantly associated to psychological distress [36]. Several studies measured the WHO-quality of life (WHOQOL) and found that physical health scores among wind turbine exposed subjects were lower than those of the unexposed controls as well as those of the general population (Table 3) [42, 48, 52]. The social and psycho-social scores in a study from New Zealand, however, did not differ between exposed and unexposed subjects in the initial investigation, and neither were these scores altered in a follow-up study two years later [42, 48]. Nonetheless, the general health of the turbine-exposed group was reported to be significantly lower when compared to controls [42, 48].

Another general health questionnaire (SF-36) was used to measure mental and physical component scores in wind turbine noise exposed subjects [37, 52]. Mental component scores were significantly lower with decreasing distance between the dwelling and the wind turbines, and the scores were also lower if they were compared to those of the general population [37, 52]. These studies may have been affected by selection bias, and the two wind farms investigated in the study by Nissenbaum et al. do not seem to be comparable in terms of exposure. The sound was measured at various distances from the wind turbines and then compared. It is evident that the sound levels measured at various distances were

Table 3. Psychological distress.

Study	N	Dose- response-relationship	Effects	Other factors influencing psychological distress
Bakker et al. 2012 [36].	725	Yes	Highly exposed reported psychological distress (General health questionnaire).	Annoyance influence psychological distress and in this case psychological distress is not predicted by sound-exposure.
Nissenbaum et al. 2012 [37].	38 subjects near wind turbines41 controls far from wind turbines.	Not related to sound but sleep scores related to distance.	Subjects near wind turbines had worse mental scores (Mental Component Score of SF-36) compared to subjects far from wind turbines.	
Shepherd et al. 2011 [42].	39 subjects.158 controls.	Not related to sound.	No differences found in psychological and social health-related quality of life (WHOQOL) questionnaire parameters.	
McBride et al. 2013– a follow-up of Shepheard et al. 2011 [42, 48].	Selected from 56 exposed houses and 250 control houses.	Not related to sound.	WHO-quality of life (WHOQOL) did not change in the follow-up period in the exposed group. The physical domain and general satisfaction with health scored significantly lower in the exposed group compared to the control group in the most recent study.	Amenity decreased significantly in the control group over time. Amenity was stable in the exposed group over time.
Harry 2007 [66].	42	Not related to sound.	More than 50% of cases reported anxiety and stress.	No control group. Cases are just reported to live near wind turbines.
Iser 2004 [65].	19	Not related to sound.	8/19=42% reported stress and likely symptoms.	No control group. Cases were just living near wind turbines.
Wind Concerns Ontario 2009 [64].	112	Not related to sound.	A majority reported stress, anxiety, excessive tiredness, depression.	No influencing factors except living near wind turbines were investigated.
Thorne 2012 [52].	25	Not related to sound, but sound levels measured.	Mental component score of SF-36 were much lower than expected from known population scores.	No influencing factors except living near wind turbines were investigated.
Pierpont 2009 [1].	38 subjects from 10 families.	Not related to sound.	93% reported memory and concentration problems.	No influencing factors except living near wind turbines were investigated.

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quite different in the two wind turbine parks. It is not, however, known if weather conditions or different terrains were the main causes of these differences, and it is also difficult to determine if the wind turbines were responsible for the sleep disturbance and low mental component scores in this study [37].

Associations between A-weighted sound pressure levels and subjective tinnitus and diabetes were demonstrated in one of the previous Swedish studies by Pedersen et al. [35]. As pointed out by the authors this could be a coincidental finding due to a multiplicity of logistic regressions since this finding was only demonstrated in one out of three studies investigating the association between sound exposure and tinnitus or diabetes. No significant associations between A-weighted sound pressure levels and headache, impaired hearing, chronic disease, cardiovascular diseases, high blood pressure, undue tiredness, irritability, tension, or stress were observed [35].

Case series studies of wind turbine noise exposed subjects often report headache, vertigo, tinnitus and hearing loss as frequent symptoms [1, 64–66]. Likewise, 8 out of 23 households reported headache and 4 out of 23 households reported dizziness in a study from a single Australian wind farm [54]. Self-reported symptoms like tinnitus, hearing problems, headache, stress and anxiety were not shown to be significantly related to the actual distance from the wind turbines, although one study did approach statistical significance for the symptom of tinnitus in relation to the distance from the wind turbines ($p<0.08$) [45, 49]. Symptoms of self-reported vertigo ($p<0.001$) were also increased for residents living closer to wind turbines in this study [45].

It is hypothesized that sound may affect the vestibular organ in the inner ear even at subaudible levels [84, 102]. A clinical test of vestibular function such as the vestibular-evoked myogenic potential (VEMP) test demonstrates that the vestibular system is sensitive to acoustic frequencies. Some vestibular diseases are known to be sensitive to change in pressure, such as perilymphatic fistula (PLF), superior canal dehiscence (SCD) and Meniere Disease (MD). The SCD (known as "a third window"), a defect in the superior semi-circular canal can give rise to Tullio phenomenon with sound-induced dizziness [103]. Such pressure-sensitive vestibular patients, however, have not as yet been evaluated with regard to wind turbine noise exposure even though such speculations have been made [84]. In our own clinical experience we have never seen PLF, SCD or MD patients complaining of aggravation of vestibular symptoms due to neighbouring wind turbines.

It has been further speculated that rotating wind turbine wings passing through the sunlight can induce epileptic attacks in sensitive subjects because the sunlight will be seen to flicker on the horizon. This phenomenon is known in the field of aviation medicine and can actually disqualify a pilot at the aeromedical health check-up due to the risk assessment associated with flying a turbo prop plane or helicopter. If light flickers at a frequency around 3 Hz there is a known risk that this can induce an epileptic attack in sensitive subjects [104]. The risk has been calculated as minimal in the case of large wind turbines which are unlikely to rotate fast enough to create an abruption of sun-light of more than three times per second, but there could be a risk with smaller wind turbines [105]. Shadow flickering is, however, a concern. It is often described in case series reports and studies from single wind farms and it may contribute to the overall annoyance from wind turbine exposure [1, 50, 51, 53].

Discussion

Noise from wind turbines results in significant annoyance for neighbours of wind turbines, and the level of annoyance is related to the A-weighted sound exposure [33–35, 38–40, 44, 46, 106]. It has been shown that the sound exposure from wind turbine noise increases noise annoyance by dose-responsive degrees, and this annoyance may be the primary mediating agent causing sleep disturbance and increased psychological distress [35, 36]. On the other hand, it is also possible that sleep disturbance may lead to increased annoyance. Self-reported sleep disturbance was found to be significantly related to the given sound exposure and more frequently reported from subjects living closer to wind turbines compared to subjects living further away [35–37, 42, 46, 49].

Annoyance was significantly related to psychological distress and the mental component scores of SF-36 were significantly affected in wind turbine exposed subjects in some studies [36, 37, 52]. However, no differences in the psychological and social health-related quality of life (WHOQOL) questionnaire parameters were observed in other studies [42, 48].

The quality of the studies included in this review is quite varied. There are five cross-sectional studies of reasonable sample size from which a dose-response relationship between sound exposure and health outcomes, particularly in relation to annoyance and sleep disturbance, was demonstrated [33–36, 38–41, 44, 46]. Selection bias and recall bias may, however, still have affected the outcomes of these studies, and it should be acknowledged that the sample groups in these studies were from many different wind turbine sites located in quite different geographical regions. Virtually all of the studies did point toward an association between wind turbine exposure and annoyance or sleep disturbance; however, one of the significant limitations of these cross-sectional studies is their inherent inability to evidence a clear causal relationship between exposure to wind turbines and health-related outcomes. It is therefore not known with certainty if the association between wind turbine exposure and health-related outcomes is caused by sound exposure, visual disturbance, economic aspects or something else. Cross-sectional studies are simply more explorative by nature.

Several studies investigated sleep disturbance and psychological distress in relation to an unexposed or low exposed control group [37, 42, 43, 48]. Sleep disturbance and psychological distress were only reported in self-reported questionnaires which increase the risk of introducing information bias into the study. Selection bias is a concern as well if the study population is not representative for an entire population of wind turbine exposed subjects. As such, selection bias as well as information bias related to the outcome are of concern and may potentially affect conclusions drawn by the studies. The study by Kuwano et al., however, was relatively large, investigating several different geographical areas of Japan. Thus selection bias would be less of concern in this study [43].

Several case reports have raised concerns that wind turbine noise may lead to various symptoms such as tinnitus, vertigo and headache. Until now, however, of these suspected symptoms, only tinnitus has been shown to have an association with A-weighted sound exposure, and that only in a single study out of three similar studies [35]. Neither was this association between wind turbine noise exposure and tinnitus supported in other studies either [45, 49]. These findings, as well as the finding of an association of A-weighted sound exposure to diabetes in one out of three similar studies, may be a result of multiple logistic regressions which can lead to spurious conclusions [35]. These results need to be confirmed by additional studies, before sufficient evidence can be established to support this association.

Most studies investigating a dose-response relationship between sound exposure and annoyance have used calculated values of L_{Aeq} or L_{den} based on model assumptions of sound propagation from wind turbines over distance [35, 38–40, 44, 46, 106]. It might be relevant to include another type of sound weighting rather than just the A-weighting in future studies. In fact G-weighted sound exposure was estimated in one study, but these values were not related to adverse health effects [46]. Furthermore, it has been demonstrated that other characteristics of the noise from wind turbines may correlate better with noise annoyance than the frequently used A-weighted metric [107, 108]. It seems evident that low-frequency sound exposure may increase with increasing turbine size [32]. However, others reports have demonstrated that the content of low-frequency sounds from wind turbines may not be particularly different compared to other environmental background noises [29]. Sound from several wind turbines may increase the sound pressure level of swishing pulses from the wind turbines, and this could be a factor relevant to the perceived noise annoyance [15, 20, 34, 71, 109]. It may therefore be relevant to focus future studies on serial monitoring of the sound exposure to include the nature of the amplitude-modulated sound and the low-frequency sound exposure in dwellings near wind turbines. It is known that wind turbine noise is quite dependent on the existing wind speed, and health-related effects of wind turbine noise could, therefore, be speculated to fluctuate depending on the different noise levels at different wind speeds [110]. It has also been suggested that G-weighed sound exposure levels could be used as well to demonstrate the exposure to infrasound [32]. An experimental study, however, found a possible link between the psychological expectations of symptoms following both actual infrasound and a sham sound exposure trial. In these trials a difference between the infrasound and sham sound could not be demonstrated [85]. These results should, however, be interpreted with caution, as laboratory conditions may not be comparable to the real life exposure of wind turbine noise.

One study has already measured objective sleep parameters in relation to sound exposure, but the sample size of the study was a limiting factor in reaching any conclusions [57]. Future studies should focus more on objective measurements of health-related disorders in relation to wind turbine noise exposure. Sleep could be monitored parallel with sound exposure measurements, and stress hormones could be measured as well. Objective measurements of health can be a valuable asset in combination with more subjective measurements when used in questionnaires regarding annoyance from wind turbine noise. Both types of data can be related to sound exposure measurements, and it could be relevant to report both A- and G-weighted sound exposure measurements as well as a thorough characterisation of exposure in the low-frequency area including the maximum peak values of the swishing pulses from wind turbines.

It is currently known that traffic noise exposure may increase the risk of cardiovascular disease and diabetes [111, 112]. The mechanism here could be increased stress and reduced quality of sleep which can increase the risk of cardiovascular diseases and diabetes [111, 112]. It is not yet known if wind turbine noise exposure during the night could result in identical health effects.

Furthermore, it should also be acknowledged that some patients might have symptoms of a functional somatic syndrome, describing persistent bodily complaints for which no objective findings supporting the symptoms can be found [113]. Many of the core symptoms of the wind turbine syndrome, such as tinnitus, headache, dizziness, nausea, sleep disorders and lack of concentration, as reported by subjects exposed to wind turbine noise, show a similar bodily distress as described in other functional somatic syndromes [1, 113]. Events like accidents and potential environmental health hazards can induce a functional somatic syndrome in certain individuals, and this may be potentiated by mass hysteria in the media [113, 114]. Issues of possible wind turbine health impacts have also been addressed by the mass media using emotionally-charged words and phrases such as "dread" and "poorly understood by science", and fright tactics like these may well have contributed to a mass hysteria regarding wind turbines [115, 116]. There are, nonetheless, numerous reports of many complaints related to wind turbine noise from various case studies [1, 6, 51, 55, 66]. These symptoms could be stress-related, and it is possible that these symptoms could occur as a result of sleep disturbance. On the other hand, these symptoms could be psychosomatic and explained as another sort of a functional somatic syndrome [12].

Conclusion

At present it seems reasonable to conclude that noise from wind turbines increases the risk of annoyance and disturbed sleep in exposed subjects in a dose-response relationship. There seems to be a tolerable limit of around L_{Aeq} of 35 dB. Logically, accepting higher limits in legislations may lead to increased numbers of annoyed subjects. It therefore seems reasonable to conclude that a cautious approach is needed when planning future wind farms. Furthermore, there is an indication that noise annoyance and sleep disturbance are related and that disturbed sleep potentially can lead to adverse health effects. These conclusions are, however, affected by a potential risk for selection and information bias even in the larger cross-sectional studies providing the current best evidence. The evidence for adverse health effects other than sleep disturbance is primarily supported by case-series reports which certainly may be affected by various sources of bias. Larger cross-sectional surveys have so far been unable to document a relationship between various symptoms such as tinnitus, hearing loss, vertigo, headache and exposure to wind turbine noise. One limitation causing this could be that most studies so far have only measured L_{Aeq} or L_{den}. An additional focus on the measurement of low-frequency sound exposure as well as a more thorough characterisation of the amplitude modulated sound and the relationship between objective and subjective health parameters could lead to different conclusions in the future. Finally, in regards to the objective measurement of health-related disorders in relation to wind turbine noise, it would be valuable to demonstrate if such health-related outcomes fluctuate depending on exposure to wind turbine noise.

Supporting Information

Checklist S1. PRISMA 2009 checklist.
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Author Contributions

Conceived and designed the experiments: JHS MK. Performed the experiments: JHS MK. Analyzed the data: JHS MK. Contributed reagents/materials/analysis tools: JHS MK. Contributed to the writing of the manuscript: JHS MK.

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EXHIBIT
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A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise

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Abstract

This review considers the nature of the sound generated by wind turbines focusing on the low-frequency sound (LF) and infrasound (IS) to understand the usefulness of the sound measures where people work and sleep. A second focus concerns the evidence for mechanisms of physiological transduction of LF/IS or the evidence for somatic effects of LF/IS. While the current evidence does not conclusively demonstrate transduction, it does present a strong prima facia case. There are substantial outstanding questions relating to the measurement and propagation of LF and IS and its encoding by the central nervous system relevant to possible perceptual and physiological effects. A range of possible research areas are identified.

Keywords

auditory transduction, infrasound, low-frequency sound, wind turbine noise

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Introduction

In recent years, there has been growing debate about the effects of wind turbine noise (WTN) on human health. A number of reviews have recently been published (e.g., Knopper et al., 2014; McCunney et al., 2014; Schmidt & Klokker, 2014; Van Kamp & Van Den Berg, 2017), some under the auspice of different government bodies in Australia (National Health and Medical Research Council, 2015), Canada (Council of Canadian Academies, 2015), and France (Lepoutre et al., 2017), with some appearing in the indexed scientific literature (most recently the Health Canada study; D. Michaud, 2015; D. S. Michaud et al., 2016a, 2016b; D. S. Michaud, Keith, et al., 2016). Many of these studies have adopted an epidemiological approach including various meta-analyses of the existing research reports concerning the health effects of WTN. By contrast, the popular press portrays a largely polarized picture where the discourse often appears less informed and more opinionated than scientifically based.

There are clearly complex factors surrounding complaints about WTs that, apart from the health and safety concerns, include financial and other material factors and potential interactions with individuals' perceptions of devices themselves, including their appearance and the sounds they make. These factors are all potential contributors to the annoyance produced by WTs. Many of these concerns—sometimes referred to as nocebo effects—have been recently reviewed in the literature (Chapman & Crichton, 2017; C. H. Hansen, Doolan, & Hansen, 2017). There seems, however, to have been little discussion (or systematic review) of potential perceptual and physiological effects of WTN at the level of the individual. This provides the principal motivation for this review. This review does not consider the important question of whether WTN affects human health, given the reviews and debates referred to earlier, but focuses on two important foundational issues. The first section reviews recent research examining the nature of the sound generated by WTs with a particular focus on the low-frequency sound (LF) and infrasound

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(IS), together with the mechanisms of its generation, propagation, and measures of human exposure. The objective of this first part is to understand the accuracy and usefulness of measures of this sound pressure at locations where people work and sleep. The second issue for focus concerns whether there are plausible mechanisms of transduction of LF/IS or evidence for somatic effects of LF/IS. This is an important question as a key link in any argument attempting to relate WTN exposure to ill health is the extent to which that sound can have a somatic influence. In closing, some of the existing peer-reviewed research examining the perceptual effects of exposure to LF and IS in the laboratory setting is reviewed.

This review has been confined largely to the scientific literature represented by the relevant peer-reviewed articles in indexed journals.

WTN, LF, and IS

There are a range of potential sound generators produced by WTs which include mechanical generators (gearboxes, electrical generators, cooling systems, etc., in the WT nacelle) as well as interactions between the moving blades and the air, particularly where there are variations in flow, angle of incidence, and pressure.

Sound produced by rotating blades on modern upwind WTs (where the rotor is on the front of the nacelle when viewed from the direction that the wind is coming) results in part from an interaction between the airflow disturbed by the rotating blade interacting with the supporting tower (e.g., Jung, Cheung, Cheong, & Shin, 2008; Sugimoto, Koyama, Kurihara, & Watanabe, 2008; reviewed in detail Van den Berg, 2006; Zajamšek, Hansen, Doolan, & Hansen, 2016). The sound generated by this mechanism is tonal in nature with a fundamental frequency at the blade passing frequency (BPF) and a series of six or so harmonics (Figure 1; for further details, see Schomer, Erdreich, Pamidighantam, & Boyle, 2015, their Figures 2 and 3). The fundamental frequency is dependent on the rate of rotation and number of blades and for a modern WT, the sound energy produced by this mechanism is generally well below 20 Hz.

Other sources of sound include the aerodynamic noise generated by air flow across and leaving the trailing edge of the blades (trailing edge noise) and mechanical noise from the nacelle equipment. By contrast with BPF noise, the aerodynamic noise from the blades is broadband with a low-pass roll-off (~5 dB per octave > 1 kHz; Figure 2; Oerlemans, Sijtsma, & López, 2007, their Figures 5, 9, and 11). The center frequency (500–750 Hz, A-weighted) is related to the size and power generation capacity of the turbine with a downward shift of around 1/3 octave comparing 2.3 to 3.6 MW turbines to <2 MW turbines accompanied by a relative increase in the proportion of energy at low frequencies for larger turbines (Moller & Pedersen, 2011).

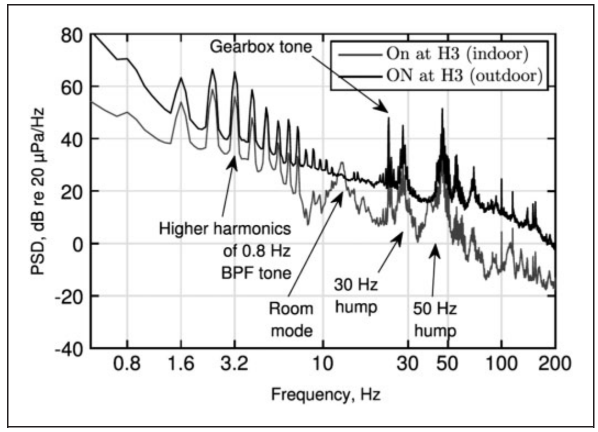

Figure 1. Comparison of indoor and outdoor spectral density recorded at an unoccupied dwelling approximately 3 km from a wind turbine. BPF = blade passing frequency; PSD = power spectral density.
Source: Reproduced with permission from Zajamsek et al. (2016), Figure 4.

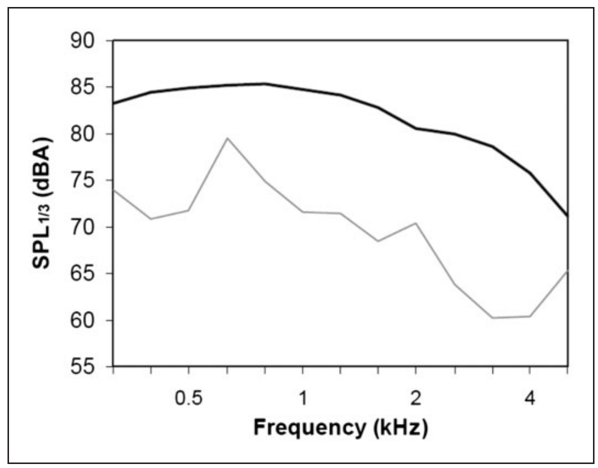

Figure 2. A-weighted average spectra of hub noise (thin line) and blade noise (thick line) recorded from a three-bladed pitch–controlled GAMESA G58 wind turbine (rotor diameter 58 m) using an acoustic array of 148 Panasonic WM-61 microphones 58 m upwind from the turbine.
Source: Reproduced with permission from Oerlemans et al. (2007).

In summary, from both a theoretical and an empirical standpoint, there is ample evidence demonstrating that a component of the sound energy produced by a WT is in the low and infrasonic frequency range. There are three other characteristics of LF that are relevant to understanding the measurements of sounds produced by WTs.

First, both modeling and measurement data have shown that the atmospheric boundary layer which extends from ground level to between 100 to thousands

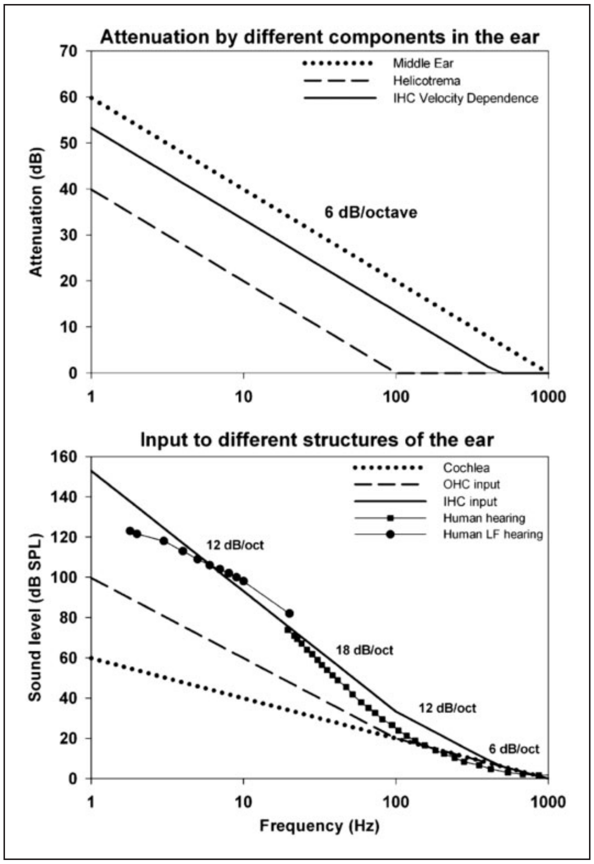

Figure 3. Upper panel: Estimated properties of high-pass filters associated with cochlear signal processing (based on Cheatham & Dallos, 2001). The curves show the low-frequency attenuation provided by the middle ear (6 dB/octave below 1000 Hz), the helicotrema (6 dB/octave below 100 Hz), and by the fluid coupling of the IHC resulting in the IHC dependence on stimulus velocity (6 dB/octave below 470 Hz). Lower panel: Combination of the three processes in the upper panel into threshold curves demonstrating: input to the cochlea (dotted) as a result of middle ear attenuation, input to the IHC as a result of additional filtering by the helicotrema, and input to the IHC as a result of their velocity dependence. Shown for comparison is the sensitivity of human hearing in the audible range (ISO226, 2003) and the sensitivity of humans to infrasound (Moller & Pedersen, 2004). The summed filter functions account for the steep (18 dB/octave) decrease in sensitivity below 100 Hz. OHC = outer hair cells; IHC = inner hair cells; LF = low-frequency sound.

Source: Reproduced with permission from Salt and Hullar (2010), Figure 3.

of meters can act as a low-frequency wave guide under a variety of common meteorological conditions (for review, see Marcillo, Arrowsmith, Blom, & Jones, 2015). With a stable boundary layer, which is common at night, LF radiation occurs as cylindrical waves and follows a two-dimensional decay model (−3 dB per doubling of distance) when measured downwind of a source (Zorumski & Willshire, 1989) in contrast to a three-dimensional decay model for higher frequency audible sound. Under such conditions, therefore, LF and IS levels decay more slowly with distance when compared with higher frequencies. Consistent with this, propagation of sound at the BPF from a 60-turbine wind farm has been recently measured using particularly sensitive equipment as far as 90 km from the source (Marcillo et al., 2015).

Second, IS and LF have wavelengths comparable with the dimensions of building structures such as homes which also allows for resonant interactions with those structures. Recent high-resolution data recorded inside and outside dwellings demonstrate such building cavity resonance in the 10 - to 20-Hz range (Pedersen, Møller, & Waye, 2007; Schomer et al., 2015; Zajamšek et al., 2016) along with other building resonances over a 2- to 80-Hz range. Third, sound attenuation provided by building walls is much less at low frequencies compared with higher frequency sounds (K. L. Hansen, Hansen, & Zajamšek, 2015; Thorsson et al., 2018) and very irregular because of the building resonances. These two observations indicate that exterior measures of LF and IS pressure are not necessarily good predictors of interior sound pressures as these are dependent on the particular characteristics of the structure.

Accurate measures of the sound pressure levels of LF and IS around WTs is complicated because of the very long wavelengths of sound at such low frequencies, and the high susceptibility of measurement microphones to atmospheric turbulence (i.e., wind noise). Special strategies such as very high performance wind-shields (Dauchez, Hayot, & Denis, 2016; K. Hansen, Zajamsek, & Hansen, 2014; Turnbull, Turner, & Walsh, 2012; Zajamšek et al., 2016) and the use of microphone arrays with sophisticated signal processing (Walker, 2013) are needed. There is a complex relationship between the wind speed and angle of incidence, atmospheric conditions, terrain, distance to the source and the number and distribution of sources, and the measurement of LF and IS (for an excellent review, see Van den Berg, 2006). External measures are complicated by wind noise and other interactions with the measuring instrument. The greater majority of measurements are external (rather than internal where the greatest disability is reported) and use A weighting which effectively filters out LF and IS frequencies. Even lower pass weightings (e.g., C weighting) exclude crucial low frequencies particularly at the BPF and first few harmonics. Measures made external to dwellings are not necessarily good predictors of dwelling interior pressures where people spend the majority of their time (particularly sleeping). In turn, internal measurements are also complicated, and often avoided by acousticians because of the influence of the room modes and occupational sources of noise, such as refrigerators and other household equipment. That there is a wide range of reported levels of LF and IS in and around wind farms should not be surprising, given the diversity of relevant factors (e.g., cf. Jung et al., 2008; Schomer et al., 2015; Sugimoto et al., 2008; Van den Berg, 2006). Given some of the physiological work reviewed later (particularly that relating to hydrops and basilar membrane biasing), use of a dosimetry approach to LF and IS exposure may prove a more appropriate measure for determining human exposure although this would require the development of new equipment and measurement techniques.

Sound Pressure Weighting Scales and WTN

The abovementioned considerations indicate that a complete understanding of sound energy emitted by WTs requires careful measurement and modeling approaches that are sensitive to the full range of possible sound frequencies. While the current practice of measuring and analyzing WTN using an A-weighted correction offers convenience and practicality, it will necessarily filter out much of the LF energy actually emitted by a WT. This approach appears to be motivated by practical measurement considerations and the assumption that, from the point of view of human perception, the auditory system sensitivity to sound level (loudness perception) is nonlinear and rolls off very sharply for frequencies below 1 kHz reaching −50 dB by 20 Hz (Keith et al., 2016; Yokoyama, Sakamoto, & Tachibana, 2014). These authors also argued that the A-weighted sound level of a wind farm is highly correlated with the sound levels of the LF and IS, and so A-weighted measures could act as a proxy for LF and IS levels. This supposition is, however, based on 1/3 octave C-weighted measures extending only to 16 Hz which is well above the BPF and it is not consistent with some recent data (e.g., Hansen, Walker, Zajamsek, & Hansen, 2015; Schomer et al., 2015). As reviewed earlier, there are also complicating factors relating to the potential difference in the propagation of IS and LF compared with the middle to high frequencies to which humans are sensitive. This suggests that, even if A-weighted measures are correlated with the total WT energy at a particular point in space, this may not provide an adequate indication of the relative sound levels at other distances from the source (see also Moller & Pedersen, 2011).

There is clearly a need for more research and development of methods to accurately measure and assess the level of exposure of individuals to LF and IS particularly in the built environment where individuals live and sleep. To be clear, in the first instance, this work needs to focus on the collection of high-quality scientific data to provide insights into the mechanisms and processes in play. While this may subsequently have implications for methods of making acoustic measurements in the field, the emphasis first needs to be on collecting high-quality scientific data to address the questions of sound propagation and human exposure.

Perceptual Sensitivity

Perceptual sensitivity to LF and IS has been studied for more than 80 years (reviewed in Moller & Pedersen, 2004), and although there is no international standard, the experimental data are in good agreement. Threshold rises sharply from 80 dB (SPL) at 20 Hz to around 124 dB SPL at 2 Hz and the perceptual effects also include vibration and the sensation of pressure at the ear drums. Consistent with these data, Yokoyama et al. (2014) showed that listeners were insensitive to resynthesized WTN in the laboratory at levels up to 56 dBA.

For a variety of biomechanical and other physiological reasons, the cochlea is known to be a highly nonlinear transducer. Given the relatively high sound levels required to achieve perceptual response to IS, the question arises as to whether this represents neural transduction at the fundamental frequency or sensitivity to nonlinear distortion products produced on the basilar membrane. While mechanisms of transduction are considered in more detail later, recent functional magnetic resonance imaging (fMRI) data (Dommes et al., 2009; Weichenberger et al., 2015) show auditory cortical activation to a 12-Hz tone at thresholds that are broadly consistent with those reviewed by Moller and Pederson (2004). This indicates that, regardless of whether IS is transduced as a fundamental or as a consequence of nonlinear distortion products, it does lead to activation of the auditory cortex providing a primary neural representation of these acoustic stimuli.

A more recent fMRI study (Weichenberger et al., 2017) took a different analytical approach using a regional homogeneity resting mode analysis and a relatively prolonged (200 s) 12-Hz stimulus. They report that subliminal sound levels (2 dB below measured threshold) also activated brain regions known to be involved in autonomic and emotional processing: In particular, the anterior cingulate cortex and amygdala—the latter is believed to be involved with stress and anxiety-related psychiatric disorders. The amygdala is also part of the nonleminiscal auditory pathway that mediates subcortical processing and has input to the reticular activating system, a key component regulating arousal and sleep (for discussion, see Weichenberger et al., 2017). This latter observation provides some explanation as to how subliminal IS stimulation could lead to arousal and potentially mediate sleep disturbances reported by some individuals.

Related to the question of individual differences, Moller and Pedersen (2004) make the observation that the dynamic range of the auditory system decreases significantly at low frequencies, demonstrated in the extreme compression of the equal loudness contours at 2 Hz (20–80 phon from 130 to 140 dB). This indicates that even small changes in pressure can result in very large changes in loudness perception. Likewise, small variations in threshold between individuals could produce significant differences in perceived loudness for the same pressure level stimulus. This would also result in differences in suprathreshold levels which, when taken in the context of the recent report of Weichenberger et al., could in turn explain some of the individual differences in reported physiological effects of WTN. A simple test of this prediction would be to measure the IS thresholds of individuals reporting physiological effects of exposure to WTN compared with those who report no effects under the same exposure conditions. If this proved to be discriminatory, then simple IS threshold measures would provide an indicator of likely susceptibility to WTN. Such measurements could involve perceptual impressions (Kuehler, Fedtke, & Hensel, 2015) or objective assessments such as fMRI (Weichenberger et al., 2017) or magnetoencephalogy (Bauer et al., 2013).

Physiological Transduction of LF and IS

Before considering the evidence for potential sensory or other transduction of LF and IS, it is useful to contextualize this discussion. As indicated in the Introduction section, a critical component in any argument attempting to link the sound level output from WTs (or any mechanical device) to ill health is the extent to which sound energy is able to influence the human body perceptually or somatically. If there is no influence, then it would be difficult to argue that reported health effects could be induced by sound or vibration. For instance, people in urban environments are exposed daily to significant qualities of low-level microwave radiation in the form of communications transmissions (radio, TV, cellular network, etc.) without any known effects of ill health (Valberg, Van Deventer, & Repacholi, 2007). This would likely be a consequence of the fact that, at these levels of exposure, microwave radiation is not an effective stimulus perceptually or somatically for the human body. By contrast, there is much debate and opinion as to whether the human nervous system is sensitive to the infrasonic and LF that is emitted by WTs. There are, unfortunately, very few peer-reviewed publications that consider the potential physiological mechanisms that might underlie sensory transduction of LF and IS. There is a much wider range of opinion pieces on the topic presented in a variety of formats (popular science magazines, newspaper articles, and self-published monographs and newsletters). Subsequently, we will consider principally reports or reviews in peer-reviewed scientific publications.

In a review in *Hearing Research*, Salt and Hullar (2010) outline a number of possible mechanisms by which the LF and IS could influence the function of the inner ear and lead to neural stimulation that may or may not be perceived as sound. These authors describe how, under normal physiological circumstances, the inner ear is remarkably insensitive to LF and IS. This results from the need to mechanically tune the sensory apparatus to sounds of greatest biological interest (in this case, from 100 Hz to a few kilohertz which is the range of human communication and of the inadvertent sounds of movement of predator or prey). Consequently, the anatomical structures of the cochlea would suffer significant damage in response to large mechanical displacements that would result from stimulation by even relatively low pressure LFs (for sounds of constant pressure, particle displacement is inversely proportional to frequency at +6 dB per octave).

There are three principal mechanisms providing this protective attenuation (see Figure 3; Salt & Hullar, 2010; for a very detailed review, see Dallos, 2012). First, the band-pass characteristics of the middle ear are roughly centered on 1 kHz and attenuate frequencies below that at 6 dB/octave. For a constant pressure, this inversely matches the increase in particle displacement so that for frequencies below 1 kHz, movement of the stapes and the amplitude of displacement input to the cochlea is constant. Second, low-frequency stimulation of the cochlea is reduced by the shunting of perilymph fluid between the chambers of the scala tympani and scala vestibuli through the helicotrema resulting in 6 dB/octave attenuation for frequencies less than 100 Hz. Third, the auditory transduction receptors, the inner hair cells (IHC) are sensitive to fluid velocity in the cochlea which results in a further attenuation of 6 dB octave below about 470 Hz. These three mechanisms add linearly to reduce stimulation of the IHC by 18 dB/octave between 100 Hz and 20 Hz.

Salt and Hullar (2010) make the important observation that as the outer hair cells (OHC) are sensitive to displacement (i.e., they are mechanically coupled and not fluid coupled to the tectorial membrane) which is constant for low frequencies, so even under physiologically normal conditions, at these low frequencies they should be stimulated at lower sound levels than the IHC. This prediction is borne out by the thresholds of endolymphatic potentials in the guinea pig cochlea to 5-Hz stimuli which represent strial current gated by OHC activity (Salt, Lichtenhan, Gill, & Hartsock, 2013). In contrast to the original estimates of OHC threshold (~40 dB lower than IHC at 5 Hz; Salt & Hullar, 2010), gain calculations in the later work suggest that the human apical cochlea could be similarly activated at around 55 dB to 65 dB SPL (corresponding to −38 to −28 dBA). This surprisingly high level of sensitivity of

OHCs to LF (when compared with IHC activation and perceptual threshold) is strongly supported by recent work examining the spontaneous otoacoustic emissions in humans (Drexl, Krause, Gürkov, & Wiegrebe, 2016; see also Drexl, Otto, et al., 2016; Jeanson, Wiegrebe, Gürkov, Krause, & Drexl, 2017; Kugler et al., 2014). It has been known for quite some time using human distortion product otoacoustic emissions (e.g., Hensel, Scholz, Hurttig, Mrowinski, & Janssen, 2007) as well as in vivo animal data (Patuzzi, Sellick, & Johnstone, 1984) that LF and IS do affect cochlear processing and that the cochlea aqueduct does pass IS frequencies into the inner ear (Traboulsi & Avan, 2007). The perceptual and other downstream consequences, however, are still not well studied. The more recent focus on the modulation of OHC activity is likely to provide important insights as to the physiological effects of IS and LF on cochlear processing. While the sensory role of OHCs are currently not well understood, they do carry sensory information via Type-II afferent fibers into the brain and probably play a role in signaling the off-set bias (and therefore operating point) of the basilar membrane and therefore also affect IHC transduction.

Before considering the effects of possible dysfunction of this system, it is worth summarizing the implications mentioned earlier. The healthy human ear significantly attenuates low-frequency input to the IHCs below around 100 Hz (~18 dB/octave). It is likely that at very low frequencies (<20 Hz), the OHCs are responding to stimuli at levels well below those producing activation of the IHCs. It is acoustic stimulation of the IHC which is the effective perceptual stimulus for hearing. Nonetheless, OHCs also have a sensory (afferent) input to the brain, although their stimulation is unlikely to lead to auditory perception per se. What is critical to emphasize at this juncture is that although the mechanisms outlined by Salt and Hullar (2010) are plausible and based on a large body of well-founded research, they do not by themselves constitute a demonstration of direct transduction of LF and IS by the inner ear. The effects of LF on OHC activity, however, could modulate transduction by the IHC, and such affects would likely be perceptible.

These data do provide, however, a strong prima facia case for neural transduction of LF and IS that needs to be properly examined at a functional and perceptual level in both animal and human models. Some critics of Salt and Hullar (2010) have argued that the level of LF and IS required to stimulate the OHCs is much greater than that recorded near wind farms. Given, however, the range of technical issues in making such acoustic measurements and the diversity of reported levels reviewed earlier, this claim is similarly limited by the available acoustic data. Furthermore, the recent work examining the guinea pig endocochlear potential (Salt et al., 2013) and human otoacoustic emissions (e.g., Drexl, Otto, et al., 2016; Kugler et al., 2014) indicate even greater levels of sensitivity of OHCs to LF when compared with the perceptual threshold mediated by IHC activity than first predicted. This suggests the need for a review of such conclusions.

Salt and Hullar (2010) also review the consequences of some pathologic conditions of the inner ear in terms of the potential to increase sensitivity to LF and IS. For instance, blockage or increased resistance of the helicotrema by a condition such as endolymphatic hydrops will reduce fluid shunting and reduce the attenuation for frequencies <100 Hz by up to 6 dB. Acute endolymphatic hydrops can be induced by exposure to low frequencies, although the relationship is complex and suggests that a dosimetry approach to exposure could be most informative. Hydrops would also lead to changes in the operating point of the basilar membrane resulting in a variety of changes in IHC sensory transduction including increased distortion. A further mechanism considered by Salt and Hullar is the increased fluid coupling of vestibular cells to sound input produced by changes in the input impedance of the vestibular system in conditions such as superior canal dehiscence (SCD), which can result in sound induced dizziness or vertigo, nausea, and nystagmus (Tullio phenomena).

Schomer et al. (2015) also examine potential physiological mechanisms that could mediate effects of LF and IS. They draw a link between the nauseogenic effects of low-frequency vestibular stimulation in seasickness and the potential vestibular stimulation by IS under normal listening conditions (as opposed to pathologic conditions of SCD). Using data collected by the U.S. Navy on nauseogenic effectiveness of low-frequency vestibular stimulation produced by whole body motion, they found significant overlap between the most effective nauseogenic frequencies and BPF of modern and larger WTs. Using a first-order model, they also demonstrate a better than order of magnitude equivalence between the force applied to the otoconia in the vestibular apparatus produced by whole body motion of 0.7 Hz at 5 m/s^2 peak and by IS of 0.7 Hz at 54 dB (SPL). Building on previous anatomical work (Uzun-Coruhlu, Curthoys, & Jones, 2007), Schomer et al. argue that pressure normal to the surface of the macular in the inner ear will provide an effective stimulus to the vestibular hair cells in the same way as the sheer motion between the otoconial membrane produced during linear acceleration of the head. While a plausible explanation, it is important to recognize that this suggestion is highly speculative and no data have yet been provided to support this latter assertion. Leventhall (2015) has also questioned this model although not in a peer-reviewed forum. Of note, however, the comparison with seasickness does add to the argument that a dosimetric approach to exposure may be more appropriate than measures of peak or root-mean-square sound pressure.

Perceptual Effects of Laboratory Exposure to LF and IS

A number of laboratory studies have directly exposed human listeners to IS and LF (e.g., Crichton, Dodd, Schmid, Gamble, & Petrie, 2014; Tonin, Brett, & Colagiuri, 2016) either directly recorded from WT (e.g., Yokoyama et al., 2014) or synthesized to reproduce key elements of these recordings (e.g., Tonin et al., 2016). A range of exposure symptoms have been reported but no systematic or significant effects of IS and LF have been demonstrated.

In general, sample sizes have been relatively small (e.g., $n = 2$, Hansen, Walker, et al., 2015; $n = 72$, Tonin et al., 2016) with studies likely to be statistically under powered (see Supplementary Material). Exposure times have been in the order of minutes to a few 10 s of minutes with a diversity of presentation levels above and below the IS/LF levels reported in the field.

Some free field stimulus playback systems have failed to deliver sound at the BPF and low-order harmonics frequencies (Yokoyama et al., 2014) while others have used headphone playback (Tonin et al., 2016). Many studies have not been blinded or double blinded, while others have been specifically designed to examine the effects of demand characteristics by manipulating expectancy (e.g., Crichton et al., 2014; Tonin et al., 2016). The latter studies have demonstrated, unsurprisingly, that manipulation of expectancy regarding the physiological effects of WT IS and LF has a moderate effect on the number and strength of symptoms reported by subjects regardless of the noise exposure conditions. Interestingly, Tonin et al. (2016) also report in their double-blind study that the presence of IS increased concern about health effects of WTN-expressed postexposure although subjects reported not hearing the IS stimulus.

In summary, there appears a prima facia case for the existence of sensory transduction of LF and IS and its representation in the nervous system. While a number of plausible mechanisms have been proposed, the actual mechanism of transduction has yet to be demonstrated. There are some laboratory-based studies examining the exposure to either recorded or simulated WTN, but the current data regarding potential perceptual or physiological are inconclusive.

General Summary and Conclusions

Although not an exhaustive survey of this literature, this review indicates that there are questions relating to the measurement and propagation of LF and IS and its encoding by the central nervous system (e.g., Dommes et al., 2009; Weichenberger et al., 2017) that are relevant to the possible perceptual and physiological effects of WTN but for which we do not have a good scientific understanding. There is much contention and opinion in these areas that, from a scientific perspective, are not well founded in the data, simply because there are little data available that effectively address these issues. This justifies a clear call to action for resources and support to promote high-quality scientific research in these areas.

Some of the research questions that arise from this review include the need for the following:

1. A more complete characterization and modeling of the sound generated by individual WTs and the large aggregations that comprise the modern windfarm. Such research needs to consider the spectrum from the BPF to its higher harmonics and incorporate the different propagation models that apply to different frequency ranges along with the effects of terrain, atmospheric conditions, and other potential modifiers of the sound.
2. The development of a more complete understanding of the interactions between WTN and the built structures in which people live and sleep. Such research needs to consider the different modes of excitation including substrate vibration, cavity resonances (including Helmholtz resonance and the interconnection of rooms), and differential building material sound insulation. New methods need to be developed for accurately and effectively measuring acute and chronic exposure (dosimetry) and for managing wind and other interference in the measurements.
3. Structural and aeronautic engineering research to discover ways to minimize the BPF generation and other potentially annoying sound sources.
4. Research to directly examine the effects of IS on the cochlea and vestibular apparatus. Although different theories have been advanced as to how IS and LF might be transduced and excite the central nervous system, there are little direct data demonstrating whether and how this occurs.
5. Research to better understand the neural connectivity of the putative transducers in the inner ear and an understanding of the consequences of their possible activation by IS and LF, notwithstanding the recent brain imaging data demonstrating differential activation of different brain structures (including the auditory cortex) by IS.
6. Research to better characterize the physiology of individuals who report susceptibility to WTN with a focus on whether these individuals represent a statistical tail of a normally distributed population or display other dysfunction or pathology that mediates susceptibility (e.g., SCD or lymphatic hydrops). In particular, an examination is required of the

hypothesis that small individual differences in threshold sensitivity to IS could underlie the differential activation of the anterior cingulate cortex and amygdala at subliminal sound levels.

This is not intended to be an exhaustive list of possible research areas. A research initiative to encourage and develop a very wide diversity of proposals is warranted as it is from the depth, capacity, and ingenuity of the researchers that work in these areas that the insights and the most effective research questions will come.

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EXHIBIT
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Infrasound From Wind Turbines Could Affect Humans

Alec N. Salt[1] and James A. Kaltenbach[2]

Abstract

Wind turbines generate low-frequency sounds that affect the ear. The ear is superficially similar to a microphone, converting mechanical sound waves into electrical signals, but does this by complex physiologic processes. Serious misconceptions about low-frequency sound and the ear have resulted from a failure to consider in detail how the ear works. Although the cells that provide hearing are insensitive to infrasound, other sensory cells in the ear are much more sensitive, which can be demonstrated by electrical recordings. Responses to infrasound reach the brain through pathways that do not involve conscious hearing but instead may produce sensations of fullness, pressure or tinnitus, or have no sensation. Activation of subconscious pathways by infrasound could disturb sleep. Based on our current knowledge of how the ear works, it is quite possible that low-frequency sounds at the levels generated by wind turbines could affect those living nearby.

Keywords

cochlea, hair cells, A-weighting, wind turbine, Type II auditory afferent fibers

Wind Turbines Generate Infrasound

The sounds generated by wind turbines vary widely, depending on many factors such as the design, size, rotor speed, generator loading, and different environmental conditions such as wind speed and turbulence (e.g., Jakobsen, 2005). Under some conditions, such as with a low wind speed and low generator loading, the sounds generated appear to be benign and are difficult to detect above other environmental sounds (Sonus, 2010).

But in many situations, the sound can contain a substantial low-frequency infrasound component. One study (Van den Berg, 2006) reported wind turbine sounds measured in front of a home 750 m from the nearest turbine of the Rhede wind farm consisting of Enercon E-66 1.8 MW turbines, 98 m hub height, and 35 m blade length. A second study (Jung & Cheung, 2008) reported sounds measured 148 to 296 m from a 1.5 MW turbine, 62 m hub height, 36 m blade length. In both these studies, which are among the few publications that report full-spectrum sound measurements of wind turbines, the sound spectrum was dominated by frequencies below 10 Hz, with levels of over 90 dB SPL near 1 Hz.

The infrasound component of wind turbine noise is demonstrated in recordings of the sound in a home with GE 1.5 MW wind turbines 1,500 ft downwind as shown in Figure 1. This 20-second recording was made with a microphone capable of recording low-frequency components. The sound level over the recording period, from which this excerpt was taken, varied from 28 to 43 dBA. The audible and inaudible (infrasound) components of the sound are demonstrated by filtering the waveform above 20 Hz (left) or below 20 Hz (right). In the audible, high-pass filtered waveform, the periodic "swoosh" of the blade is apparent to a varying degree with time. It is apparent from the low-pass filtered waveform that the largest peaks in the original recording represent inaudible infrasound. Even though the amplitude of the infrasound waveform is substantially larger than that of the audible component, this waveform is inaudible when played by a computer's sound system. This is because conventional speakers are not capable of generating such low frequencies and even if they could, those frequencies are typically inaudible to all but the most sensitive unless played at very high levels. It was also notable in the recordings that the periods of high infrasound level do not coincide with those times when the audible component is high.

This shows that it is impossible to judge the level of infrasound present based on the audible component of the sound. Just because the audible component is loud does not mean that high levels of infrasound are present. These measurements show that wind turbine sounds recorded inside a home can contain a prominent infrasound component.

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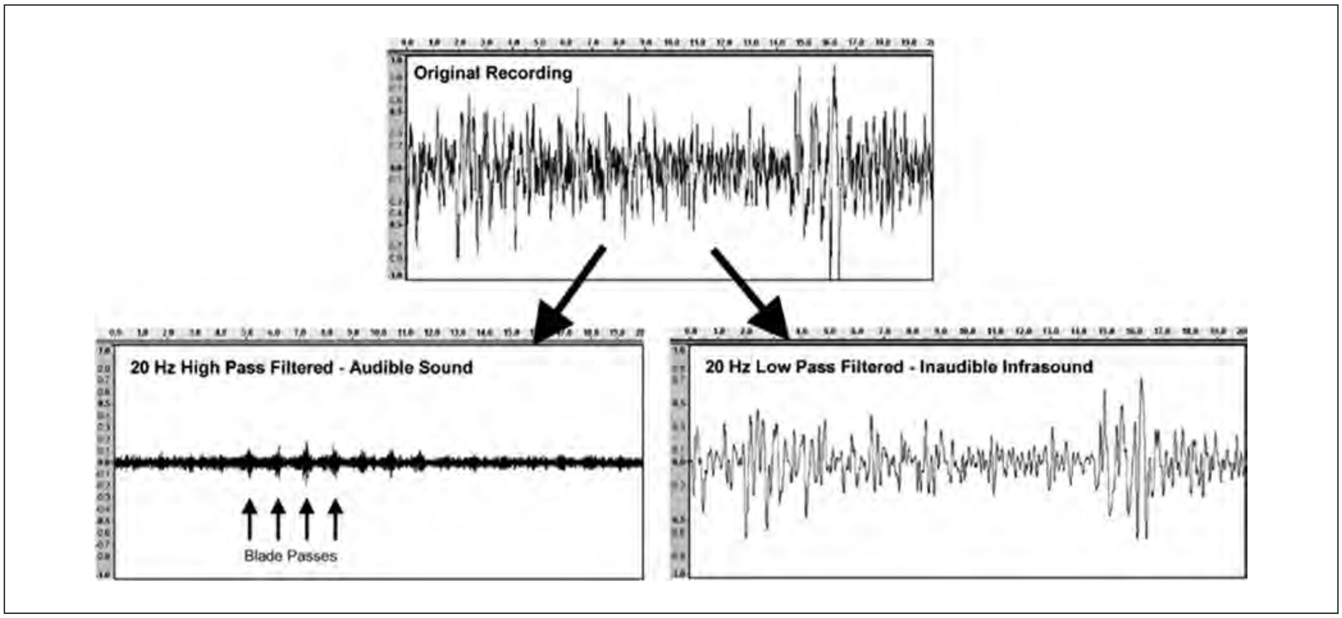

Figure 1. *Upper Panel:* Full-spectrum recording of sound from a wind turbine recorded for 20 seconds in a home with the wind turbine 1,500 ft downwind (digital recording kindly provided by Richard James). *Lower Left Panel:* Result of high-pass filtering the waveform at 20 Hz, showing the sound that is heard, including the sounds of blade passes. *Lower Right Panel:* Result of low-pass filtering the waveform at 20 Hz, showing the infrasound component of the sound

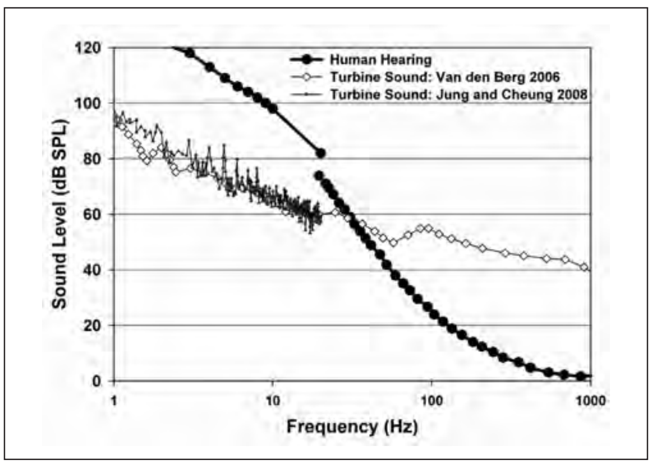

Figure 2. Wide band spectra of wind turbine sounds (Jung & Cheung, 2008; Van den Berg, 2006) compared with the sensitivity of human hearing (International Organization for Standardization, 2003, above 20 Hz; Møller & Pederson, 2004, below 20 Hz). The levels of sounds above 30 Hz are above the audibility curve and would be heard. Below 30 Hz, levels are below the audibility curve so these components would not be heard

Wind Turbine Infrasound Is Typically Inaudible

Hearing is very insensitive to low-frequency sounds, including those generated by wind turbines. Figure 2 shows examples of wind turbine sound spectra compared with the sensitivity of human hearing. In this example, the turbine sound components above approximately 30 Hz are above threshold and therefore audible. The sounds below 30 Hz, even though they are of higher level, are below the threshold of audibility and therefore may not be heard. Based on this comparison, for years it has been assumed that the infrasound from wind turbines is not significant to humans. Leventhall (2006) concluded that “infrasound from wind turbines is below the audible threshold and of no consequence.” (p.34) Leventhall (2007) further stated that “if you cannot hear a sound you cannot perceive it in other ways and it does not affect you.” (p.135)

Renewable UK (2011), the website of the British Wind Energy Association, quotes Dr. Leventhall as stating, “I can state quite categorically that there is no significant infrasound from current designs of wind turbines.” Thus, the fact that hearing is insensitive to infrasound is used to exclude the possibility that the infrasound can have any influence on humans. This has been known for many years in the form of the statement, “What you can’t hear can’t affect you.” The problem with this concept is that the sensitivity of “hearing” is assumed to equate with sensitivity of “the ear.” So if you cannot hear a sound then it is assumed that the sound is insufficient to stimulate the ear. Our present knowledge of the physiology of the ear suggests that this logic is incorrect.

The Ear Is Sensitive to Wind Turbine Infrasound

The sensory cells responsible for hearing are contained in a structure in the cochlea (the auditory portion of the inner ear) called the organ of Corti. This organ runs the entire length of the cochlear spiral and contains two types of sensory cells, which have completely different properties. There is one row

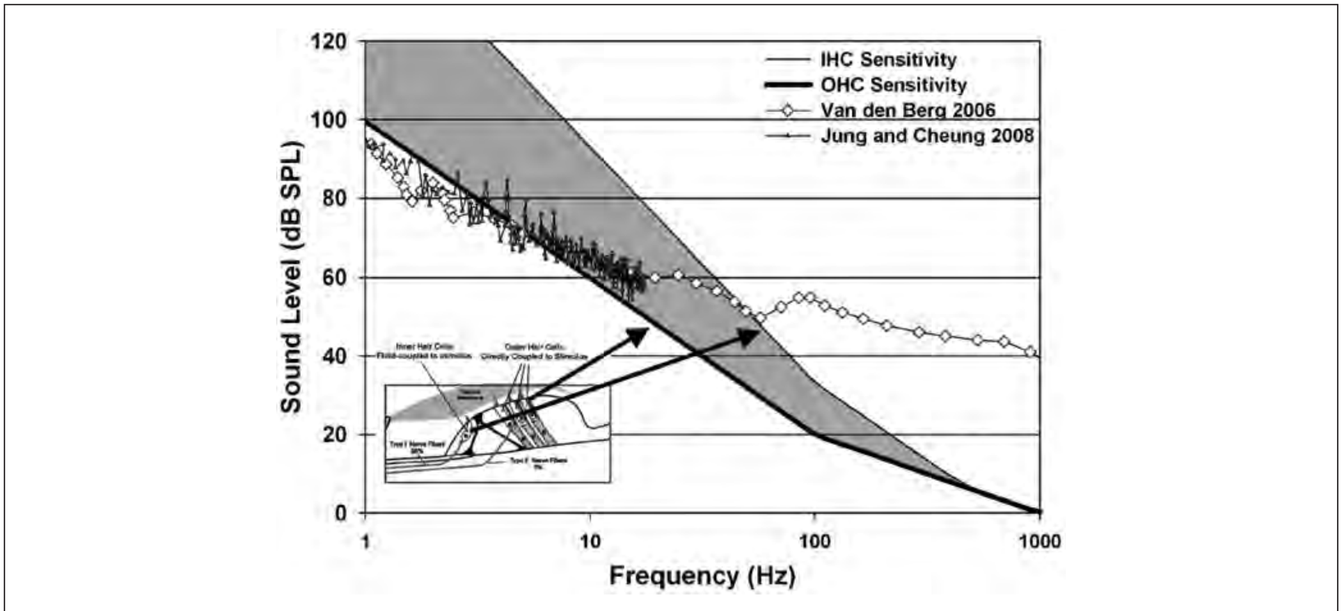

Figure 3. The thin line shows the estimated sensitivity of inner hair cells (IHC) as a function of frequency, which is comparable with the human audibility curve shown in Figure 2 and which is consistent with hearing being mediated by the IHC (based on Cheatham & Dallos, 2001). The thick line shows the estimated sensitivity of the outer hair cells (OHC), which are substantially more sensitive than the IHC. Sound components of the overlaid wind turbine spectra within the shaded region (approximately 5 to 50 Hz) are too low to stimulate the IHC and cannot therefore be heard but are of sufficient level to stimulate the OHC. The inset shows a cross section of the sensory organ of the cochlea (the organ of Corti) showing the locations of the IHC and OHC

of sensory inner hair cells (IHC) and three rows of outer hair cells (OHC) as shown schematically in the inset to Figure 3. For both IHC and OHC, sound-induced deflections of the cell's sensory hairs provide stimulation and elicit electrical responses. Each IHC is innervated by multiple nerve fibers that transmit information to the brain, and it is widely accepted that hearing occurs through the IHC. The rapidly declining sensitivity of hearing at lower frequencies (Figure 2) is accounted for by three processes that selectively reduce low-frequency sensitivity (Cheatham & Dallos, 2001), specifically the properties of middle ear mechanics, from pressure shunting through the cochlear helicotrema and from "fluid coupling" of the inner hair cell stereocilia to the stimulus (reviewed in detail by Salt & Hullar, 2010).

The combined effect of these processes, quantified by Cheatham and Dallos (2001), are shown as the "IHC sensitivity" curve in Figure 3. The last component attenuating low frequencies, the so-called fluid coupling of input, arises because the sensory hairs of the IHC do not contact the overlying gelatinous tectorial membrane but are located in the fluid space below the membrane.

As a result, measurements from the IHC show that they do not respond to sound-induced displacements of the structure but instead their amplitude and phase characteristics are consistent with them responding to the velocity of the stimulus. As stimulus frequency is lowered, the longer cycles result in lower stimulus velocity, so the effective stimulus falls by 6 dB/octave. This accounts for the known insensitivity of the IHC to low-frequency stimuli. For low frequencies, the calculated sensitivity of IHC (Figure 3) compares well with measures of hearing sensitivity (Figure 2), supporting the view that hearing is mediated by the IHC.

The problem, however, arises from the more numerous OHC of the sensory organ of Corti of the ear. Anatomic studies show that the sensory hairs of the OHC are embedded in the overlying tectorial membrane, and electrical measurements from these cells show their responses depend on the displacement rather than the velocity of the structure. As a result, their responses do not decline to the same degree as IHC as frequency is lowered.

Their calculated sensitivity is shown as the "OHC sensitivity" curve in Figure 3. It is important to note that the difference between IHC and OHC responses has nothing to do with frequency-dependent effects of the middle ear or of the helicotrema (the other two of the three components mentioned above). For example, any attenuation of low-frequency stimuli provided by the helicotrema will equally affect both the IHC and the OHC. So the difference in sensitivity shown in Figure 3 arises purely from the difference in how the sensory hairs of the IHC and OHC are coupled to the overlying tectorial membrane.

The important consequence of this physiological difference between the IHC and the OHC is that the OHC are stimulated at much lower levels than the IHC. In Figure 3, the portion of the wind turbine sound spectrum within the shaded region represents frequencies and levels that are too low to be heard, but which are sufficient to stimulate the OHC of the ear.

This is not confined to infrasonic frequencies (below 20 Hz), but in this example includes sounds over the range from 5 to 50 Hz. It is apparent that the concept that "sounds you can't hear cannot affect you" cannot be correct because it does not recognize these well-documented physiologic properties of the sensory cells of the inner ear.

Stimulation of OHC at inaudible, low levels can have potentially numerous consequences. In animals, cochlear microphonics demonstrating the responses of the OHC can be recorded to infrasonic frequencies (5 Hz) at levels as low as 40 dB SPL (Salt & Lichtenhan, in press). The OHCs are innervated by Type II nerve fibers that constitute 5% to 10% of the auditory nerve fibers, which connect the hair cells to the brainstem. The other 90% to 95% come from the IHCs. Both Type I (from IHC) and Type II (from OHC) nerve fibers terminate in the cochlear nucleus of the brainstem, but the anatomical connections of the two systems increasingly appear to be quite different. Type I fibers terminate on the main output neurons of the cochlear nucleus. For example, in the dorsal part of the cochlear nucleus, Type I fibers connect with fusiform cells, which directly process information received from the ear and then deliver it to higher levels of the auditory pathway. In contrast, Type II fibers terminate in the granule cell regions of the cochlear nucleus (Brown, Berglund, Kiang, & Ryugo, 1988). Some granule cells receive direct input from Type II fibers (Berglund & Brown, 1994). This is potentially significant because the granule cells provide a major source of input to nearby cells, whose function is inhibitory to the fusiform cells that are processing heard sounds. If Type II fibers excite granule cells, their ultimate effect would be to diminish responses of fusiform cells to sound. Evidence is mounting that loss of or even just overstimulation of OHCs may lead to major disturbances in the balance of excitatory and inhibitory influences in the dorsal cochlear nucleus. One product of this disturbance is the emergence of hyperactivity, which is widely believed to contribute to the perception of phantom sounds or tinnitus (Kaltenbach et al., 2002; Kaltenbach & Godfrey, 2008). The granule cell system also connects to numerous auditory and nonauditory centers of the brain (Shore, 2005). Some of these centers are directly involved in audition, but others serve functions as diverse as attentional control, arousal, startle, the sense of balance, and the monitoring of head and ear position (Godfrey et al., 1997).

Functions that have been attributed to the dorsal cochlear nucleus thus include sound localization, cancellation of self-generated noise, orienting the head and ears to sound sources, and attentional gating (Kaltenbach, 2006; Oertel & Young, 2004). Thus, any input from OHCs to the circuitry of the dorsal cochlear nucleus could influence functions at several levels.

A-Weighted Wind Turbine Sound Measurements

Measurements of sound levels generated by wind turbines presented by the wind industry are almost exclusively A-weighted and expressed as dBA. When measured in this manner, the sound levels near turbines are typically in the range of 30 to 50 dBA, making wind turbine sounds,

> about the same level as noise from a flowing stream about 50-100 meters away or the noise of leaves rustling in a gentle breeze. This is similar to the sound level inside a typical living room with a gas fire switched on, or the reading room of a library or in an unoccupied, quiet, air-conditioned office. (Renewable UK, 2011)

On the basis of such measurements, we would expect wind turbines to be very quiet machines that would be unlikely to disturb anyone to a significant degree. In contrast, the human perception of wind turbine noise is considerably different. Pedersen and Persson-Waye (2004) reported that for many other types of noise (road traffic, aircraft, railway), the level required to cause annoyance in 30% of people was over 70 dBA, whereas wind turbine noise caused annoyance of 30% of people at a far lower level, at around 40 dBA. This major discrepancy is probably a consequence of A-weighting the wind turbine sound measurements, thereby excluding the low-frequency components that contribute to annoyance. A-weighting corrects sound measurements according to human hearing sensitivity (based on the 40 phon sensitivity curve). The result is that low-frequency sound components are dramatically deemphasized in the measurement, based on the rationale that these components are less easily heard by humans. An example showing the effect of A-weighting the turbine sound spectrum data of Van den Berg (2006) is shown in Figure 4. The low-frequency components of the original spectrum, which resulted in a peak level of 93 dB SPL at 1 Hz, are removed by A-weighting, leaving a spectrum with a peak level of 42 dBA near 1 kHz. A-weighting is perfectly acceptable if hearing the sound is the important factor. A problem arises though when A-weighted measurements or spectra are used to assess whether the wind turbine sound affects the ear. We have shown above that some components of the inner ear, specifically the OHC, are far more sensitive to low-frequency sounds than is hearing. Therefore, A-weighted sounds do not give a valid representation of whether wind turbine noise affects the ear or other aspects of human physiology mediated by the OHC and unrelated to hearing. From Figure 3, we know that sound frequencies down to 3 to 4 Hz may be stimulating the OHC, yet the A-weighted spectrum in Figure 4 cuts off all components below approximately 14 Hz. For this reason, the determination of whether wind turbine sounds affect people simply cannot be made based on A-weighted sound measurements. A-weighted measurements are inappropriate for this purpose and give a misleading representation of whether the sound affects the ear.

Alternatives to A-weighting are the use of full-spectrum (unweighted), C-weighted, or G-weighted measurements. G-weighted measurements use a weighting curve based on the human audibility curve below 20 Hz and a steep cutoff above 20 Hz so that the normal audible range of frequencies is deemphasized. Although the shape of this function is arbitrary

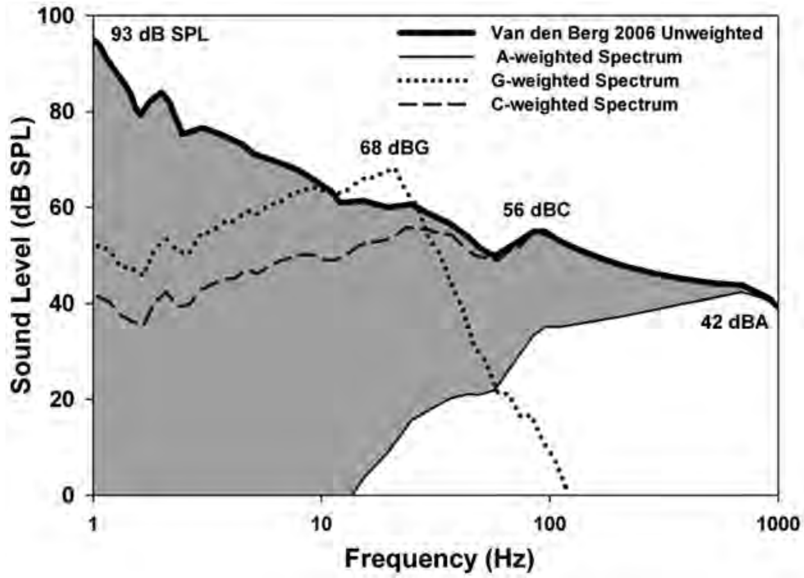

Figure 4. Low-frequency components of wind turbine sound spectrum (below 1 kHz) before and after A-weighting. The original spectrum was taken from Van den Berg (2006). The shaded area represents the degree of alteration of the spectrum by A-weighting. A weighting (i.e., adjusting the spectrum according to the sensitivity of human hearing) has the effect of ignoring the fact that low-frequency sounds can stimulate the OHC at levels that are not heard. Representing this sound as 42 dBA, based on the peak of the spectrum, ignores the possibility that low-frequency components down to frequencies as low as 5 Hz (from Figure 3) are stimulating the OHC. Also shown are the spectra after G-weighting (dotted) and C-weighting (dashed) for comparison

when hearing is not the primary issue, it does give a measure of the infrasound content of the sound that is independent of higher frequency, audible components, as shown in Figure 4. By applying the function to the normal human hearing sensitivity curve, it can be shown that sounds of approximately 95 dBG will be heard by humans, which agrees with observations by Van den Berg (2006). Similarly, by G-weighting the OHC sensitivity function in Figure 3, it can be estimated that sound levels of 60 dBG will stimulate the OHC of the human ear. In a survey of infrasound levels produced by wind turbines measured in dBG (Jakobsen, 2005), upwind turbines typically generated infrasound of 60 to 70 dBG, although levels above and below this range were observed in this and other studies. From Jakobsen's G-weighted measurements, we conclude that the level of infrasound produced by wind turbines is of too low a level to be heard, but in most cases is sufficient to cause stimulation of the OHC of the human ear. C-weighting also provides more representation of low-frequency sound components but still arbitrarily de-emphasizes infrasound components.

Is the Infrasound From Wind Turbines Harmful to Humans Living Nearby?

Our present understanding of inner ear physiology and of the nature of wind turbine sounds demonstrates that low-level infrasound produced by wind turbines is transduced by the OHC of the ear and this information is transmitted to the cochlear nucleus of the brain via Type II afferent fibers. We therefore conclude that dismissive statements such as "there is no significant infrasound from current designs of wind turbines" are undoubtedly false. The fact that infrasound-dependent information, at levels that are not consciously heard, is present at the level of the brainstem provides a scientific basis for the possibility that such sounds can have influence on people. The possibility that low-frequency components of the sound could contribute both to high annoyance levels and possibly to other problems that people report as a result of exposure to wind turbine noise cannot therefore be dismissed out of hand.

Nevertheless, the issue of whether wind turbine sounds can cause harm is more complex. In contrast to other sounds, such as loud sounds, which are harmful and damage the internal structure of the inner ear, there is no evidence that low-level infrasound causes this type of direct damage to the ear. So infrasound from wind turbines is unlikely to be harmful in the same way as high-level audible sounds.

The critical issue is that if the sound is detected, then can it have other detrimental effects on a person to a degree that constitutes harm? A major complicating factor in considering this issue is the typical exposure duration. Individuals living near wind turbines may be exposed to the turbine's sounds for prolonged periods, 24 hours a day, 7 days a week for weeks, possibly extending to years, although the sound level will vary over time with varying wind conditions. Although there have been many studies of infrasound on humans, these have typically involved higher levels for limited periods (typically of up to 24 hours). In a search of the literature, no studies were found that have come close to replicating the long-term exposures to low-level infrasound experienced by those living near wind turbines. So, to date, there are no published studies showing that such prolonged exposures do not harm humans. On the other hand, there are now numerous reports (e.g., Pierpont, 2009; Punch, James, & Pabst, 2010), discussed extensively in this journal, that are highly suggestive that individuals living near wind turbines are made ill, with a plethora of symptoms that commonly include chronic sleep disturbance. The fact that such reports are being dismissed on the grounds that the level of infrasound produced by wind turbines is at too low a level to be heard appears to totally ignore the known physiology of the ear. Pathways from the OHC to the brain exist by which infrasound that cannot be heard could influence function. So, in contrast, from our perspective, there is ample evidence to support the view that infrasound could affect people, and which justifies the need for more detailed scientific studies of the problem. Thus, it is possible that people's health could suffer when turbines are placed too close to their homes and this becomes more probable if sleep is disturbed by the infrasound. Understanding these phenomena may be important to deal with other sources of low-frequency noise and may establish why some individuals are more sensitive than others. A better understanding may also allow effective procedures to be implemented to mitigate the problem.

We can conclude that based on well-documented knowledge of the physiology of the ear and its connections to the brain, it is scientifically possible that infrasound from wind turbines could affect people living nearby.

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EXHIBIT
21

WIND TURBINES AND GHOST STORIES: THE EFFECTS OF INFRASOUND ON THE HUMAN AUDITORY SYSTEM

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Introduction

Climate change and fossil fuel depletion have pushed many countries to seek and invest in alternative clean energy sources, such as wind energy. By converting kinetic energy from the wind into mechanical or electrical energy, wind farms in California, for example, power nearly 850,000 households each year, while producing negligible green house gases and contributing little to water pollution[1] (see Fig. 1). Nevertheless, several ecological and environmental concerns remain. High levels of infrasound and low frequency sounds generated by wind turbines pose a potentially serious threat to communities near wind farms. Wind energy companies remain largely dismissive, claiming that wind turbine noise is subaudible, undetectable by humans, and therefore presents minimal risk to human health. However, various cochlear microphonic, distortion product otoacoustic emission, and functional magnetic resonance imaging (fMRI) studies have demonstrated the detection of infrasound by the human inner ear and auditory cortex. Additional psychosomatic stress and disorders, including the "wind turbine syndrome" and paranormal experiences, are also linked to infrasound exposures.[2,3] With wind turbines generating substantial levels of infrasound and low frequency sound, modifications and regulations to wind farm engineering plans and geographical placements are necessary to minimize community exposure and potential human health risks.

"...studies provide strong evidence for infrasound impact on human peripheral and central auditory responses."

Infrasound definition

It is popular belief that the audio frequency range of human hearing is from 20 to 20,000 Hz and that anything beyond these limits is undetectable by humans. Infrasound is the term that describes the "inaudible" frequencies below 20 Hz. Such a belief is based on the steep slope of hearing thresholds toward the lower end of the human hearing range.[4,5] At 1 kHz, the sound pressure level (SPL) necessary to perceive a 10 phon sound is 10 dB SPL. At 20 Hz, the minimum SPL for 10 phon sound perception has increased to about 84 dB SPL. The phon is a unit that describes perceived loudness level. With decreasing frequencies, the SPLs necessary for sound perception increase rapidly, making very low frequencies at a normally audible intensity more difficult to detect than higher frequencies of the same intensity. Humans' lack of sensitivity to low frequencies is also reflected in the compression of hearing thresholds. At 1 kHz, the SPLs capable of triggering hearing range from 4 to more than 100 dB SPL, exceeding 100 dB in span and increasing at 10 dB/phon. In contrast, the SPL range at 20 Hz is from approximately 80 to 130 dB SPL, spanning only about 50 dB and increasing at 5 dB/phon.[4] In other words, a relatively small increase in SPL at 20 Hz would

Fig. 1. San Gorgonio Pass Windfarm in Riverside County, California. With more than 2,000 wind turbines installed, this windfarm produces enough electricity to power Palm Springs and the entire Coachella Valley.[28] Photograph by Annie Chen

change the perception of this tone from barely audible to very loud. On the other hand, perceivable changes in loudness level at 1 kHz would require larger changes in SPL. The combination of SPL threshold increase and range compression results in poor intensity discrimination at low-frequencies in most people.

However, this audio frequency range is misleading and variable, as inter-individual differences in hearing sensitivity allow some people to detect the "inaudible." Human hearing thresholds have been reported for frequencies from slightly below 20 Hz to as low as 2 Hz in some cases.[6,7] Furthermore, humans encounter and detect many high level infrasound sources on a regular basis, despite their high thresholds.[5] Auditory cortical responses and cochlear modulations to infrasound exposure have also been observed, despite the subjects' lack of tonal perception.[8,9] These studies provide strong evidence for infrasound impact on human peripheral and central auditory responses.

Infrasound impact on inner ear responses

While normal sound perception depends on inner hair cell (IHC) function, human sensitivity to infrasound and low frequencies is thought to rely heavily on outer hair cells (OHCs).[10] Such differential sensitivity between inner and outer hair cells stems from their distinct relationship to the surrounding inner ear structures. Although IHCs and OHCs both sit atop the basilar membrane, the hair (stereovillar) bundles of the OHCs are embedded in the overlying tectorial membrane, unlike those of the IHCs. Instead, IHC hair bundles are bathed in endolymphatic fluid within the subtectorial space and depend on this fluid movement ("squeezing waves") for their stimulation.[11] Mechanical energy must be transferred from the basilar and tectorial membranes to the endolymph to displace the IHC hair bundles. Basilar membrane velocity, however, decreases with decreasing stimulus frequency.[12] At infrasonic frequencies, the low fluid velocity may effectively eliminate IHC hair bundle displacement by fluid motion, rendering IHCs insensitive to infrasound.

In contrast, OHC stereovilli are stimulated directly by the motion of the basilar membrane relative to the tectorial membrane, as they are embedded in the overlying tectorial membrane. The vibrational amplitude of the basilar membrane is proportional to sound pressure level and inversely proportional to frequency.[11-13] OHCs' direct coupling to tectorial membrane movements results in its maintained sensitivity to low-frequency sounds; whereas IHCs' indirect coupling to velocity through fluid movements results in lowered sensitivity. As low-frequency sounds generate significant basilar membrane displacements but low basilar membrane velocities, OHCs are selectively stimulated over IHCs. Furthermore, low-frequency sounds generate minimal endolymphatic viscous forces, allowing maximal stretching of stereovillar tip links for OHC depolarization.[14] It is important, therefore, to keep in mind that high-level, low-frequency stimuli can result in large shearing forces on the OHC stereovilli, but minimal fluid-coupled displacements of IHC stereovilli.

Low-frequency induced OHC intracellular depolarization can be measured as an extracellular voltage change, namely the cochlear microphonic (CM). At 10 Hz (90 dB SPL), CM amplitudes exceed that of the IHC intracellular potentials as a result of basilar membrane displacement.[10,15] CM generation in response to this 10 Hz tone provides concrete evidence for OHC sensitivity to infrasound in the guinea pig. Meanwhile, large CMs generated by OHCs at 40 Hz (112 dB SPL) can electrically stimulate the IHCs to activate type I afferent fibers in the spiral ganglion.[15,16] While type I afferent activation by infrasound has not yet been extensively studied, these data suggest that infrasound has the potential to induce suprathreshold depolarization in IHCs and type I afferent fibers, through large CMs. Subsequent transmission and interpretation of type I afferent signals in the brain would be especially interesting to examine.

In addition to CMs, distortion product otoacoustic emissions (DPOAEs) have also demonstrated human inner ear sensitivity to infrasound. DPOAE recordings allow non-invasive, indirect evaluations of cochlear amplifier characteristics. To elicit DPOAEs, two different pure tones (primaries), f_1 and f_2, are introduced into the ear by placing into the ear canal a sound probe containing two miniature speakers. As the primaries-generated traveling waves propagate along the basilar membrane, they interact and produce additional traveling waves.[17] These waves propagate out of the inner ear, generating DPOAEs that are recorded by a microphone in the sound probe. The most prominent and easily measurable DPOAE in humans and other animals is the cubic difference distortion product, $2f_1$-f_2, typically produced by primary tone ratios (f_2/f_1) between 1.2 to 1.3.[18]

Hensel *et al.* (2007) used primaries of f_1=1.6 and f_2=2.0 kHz (f_2/f_1=1.25) at L_1=51 and L_2=30 dB SPL for their DPOAEs recordings.[8] With the primaries within the normal human audio frequency range, the returning DPOAE represents a typical operating point of the cochlear amplifier. Infrasonic biasing tones (f_b) of 6 Hz, 130 dB SPL and 12 Hz, 115 dB SPL were then introduced and resulting DPOAEs were recorded. When compared to the primaries-only-generated DPOAE pattern, f_b-generated DPOAEs showed significant changes in amplitude and phase due to the shifting of the cochlear amplifier operating point. Since the f_b-generated DPOAE pattern changed relative to the pattern evoked by the primaries-only-generated DPOAES, it may be then concluded that the infrasonic biasing tones had an observable impact on inner ear function.

High level biasing tones provide large vibrational amplitudes that can alter the movement of the cochlear partition, or net pressure across it. The induced pressure gradient in turn shifts the mean position (a DC shift) of the basilar membrane. Such a phenomenon parallels the slow motility mechanism of OHCs. Just as OHC soma contractions alter the dimensions of the subtectorial space to enhance or reduce hearing sensitivity, the shift in basilar membrane position also changes subtectorial volume and adjusts hearing sensitivity. In another words, the gain of the cochlear system can be affected by high level infrasound. Moreover, the modulations seen in f_b-generated DPOAEs reflect differential traveling wave interactions as the result of basilar membrane displacement.

Although the SPLs used for the low-frequency biasing tones approached the pain threshold for human hearing at 1 kHz, the biasing tones did not damage the subjects' cochlear integrity, as shown by consistent primaries-generated DPOAEs before and after biasing tone presentations. None of the subjects reported painful pressure at the eardrum during the experiment. While the biasing tones' high SPLs create large pressure differences in the ear, the sensation of pain may have been reduced by the tones' low vibrational velocity. It was also reported that some subjects perceived a "weak but clearly audible sound sensation, described as humming" but not a "tonal audible stimulus."[7,8,19] The absence of a clear pure-tone percept suggests that infrasonic frequencies do not adequately stimulate the IHCs and hence may not be the sources of the humming. Rather, the source of this percept is likely to be the harmonics of the biasing tone.[20]

Infrasound processing by the auditory pathway

An fMRI study by Dommes *et al.* offers additional insight to infrasound responses in humans.[9] When presented with tones of 12 Hz at 110 and 120 dB SPL, the subjects showed bilateral activation in the primary and secondary auditory cortices (superior temporal gyrus, Brodmann's Area 41, 42, 22). The subjects were also exposed to tones in the human audible frequency range, 500 Hz at 105 dB SPL and 48 Hz at 100 dB SPL. The cortical sites activated for all these frequencies were similar, suggesting that infrasound can have a major impact on brain activation via the auditory pathway. When the 12 Hz tone was reduced to 90 dB SPL, the auditory cortex showed no significant activity, except in one subject. This observation supports the idea of inter-individual differences in low-frequency sensitivity.

Intrinsic noise of fMRI machines can present severe experimental constraints. The scanner noise spectra showed frequencies from 3-10 Hz and 50-900 Hz at levels between 60-75 dB SPL and 60-80 dB SPL, respectively. While infrasound noise remained estimated below threshold,[19] noise between 50-900 Hz was audible and may have affected brain activities. However, Dommes *et al.* believe that the auditory cortex can distinguish and dismiss such background noise.[9] Infrasonic tones must also be presented at high levels in order to overcome fMRI machine background noise. At high levels, the tones produce increased harmonic distortion resulting in high level and more easily detectable harmonics that can potentially alter fMRI results. To evaluate the effects of harmonics, a 36 Hz tone (third harmonic) at 70 dB SPL was presented as a fundamental frequency to the subjects. Auditory cortical activation was observed, though noticeably less than that evoked by a 12 Hz tone at 120 dB SPL. Dommes *et al.* concluded that infrasonic frequencies themselves play significant roles in activating the auditory cortex.[9]

Infrasound exposure on physical and psychological health

Although current research provides no conclusive evidence for infrasound hearing perception by humans, it is nevertheless a worthy exercise to investigate infrasound sources in the immediate environment, as they may contain detectable harmonics. Typical infrasound sources include ocean waves, thunder, wind, machinery engines, slow speed fans, and driving a car with open windows.[5,19] As pure tones are rarely generated in nature, these infrasonic sources typically generate multiple harmonic components and other background noise. It is not unlikely for humans to be exposed to high levels of infrasound. For example, a child on a swing may experience infrasound around 0.5 Hz at 110 dB SPL.[5]

One of the most heavily studied infrasound sources is wind farms. Many wind turbine companies claim that an operating wind farm produces negligible "whooshing" sounds that are comparable only to a kitchen refrigerator around 45 dB SPL.[1,21] However, these claims are based on A-weighted sound analysis, which removes all infrasound components from wind turbine broadband noise. A-weighted filters are inadequate evaluations because they assume human insensitivity to infrasound. Wind turbine spectral analysis by Jung and Cheung has revealed substantial noise levels between 60 to 100 dB SPL for frequencies below 20 Hz.[22] As demonstrated by CMs, DPOAE modulations, and fMRI studies, high levels of infrasound can alter cochlear function and activate the auditory cortex. Potential long term changes in brain activity by nearby wind farms have raised serious concerns. Some physical and psychological health risks from infrasound exposures include the "wind turbine syndrome" and paranormal experiences.[2,10,23,24]

Symptoms of the wind turbine syndrome include sleep disturbance, headache, annoyance, irritability, and chronic fatigue. The symptoms often surface when one is close to wind turbines, or an infrasound source, and disappear when the person moves away. As reported, a family exposed continuously to 10 Hz at 35 dB SPL produced by a boiler house complained of bodily pains, increased annoyance, and difficulties sleeping.[5] This family's high sensitivity to a supposedly subthreshold stimulus supports the notion that inter-individual differences are real and that some individuals are more sensitive and susceptible to the effects of low level infrasound than others. In another study, Pedersen *et al.* interviewed 70,000 adults living within 2.5 km of wind farms.[3] They found that adults exposed to levels of A-weighted noise of 40-50 dB SPL reported higher levels of annoyance than those exposed to levels below 40 dB SPL. Moreover, 12% of the subjects exposed to noise at 40-45 dB SPL reported feeling "very annoyed" versus only 6% from subjects exposed to 35-40 dB SPL; in these cases, individual psychological distress due to wind turbine noise is evident. As audible noise levels increase with increasing proximity to wind turbines, the levels of the infrasonic components also increase. Most subjects described the noise as "swishing/lashing," rather than a pure tone sensation. The discontinuity in sound perception can be attributed the inner ear's increased sensitivity to the infrasonic harmonics, as suggested by Hensel *et al.*'s study.[8] When compared to road traffic noise of similar levels, the subjects reported higher annoyance levels from wind turbines. The high annoyance levels are in part due to the ubiquitous presence of wind turbine sounds throughout the day and night, unlike the road traffic noise which abated at night. Additionally, the inherent, high levels of infrasound in wind turbine noise may also modulate brain activity and increase annoyance levels.

In his famous "ghost-buster" study, Tandy recorded a continuous infrasound emission in a 14th century cellar near Coventry University, England.[2] The cellar has been rumored to be haunted since 1997. Various local visitors reported "very strong feeling of presence," "cold chill," and apparitions upon entering the cellar. Moreover, tourists who have never heard of the rumors also reported paranormal experiences. Tandy's previous study in a supposedly haunted laboratory revealed a steady 18.9 Hz emission by a laboratory machine.[24] Once the machine was turned off, reports of paranormal sensations and sightings also ceased. Assuming a similar phenomenon in the cellar, Tandy used broadband sound level meters and recorded a distinct 19 Hz spectral peak in the ambient noise at 38 dB SPL. Other background infrasound signals were also recorded at very low levels between 7-30 dB SPL. Given the variable sensitivities to ultra-low frequencies demonstrated by Dommes *et al.*,[9] the 19 Hz may have had an effect on sensitive visitors and evoked abnormal experiences.

Since the 19 Hz was significantly below its audible threshold, visitors' paranormal experiences could be due to changes in brain activities, despite the absence of tonal perceptions. It is known that temporal lobe epilepsy patients suffer from high risks of depression, anxiety, irritability, insomnia, and psychosis.[25,26] This suggests that hyper or abnormal activity patterns in the temporal lobe, which includes the primary and secondary auditory cortex, could be linked to the psychiatric symptoms observed in the wind turbine syndrome and paranormal experiences.

Conclusions and future directions for infrasound research

Based on CM and DPOAE modulation studies, infrasonic frequencies can have clear effects on human cochlear state and function. Contrary to the belief that the inner ear does not register infrasound, it was found that infrasound can actually be detected by the OHCs. As OHC slow motility controls hearing sensitivity, the responsiveness of these sensory cells to infrasound could potentially enhance one's ability to perceive infrasound's higher harmonics. Whether OHC-generated CMs can trigger spike generation in IHCs' type I auditory nerve fibers, resulting in direct perception of infrasonic frequencies, is a major research focus today. Infrasound induced OHC activation of auditory nerves presents an alternative pathway of focus, as about 5% of all type I afferent fibers synapse with OHCs.[26] High levels of infrasound have been shown to induce shifts in the basilar membrane position, modulating DPOAE patterns. The shift in basilar membrane parallels the function of OHC slow motility by altering subtectorial space. As changes in subtectorial space affect IHC sensitivity, Hensel *et al.* concluded that infrasound itself can affect the overall gain of the cochlear system.[8]

Knowledge gaps between changes in cochlear function, auditory cortical activity, and sound perception remain. As *in vivo* electrophysiology of human auditory afferent fibers is ethically unacceptable, self-reported sound perceptions and fMRI scans dominate current experimental efforts. While Dommes *et al.* showed significant auditory cortical activity in response to infrasound,[9] additional studies are needed to corroborate their findings. For example, activity in primary somatosensory cortex (Brodmann's Area 2, 3) should be examined and compared to that in the auditory cortex. This would reveal whether the auditory or vestibular pathway plays the more important role in human infrasound detection. In addition, subjects' hearing perceptions during fMRI-infrasound scans should be reported, as done by Hensel *et al.*[8] Since auditory cortical activity increased significantly in response to a 12 Hz tone compared to its lower-level 36 Hz harmonic, infrasound detection in humans may be more common than previously thought. In future experiments, should the subjects report tonal or humming perceptions, along with pronounced auditory cortical activities, then it may be that infrasound itself triggers the perception, as opposed to its harmonics. If the subjects do not report any perceptions, auditory cortical activity could be considered unrelated to the stimulus.

Psychosomatic health risks have been proposed to be the result of infrasound exposure, as changes in temporal lobe activity have been linked to several psychiatric disorders. With nearby communities reporting annoyance toward wind turbine noise, further studies are needed to examine the effects of wind farms on the quality of life in sensitive individuals. Long-term studies on wind turbine noise exposure are also needed. As wind energy is widely accepted for its promising role in clean energy production, putting a hold on wind farm development is highly unlikely. For now, engineering efforts and isolated geographical placements of wind farms serve as the best methods for minimizing community exposure to substantial and potentially harmful levels of wind turbine noise.**AT**

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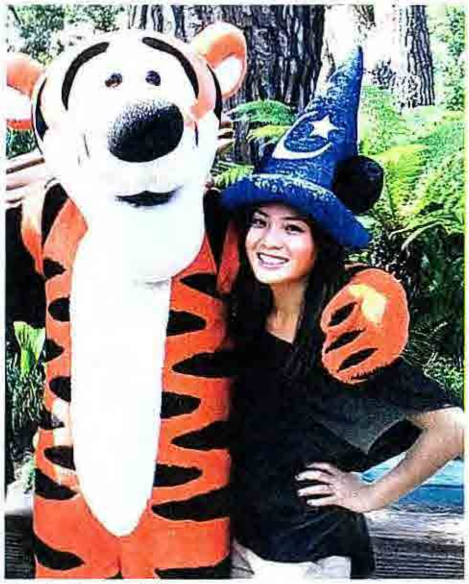
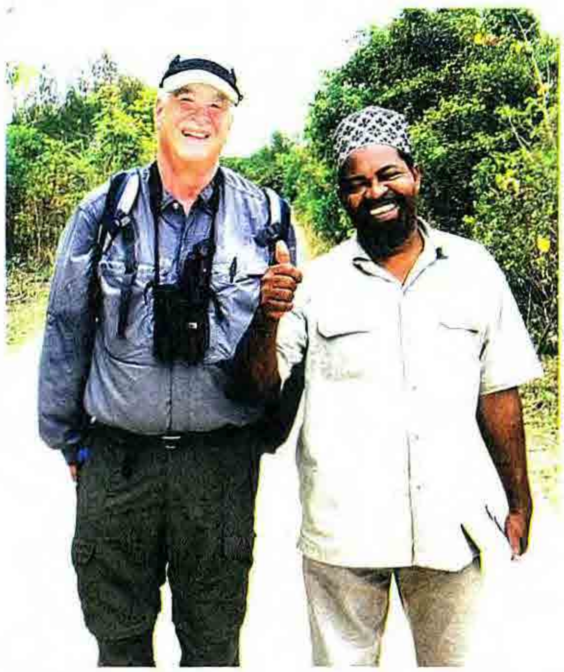


Annie Chen and friend

Hsuan-hsiu Annie Chen was born in Taipei, Taiwan and moved to San Jose, California when she was ten years old. Annie will be graduating from the University of California, Los Angeles (UCLA) with a B.S. in Neuroscience with honors in spring 2012. In addition, Annie has completed her honors research in bipolar disorder neuroimaging and is an American Heart Association certified cardiopulmonary resuscitation (CPR) and First Aid instructor. In her spare time, Annie enjoys playing tennis, going to Disneyland, and is an occasional freelance event and portrait photographer.



Peter Narins and friend

Peter M. Narins received his B.S. and M.E.E. in Electrical Engineering and his Ph.D. in Neurobiology & Behavior from Cornell University, Ithaca. He is currently a Distinguished Professor of Neuroethology in the Department of Integrative Biology & Physiology at the University of California, Los Angeles (UCLA). His research explores the mechanisms underlying the evolution of sound and vibration communication in amphibians and mammals. He has led or participated in more than 50 scientific overseas research expeditions to seven continents plus Madagascar, and has lectured on the evolution of communication systems both in English worldwide and in Spanish to universities throughout Latin America and Spain. He is an editor of the *Journal of Comparative Physiology*, and has received the Senior U.S. Scientist Award of the Alexander von Humboldt Foundation and a Fulbright Award (Montevideo, Uruguay). He was elected Fellow of the Guggenheim Foundation, Acoustical Society of America, Animal Behavioral Society, and the American Association for the Advancement of Science (AAAS). He is an Honorary Member of the Cuban Zoological Society and Professor *Ad Honorem* at the University of the Republic, Montevideo, Uruguay.

EXHIBIT
22

Perception-based protection from low-frequency sounds may not be enough

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Hearing and perception in the mammalian ear are mediated by the inner hair cells (IHC). IHCs are fluid-coupled to mechanical vibrations and have been characterized as velocity-sensitive, making them quite insensitive to low-frequency sounds. But the ear also contains more numerous outer hair cells (OHC), which are not fluid coupled and are characterized as displacement sensitive. The OHCs are more sensitive than IHCs to low frequencies and respond to very low-frequency sounds at levels below those that are perceived. OHC are connected to the brain by type II afferent fibers to networks that may further attenuate perception of low frequencies. These same pathways are also involved in alerting and phantom sounds (tinnitus). Because of these anatomic configurations, low-frequency sounds that are not perceived may cause influence in ways that have not yet been adequately studied. We present data showing that the ear's response to low-frequency sounds is influenced by the presence of higher-frequency sounds such as those in the speech frequency range, with substantially larger responses generated when higher-frequency components are absent. We conclude that the physiological effects of low-frequency sounds are more complex than is widely appreciated. Based on this knowledge, we have to be concerned that sounds that are not perceived are clearly transduced by the ear and may still affect people in ways that have yet to be fully understood.

1 INTRODUCTION

The manner in which the inner ear responds to very low-frequency sounds is still not well characterized. The pertinent anatomy and physiology is diagrammed in Figure 1. When sounds enter the cochlea they stimulate different regions, depending on the frequency, or tone, of the sound. The basilar membrane has a low-pass filter characteristic, such that the basal turn can respond to all frequencies while higher frequency components are progressively filtered out towards the apex. The apical regions are where mechanical-to-electrical transduction occurs for

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only the low-frequency components of acoustic sound. Superimposed on the passive mechanical filtering are cochlear hair cells that amplify low-level sounds for detection. This mechanical amplification is performed by the outer hair cells (OHC) so that the signal can be detected by the inner hair cells (IHC) that are the true sensory cells of the ear. The IHCs are densely innervated by type I primary afferent fibers, which is why it is generally accepted that hearing and perception are mediated by IHC activity. An important feature of the IHCs is that their sensory stereocilia ("hairs") do not contact the overlying tectorial membrane. They are therefore fluid coupled to the mechanical vibrations and have been characterized as velocity-sensitive, or ac-coupled[1]. That is to say, high-frequency vibrations stimulate IHCs but low-frequency vibration is attenuated, making IHCs insensitive to very low-frequency sounds. This contributes to the insensitivity of mammalian hearing to very low-frequency sounds and infrasound, requiring high levels to be heard. However, this is not to say that the ear itself is insensitive to very low-frequency sounds and infrasound. The stereocilia of the OHC are directly coupled to the tectorial membrane so they receive mechanical input in a displacement-sensitive manner. In early studies, Békésy[2] showed that displacements of the basilar membrane by trapezoidal stimuli generated trapezoidal response potentials that were sustained for the duration of the stimulus. The OHCs are thus dc-coupled to input and therefore highly sensitive to low-frequency stimulation. The OHC are, in part, connected to the brain by the type II afferents which make up approximately 5% of the afferent fibers in the auditory nerve. Each type II fiber contacts multiple OHC. Although no one has ever reported recordings from type II fibers with infrasound stimulation, Schermuly and Klinke[3] have shown that similar fibers in the bird, that innervate multiple hair cells, are highly sensitive to infrasound input.

Studies have suggested that the perception of low-frequency sounds by humans is influenced by the presence of higher-frequency sounds. Krahé[4,5] found that the perception of low-frequency noise alone was rated to be more annoying than low-frequency noise presented with higher-frequency sounds. These studies suggest that the perceptual consequences of low-frequency sounds should not be studied without considering the combined effects of higher-frequency sounds such as those in the range of speech.

Here we report objective measures from the low-frequency regions of the cochlea. They offer support for hypotheses that the influence of high-frequency sounds on the perception of low-frequency sounds is rooted in a cochlear mechanism in which the OHCs near the apex are stimulated by low frequency sounds more intensely than previously understood.

2 METHODS

Stimulus generation and response acquisition were performed using Tucker-Davis System 3 hardware controlled by custom-written software on a personal computer. Sound stimuli were delivered in a closed system using a hollow ear bar between the transducers and the external ear canal of anesthetized guinea pigs. Full details of stimulus delivery and presentation are given elsewhere[6]. Cochlear responses were measured from 500 mM KCl-filled glass pipettes inserted into endolymph of the cochlear third turn and connected through a high-input impedance electrometer. All procedures were approved by the Animal Studies Committee of Washington University under protocols 20070147 and 20100135.

3 RESULTS

3.1 Suppression of Infrasonic-Tone-Response by a Higher-Frequency Tone

The response of the apical, low-frequency regions of the cochlea to low-frequency sounds is complex. Responses are large when the sound is dominated by low frequencies and become smaller when higher-frequency sounds are present. In Figure 2, the response to an infrasonic (5Hz, 90 dB SPL) tone was recorded from endolymph of the third cochlear turn while a higher frequency (500 Hz) tone was superimposed after 1 second. As the level of the 500 Hz tone was increased from 50 to 80 dB SPL, the response to the 5 Hz stimulus was dramatically suppressed. Suppression of the infrasound response occurred at stimulus levels well below those that saturate the mechanical-to-electrical hair cell transducers of the inner ear (Figure 2, lower left panel), meaning that the suppression is not a result of transducer saturation.

3.2 Low-Pass Noise: A Variant of Infrasonic-Tone-Response Suppression

Responses to low-pass filtered noise were measured with electrodes located in the basal turn (sensitive to high frequency sounds) and in the third cochlear turn (sensitive to low-frequency sounds). All recordings were made with electrodes located in the endolymphatic compartment of the guinea pig inner ear. The sound stimuli used are shown in Figure 3. White noise stimuli were generated and digitally low-pass filtered with a cutoff slope of approximately 55 dB/octave. The noise was digitally generated "frozen noise" so that it had the characteristics of white noise but was exactly repeatable for each of the low-pass filtered conditions, allowing multiple responses to be time-domain averaged. The spectra here were obtained from 20 responses averaged with the noise at a level of 90 dB SPL for the 4 kHz filtered condition. The low-pass cutoff frequency of the filter was varied in half-octave steps from 125 Hz to 4 kHz. Filtered electrical signals sent to the headphone for sound stimulation are shown in the upper panel of Figure 3. These stimuli were delivered by a Sennheiser HD 580 driver and the spectra measured in the canal are shown in the middle panel of Figure 3. For each cutoff frequency the noise levels were measured either with or without filtering the microphone response with a 22 Hz high-pass filter that reduced ambient room noise. The signals were also measured with A-weighting as shown in the lower panel of Figure 3. The noise level for the 125 Hz low-pass filtered condition had an A-weighted level of 56 dB A.

Spectra shown on an expanded frequency scale (0 to 300 Hz) for three simultaneously recorded conditions are shown in Figure 4. Responses measured from the animal are expressed as dB re. 1V where -72 dB represents ~ 250 µV response amplitude. The microphone ear canal measurements of Figure 4, which are the same data as in Figure 3, show that the low-frequency components are indeed frozen, as all measures overlie each other in the 20 – 100 Hz range. The right column of Figure 4 shows the average spectral level over the 12-125 Hz range for each low-pass filter condition. When measured in the basal region of the cochlea, noise with lower frequency cutoff produced larger responses in the low-frequency range. The spectral average over the 12-125 Hz range was approximately 3 dB greater for the 125 Hz cutoff noise than it was with the cutoff set to 2000 Hz, a characteristic that was not present in the simultaneously measured sound levels in the ear canal demonstrating that our inner-ear measures are not an analysis artifact. This same tendency was more pronounced when responses were measured from the third cochlear turn in that the noise with the lowest cutoff frequency generated a substantially larger response. When the response amplitude from the third turn was averaged across the 12-125 Hz range, an approximately 6 dB decline was seen between the 125 Hz and 2000 Hz low-pass filter settings. The results of similar measurements made in 5 animals are summarized in Figure 5. The responses in the low-frequency spectral region (12-125 Hz) were 8.8 dB greater from the 125 Hz low-pass cutoff noise as compared to that from the 2 kHz or higher cutoff frequencies. In other words, *responses from low-frequency stimulus components were 2-3x greater in amplitude when high-frequency sounds were not present.*

3.3 The Effect of A-Weighting

Although the low-pass filtered noise with a cutoff frequency of 2 kHz or greater was set to 90 dB SPL, the measured sound levels decreased, as expected, for stimuli with lower cutoff frequencies as higher frequency components were filtered out. The decline with cutoff frequency, measured in dB SPL, is shown in the lower panel of Figure 3. The changes as cutoff frequency was varied become even more pronounced when the sound was A-weighted. The A-weighted level of the noise with the cutoff filter set at 125 Hz was 56 dB A.

The low frequency responses of the ear, measured as the average spectral components from 12 – 125 Hz, as a function of noise levels is summarized in the left panel of Figure 6. As level was increased, the response from the 125 Hz low-pass filtered noise was always larger than the 4 kHz low-pass filtered noise. In this plot, the sound level represents how the data were collected, based on the noise level for the 4 kHz low-pass (i.e., wide-band) condition. In the right panel, we provide a comparison of the two noise–band responses corrected by A-weighted levels. There are two major observations that result from the comparison in Figure 6 (right panel):

1) **Low-pass filtered noise with a cutoff frequency of 125 Hz presented at a level of ~43 dB A stimulated the apical regions of the cochlea to the same degree as noise with a low-pass cutoff frequency of 4 kHz (i.e. wide band) at a level of 90 dB A.**
2) **At stimulus levels above 45 dB A, 125 Hz low-pass filtered noise generated larger responses at the apical regions of the cochlea than were generated by ANY level of 4 kHz low-frequency cutoff (i.e. wide band) noise.**

4 DISCUSSION AND CONCLUSIONS

The sensitivity of the apical regions of the cochlea to low-frequency sounds, and the suppressive influence of higher frequency sounds on this response, is confirmed by this study. We have demonstrated that A-weighted noise levels of as low as 45 dB A can stimulate apical regions to the same degree as wide band noise of much higher levels, as high as 90 dB A. This study shows that it cannot be assumed that noise levels as low as 40 dB A are benign and do not cause strong stimulation of the ear. Low-frequency noise around 40 dB A undoubtedly affects the ear. If the noise consists of predominantly low frequencies, then it will induce greater stimulation of the ear than has hitherto been appreciated. The observation that responses to primarily low-frequency noise stimulation are larger and do not saturate to the degree seen when higher-frequency components are present (Figure 6) is in complete agreement to the behavior previously seen with tonal stimuli[7]. The input/output functions of cochlear responses saturated at progressively higher levels for 500 Hz, 50 Hz and 5 Hz tonal stimuli presented in quiet. This means that the largest electrical responses in the apical regions of the cochlea will occur specifically when very low-frequency sound dominates the stimulus and mid-frequency components (200 – 2000 Hz) are absent.

The responses from inside the inner ear reported here may provide a physiologic basis for Krahé's psychoacoustical studies that showed how low-frequency noises with sharp cutoff slopes are judged to be more annoying than when presented with higher-frequency sounds, as is the case when lower-cutoff slopes are present[4,5]. Although our studies offer support for Krahé's findings, we do not necessarily agree with his interpretation that the annoyance is mediated by primary type I afferent auditory nerve fibers. We have shown empirically that infrasound rarely leads to direct excitation of single-auditory-nerve afferent fibers [7] and there are many other mechanisms that should not be ruled out, including:

1) Stimulation mediated by type II afferent fibers. Type II fibers innervate multiple OHC and connect to multiple cell types of the cochlear nucleus[8] in the brainstem. These pathways may be inhibitory to conscious hearing[9], and may also be linked to alerting and attention pathways.

2) Cochlear Fluids Disturbances. Low-frequency stimulation at non-damaging levels has been shown to result in a localized endolymphatic hydrops – a swelling of the endolymphatic inner-ear compartment – with associated basally-directed endolymph flow[10]. Wit et al. showed that during endolymph volume increases, pressure changes were consistent with a flow through a narrow duct (the ductus reuniens) into a more compliant chamber (the sacculus)[11]. Histologic studies showed that the sacculus is highly compliant and is one of the first structures affected by endolymphatic hydrops[12]. Low-frequency sound exposure could therefore produce saccular disturbance, with symptoms including unsteadiness and disequilibrium. Furthermore, endolymphatic hydrops has been shown to contribute to an occlusion of the cochlear helicotrema which then makes the ear approximately 20 dB more sensitive to very low-frequency sounds[13]. This leads to the possibility of a positive feedback process, with low-frequency stimulation generating hydrops that in turn makes the ear more sensitive to the low-frequency stimulation. In addition to the mechanical disturbance of the saccule caused by endolymphatic hydrops, saccular enlargement also brings the saccular membranes closer and possibly in contact with the stapes footplate which would result in more efficient, direct stimulation of the saccule.

3) Amplitude modulation of sounds in the acoustic range. We have shown that low-frequency sounds that do not directly stimulate the IHCs and primary afferents, can influence the responses of the auditory nerve (i.e., sounds that will be heard) by inducing a biological form of amplitude modulation[7]. This type of modulation occurs within the cochlea and cannot be measured with a sound level meter. Rather, because the low-frequency displacements of the basilar membrane affect the amplification properties of the OHCs, responses to high-frequency sounds are perceived as being modulated in amplitude.

It is well documented that people find noise with prominent low frequency content annoying[4,5,14]. In the context of wind turbine noise it is known that the larger wind turbines can generate high levels of low frequency noise and infrasound[15,16,17,18,19]. The concern arising from the work we report here is that the cochlear apex of people exposed to such low-frequency sounds will be stimulated to a far greater degree than is suggested by their measured A-weighted sound level. The demonstration that sounds in the range of 40 – 45 dB A may be causing intense stimulation of the cochlear apex has not previously been appreciated. This may account for why the influence of low frequency noise on humans is greater than that estimated from spectral measurements and why consideration of noise crest factors is appropriate[20]. The fact that apical stimulation is maximal when mid- and high-frequency components are absent from the sound may also be important to wind turbine noise effects. It is known that people's houses attenuate sound frequencies in the audible range but have little influence, or may even increase infrasound and low-frequency sound levels[21]. Thus, prolonged periods of exposure to wind turbine noise in an otherwise quiet environment (such as a quiet bedroom) seems to represent a condition in which apical stimulation would be maximized. Intense stimulation of the cochlear apex will certainly have some influence on human physiology. On this basis we think that the concept of “what you can’t hear can’t hurt you” is false. Similarly, there are potential mechanisms by which low-frequency sounds could influence vestibular physiology which are being ignored by some[22]. Our measurements showing that the ear generates large electrical responses to low-frequency stimulation suggest that the effects of low-frequency sound on people living near wind turbines should not be dismissed by those with little understanding of how low frequency sounds indeed affect the ear[19,21,22]. More research on this topic is necessary to enlighten the scientific, medical, and legal communities, and the public, some of whom are being chronically exposed to these sounds.

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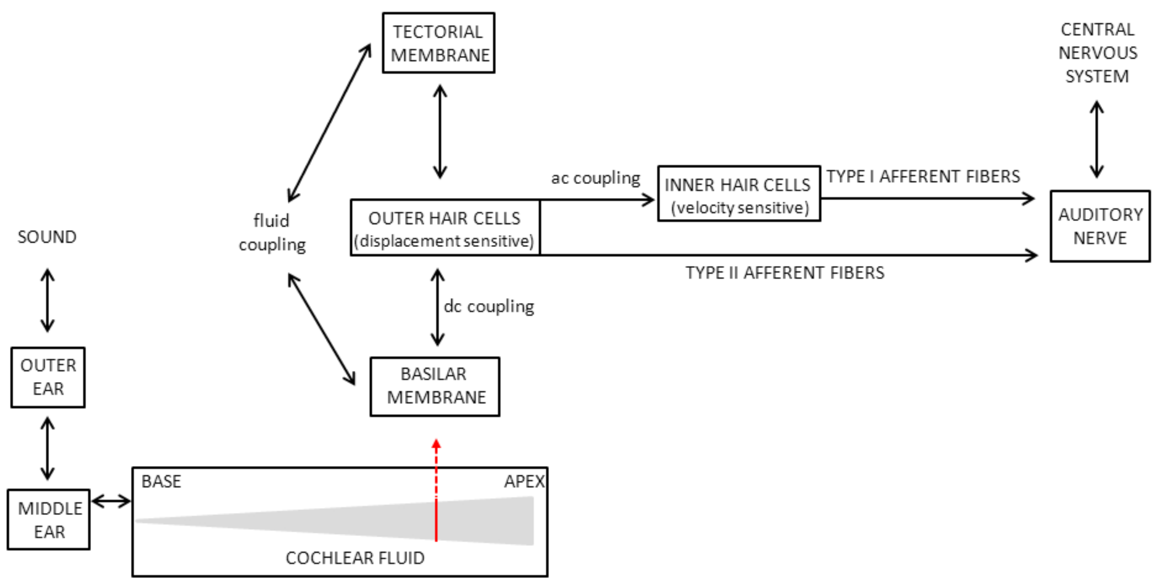

Fig. 1 – Schematic of the auditory periphery. The guinea pig cochlea has 1 row of inner hair cells (IHC) and three rows of outer hair cells (OHC) along its length. The red line and subsequent compartments describe some anatomical and physiological properties of a given segment. After sound propagates through the outer and middle ear, the basilar membrane is set into motion. OHCs in the cochlear apex region respond to low frequencies and are sensitive to the displacement of the basilar membrane motion and are dc-coupled to the sound stimulus. In contrast, the IHC are free within the cochlear fluid causing them to be excited by the velocity of basilar membrane motion, are ac-coupled to the sound stimulus, and are insensitive to low frequency stimulation.

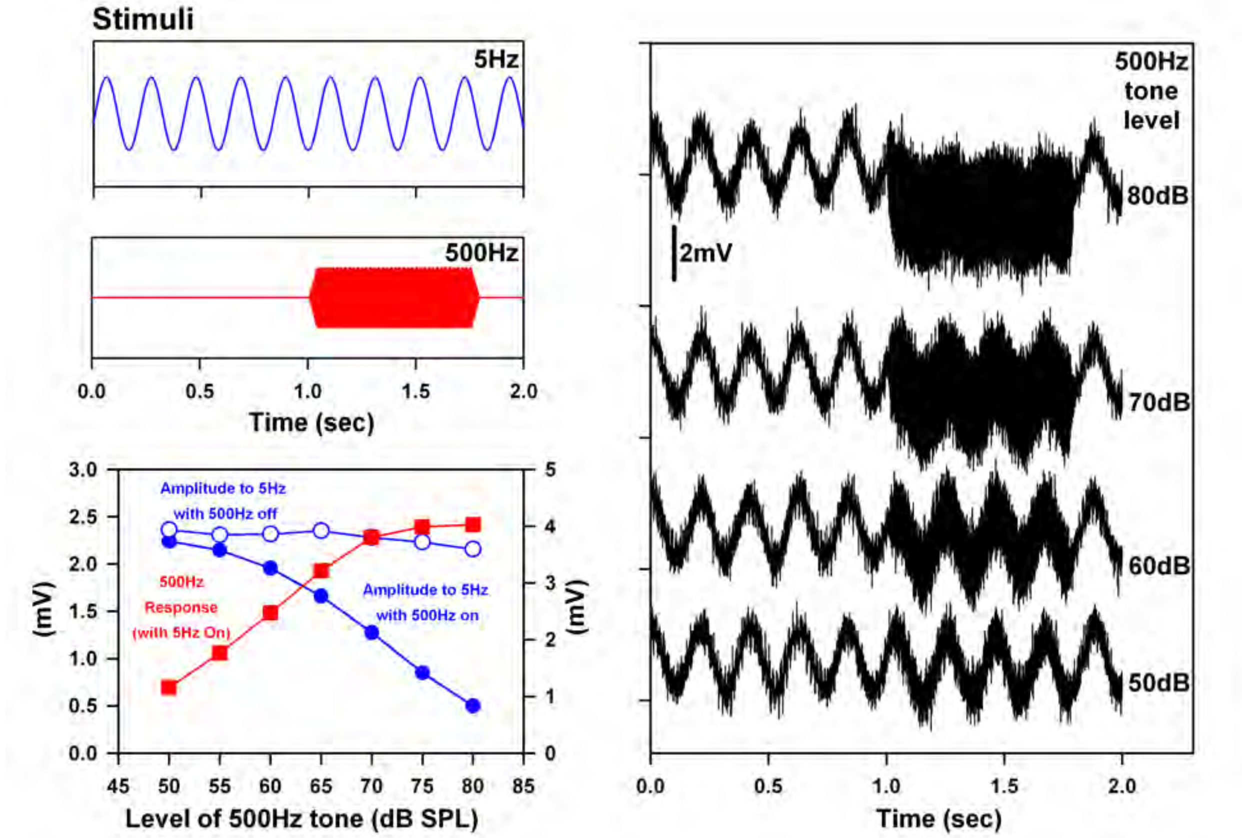

Fig. 2 – Higher-frequency stimuli (500 Hz) suppress the response to a very low-frequency (5 Hz) stimulus. A 500 Hz tone of varied level was superimposed on a 5 Hz, 90 dB stimulus. As the level of the 5 Hz tone was increased, the amplitude of the 5 Hz response declined (right panel).Amplitude measurements (lower left panel) show that 5 Hz stimulation well below saturation (red curve) caused a reduction in response amplitude to the 5 Hz.

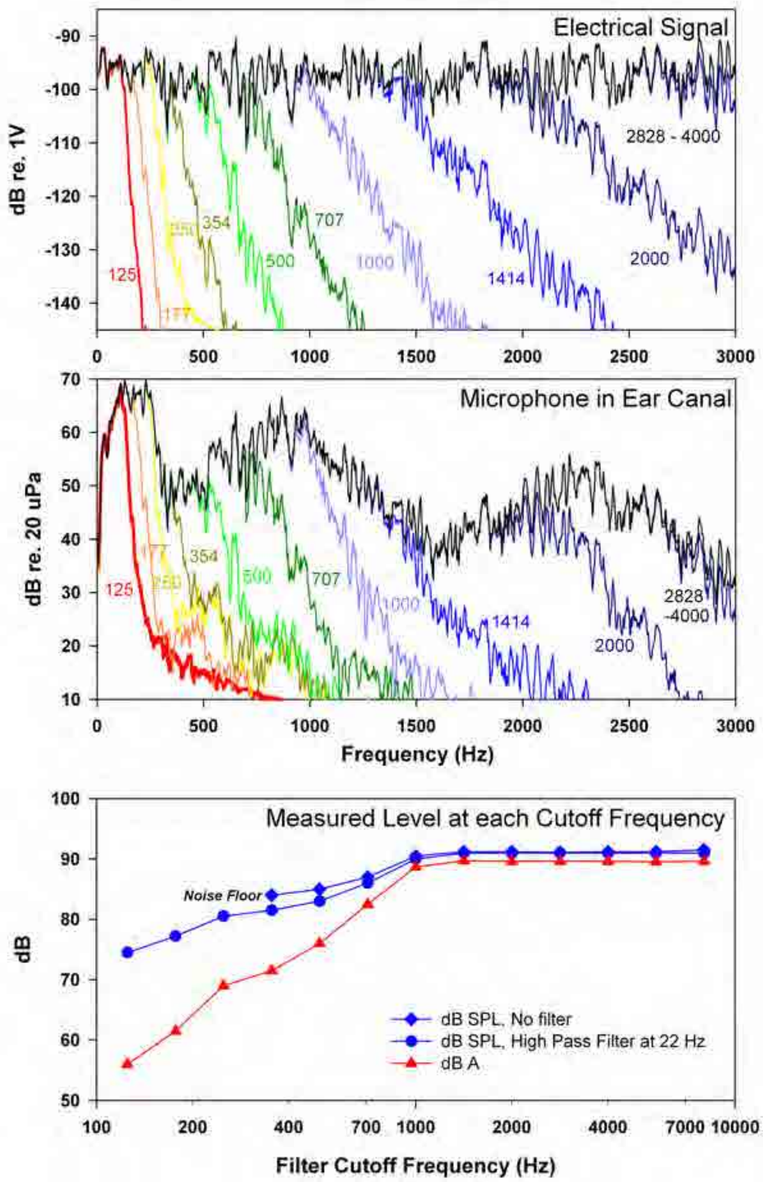

Fig. 3 – Low-pass noise used in this study. The upper panel shows the spectra of low-pass noises with cutoff frequency varied from 125 Hz to 4 kHz. Note that the filter altered the high-frequency component of the noise but had no influence on the low-frequency content (below 100 Hz). The cutoff slope was approximately 55 dB/octave. The middle panel shows the stimuli measured in vivo in the external canal after being delivered by the Sennheiser headphone. The lower panel shows the stimuli with different cutoff frequencies measured in dB SPL and in dB A.

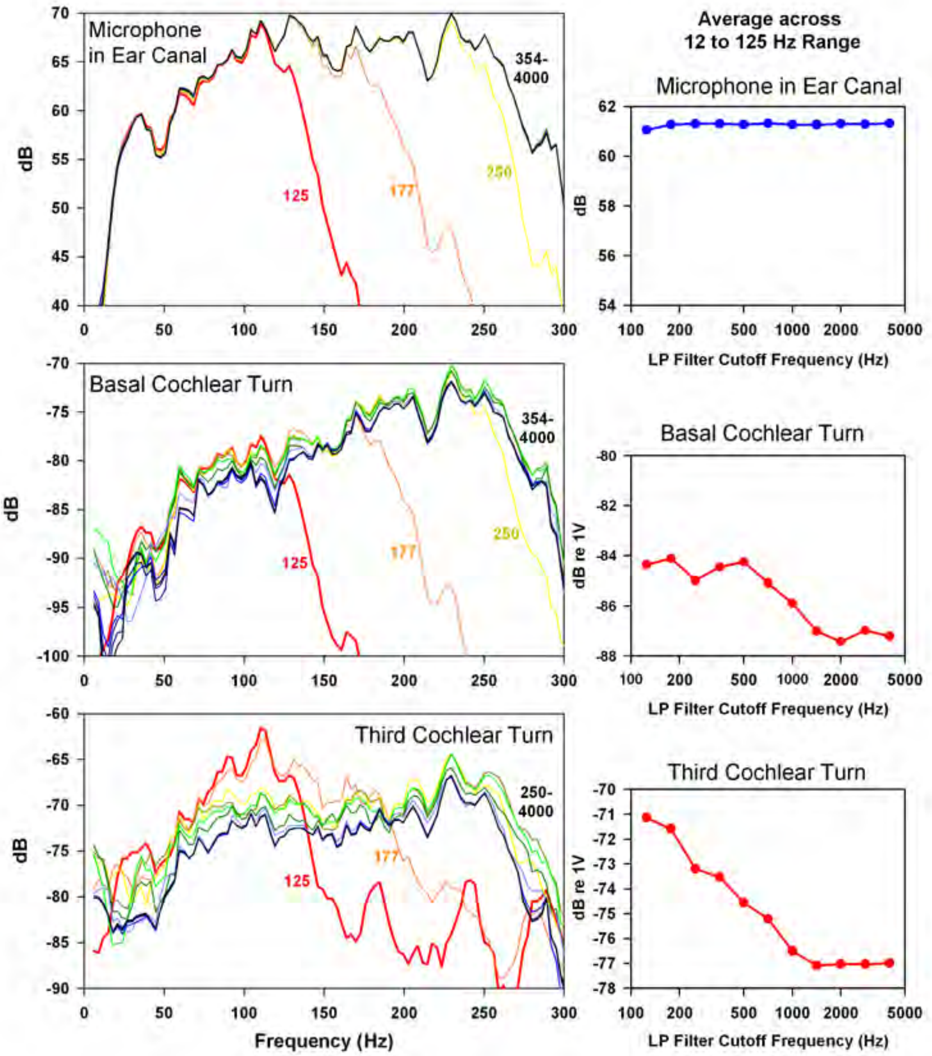

Fig. 4 – Spectra expanded to show the lowest 300 Hz of the frequency range. At each noise filter cutoff frequency, all responses (all 3 panels) were recorded simultaneously to the same stimuli. Top row: The low-frequency region of the sound field showed little variation as cutoff frequency was changed. Middle Row: Responses from the basal cochlear turn were larger when high frequency components were absent. Bottom Row: Apical (Third turn) responses were substantially greater when high frequency components were absent. In this case, the lowest band of noise (125 Hz cutoff) generated ~ 6 dB larger responses than the widest band of noise (4 kHz cutoff). For each condition, the average spectral level in to 12 Hz to 125 Hz range was graphed relative to the noise filter cutoff frequency in the right column.

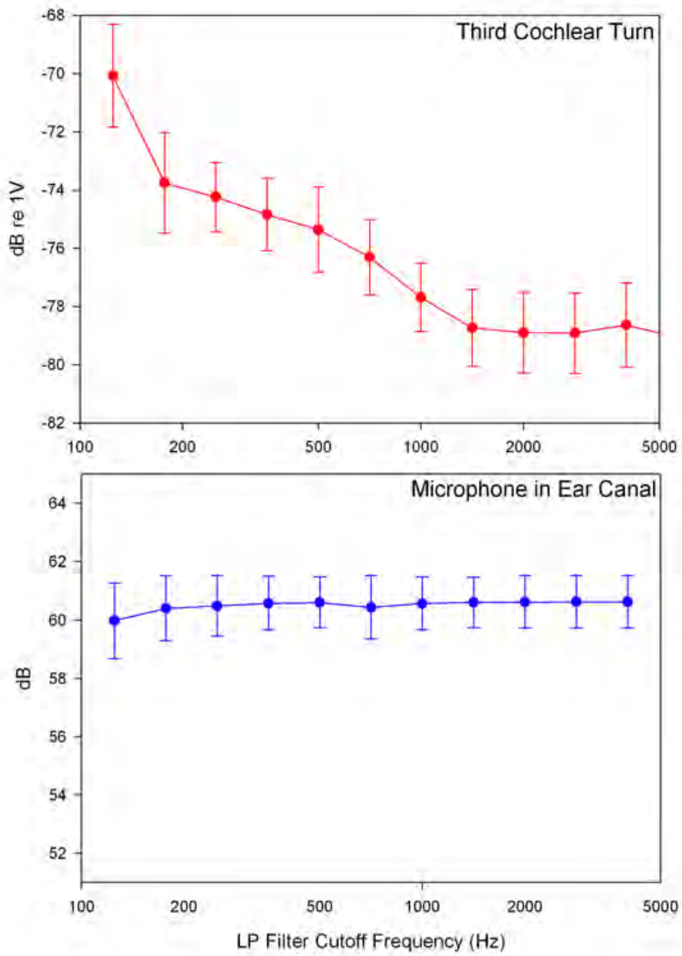

Fig. 5 – Average response amplitudes (+/- SD) in 5 experiments. At each noise cutoff frequency, response amplitude was measured as the average spectral level in the 12 – 125 Hz range. Responses from the apical region of the cochlea showed a systematic decline as noise cutoff frequency is varied, while responses from the microphone, analyzed in an identical manner, did not.

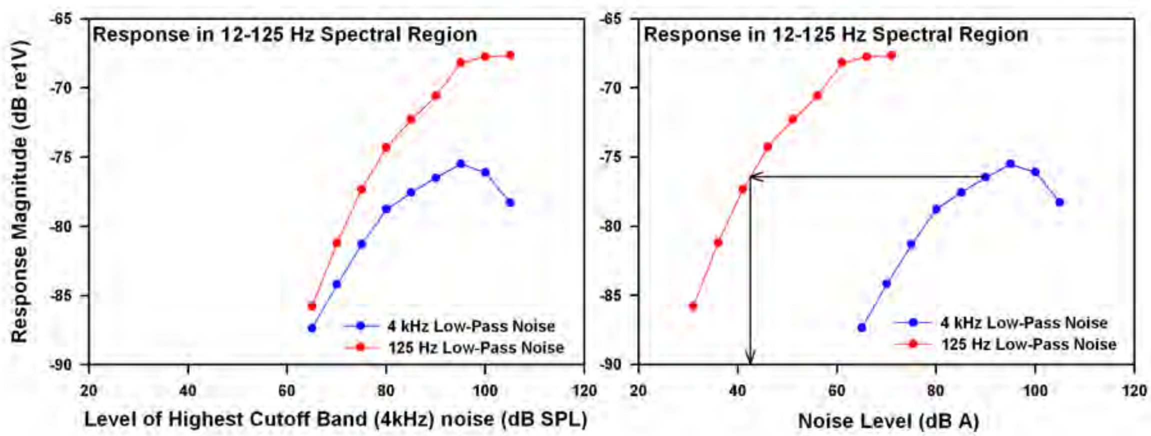

Fig. 6 – ***Left panel:*** *Response amplitudes as the noise level was varied in 5 dB steps. Shown here is only the response amplitudes to the lowest (125 Hz) and highest (4 kHz) noise filter cutoff frequencies used. Amplitudes were the average from the spectrum across the 12 – 125 Hz range (as in Figure 4). Noise with higher frequencies present always generated lower response amplitudes than when higher frequencies were absent. For the 4 kHz band, the responses saturate and decline as level was increased, while the responses to the low-band (125 Hz cutoff) noise keep increasing****. Right panel:*** *The same data plotted based on the A-weighted level of the stimuli measured at each cutoff frequency. This shows that low-frequency noise (125 Hz cutoff) of ~43 dB A generated as large of a response at low frequencies as did a 90 dB A wide band (4 kHz cutoff) noise. Indeed, for 125Hz low-pass noise of 45 dB A or greater, an ear's response will be larger than for wide band noise presented at ANY level.*

EXHIBIT
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Review Article

Responses of the ear to low frequency sounds, infrasound and wind turbines

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ABSTRACT

Infrasonic sounds are generated internally in the body (by respiration, heartbeat, coughing, etc) and by external sources, such as air conditioning systems, inside vehicles, some industrial processes and, now becoming increasingly prevalent, wind turbines. It is widely assumed that infrasound presented at an amplitude below what is audible has no influence on the ear. In this review, we consider possible ways that low frequency sounds, at levels that may or may not be heard, could influence the function of the ear. The inner ear has elaborate mechanisms to attenuate low frequency sound components before they are transmitted to the brain. The auditory portion of the ear, the cochlea, has two types of sensory cells, inner hair cells (IHC) and outer hair cells (OHC), of which the IHC are coupled to the afferent fibers that transmit "hearing" to the brain. The sensory stereocilia ("hairs") on the IHC are "fluid coupled" to mechanical stimuli, so their responses depend on stimulus velocity and their sensitivity decreases as sound frequency is lowered. In contrast, the OHC are directly coupled to mechanical stimuli, so their input remains greater than for IHC at low frequencies. At very low frequencies the OHC are stimulated by sounds at levels below those that are heard. Although the hair cells in other sensory structures such as the saccule may be tuned to infrasonic frequencies, auditory stimulus coupling to these structures is inefficient so that they are unlikely to be influenced by airborne infrasound. Structures that are involved in endolymph volume regulation are also known to be influenced by infrasound, but their sensitivity is also thought to be low. There are, however, abnormal states in which the ear becomes hypersensitive to infrasound. In most cases, the inner ear's responses to infrasound can be considered normal, but they could be associated with unfamiliar sensations or subtle changes in physiology. This raises the possibility that exposure to the infrasound component of wind turbine noise could influence the physiology of the ear.

1. Introduction

The increasing use of wind turbines as a "green" form of energy generation is an impressive technological achievement. Over time, there have been rapid increases in the size of the towers, blades, and generator capacity of wind turbines, as well as a dramatic increase in their numbers. Associated with the deployment of wind turbines, however, has been a rather unexpected development. Some people are very upset by the noise that some wind turbines produce. Wind turbine noise becomes annoying at substantially lower levels than other forms of transportation noise, with the exception of railroad shunting yards (Pedersen and Waye, 2004; Pedersen and Persson Waye, 2007; Pedersen et al., 2009). Some people with wind turbines located close to their homes have reported a variety of clinical symptoms that in rare cases are severe enough to force them to move away. These symptoms include sleep disturbance, headaches, difficulty concentrating, irritability and fatigue, but also include a number of otologic symptoms including dizziness or vertigo, tinnitus and the sensation of aural pain or pressure (Harry, 2007; Pierpont, 2009). The symptom group has been colloquially termed "wind turbine syndrome" and speculated to result from the low frequency sounds that wind turbines generate (Pierpont, 2009). Similar symptoms resulting from low frequency sound emissions from non-wind turbine sources have also been reported (Feldmann and Pitten, 2004).

On the other hand, engineers associated with the wind industry maintain that infrasound from wind turbines is of no consequence if it is below the audible threshold. The British Wind Energy Association (2010), states that sound from wind turbines are in the 30–50 dBA range, a level they correctly describe as difficult to discern above the rustling of trees [i.e. leaves].

This begs the question of why there is such an enormous discrepancy between subjective reactions to wind turbines and the measured sound levels. Many people live without problems near

Abbreviations: CA, cochlear aqueduct; CM, cochlear microphonic; CSF, cerebrospinal fluid; cVEMP, cervical vestibular evoked myogenic potential; EP, endocochlear potential; IHC, inner hair cell(s); oVEMP, ocular vestibular evoked myogenic potential; OHC, outer hair cell(s); RW, round window; ST, scala tympani; SV, scala vestibuli.

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noisy intersections, airports and factories where sound levels are higher. The answer may lie in the high infrasound component of the sound generated by wind turbines. A detailed review of the effects of low frequency noise on the body was provided by Leventhall (2009). Although it is widely believed that infrasound from wind turbines cannot affect the ear, this view fails to recognize the complex physiology that underlies the ear's response to low frequency sounds. This review considers the factors that influence how different components of the ear respond to low frequency stimulation and specifically whether different sensory cell types of the inner ear could be stimulated by infrasound at the levels typically experienced in the vicinity of wind turbines.

2. The physics of infrasound

Sounds represent fluctuating pressure changes superimposed on the normal ambient pressure, and can be defined by their spectral frequency components. Sounds with frequencies ranging from 20 Hz to 20 kHz represent those typically heard by humans and are designated as falling within the audible range. Sounds with frequencies below the audible range are termed infrasound. The boundary between the two is arbitrary and there is no physical distinction between infrasound and sounds in the audible range other than their frequency. Indeed, infrasound becomes perceptible if presented at high enough level.

The level of a sound is normally defined in terms of the magnitude of the pressure changes it represents, which can be measured and which does not depend on the frequency of the sound. In contrast, for sounds of constant pressure, the displacement of the medium is inversely proportional to frequency, with displacements increasing as frequency is reduced. This phenomenon can be observed as the difference in vibration amplitude between a subwoofer generating a low frequency tone and a tweeter generating a high frequency tone at the same pressure level. The speaker cone of the subwoofer is visibly displaced while the displacement of the tweeter cone is imperceptible. As a result of this phenomenon, vibration amplitudes to infrasound are larger than those to sounds in the auditory range at the same level, with displacements at 1 Hz being 1000 times those at 1 kHz when presented at the same pressure level. This corresponds to an increase in displacement at a rate of 6 dB/octave as frequency is lowered.

3. Overview of the anatomy of the ear

The auditory part of the inner ear, the cochlea, consists of a series of fluid-filled tubes, spiraling around the auditory nerve. A section through the middle of a human cochlea is shown in Fig. 1A. The anatomy of each turn is characterized by three fluid-filled spaces (Fig. 1B): scala tympani (ST) and scala vestibuli (SV) containing perilymph (yellow), separated by the endolymphatic space (ELS)(blue). The two perilymphatic compartments are connected together at the apex of the cochlea through an opening called the helicotrema. Perilymph is similar in ionic composition to most other extracellular fluids (high Na^+, low K^+) while endolymph has a unique composition for an extracellular fluid in the body, being

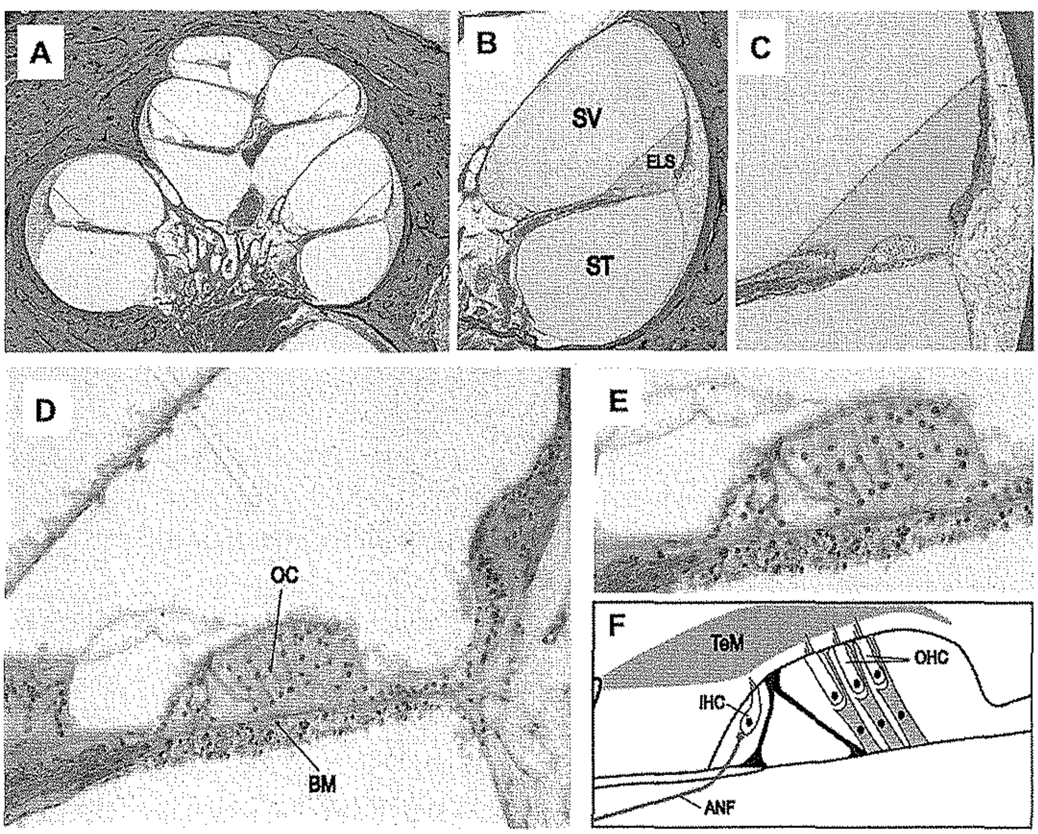

Fig. 1. Panels A–E Cross-section through the human cochlea shown with progressively increasing magnification. Panels B and C The fluid spaces containing perilymph have been colored yellow and endolymph blue. Panel D The sensory structure of the cochlea, the organ of Corti, is colored green. Panel F Schematic showing the anatomy of the main components of the organ of Corti. Abbreviations are: SV: scala vestibuli; ST: scala tympani; ELS: endolymphatic space; OC: organ of Corti; BM: basilar membrane; TeM: tectorial membrane; IHC: inner hair cell; OHC: outer hair cell; ANF: afferent nerve fiber. Original histological images courtesy of Saumil Merchant, MD, Otopathology Laboratory, Massachusetts Eye and Ear Infirmary and Harvard Medical School, Boston.

high in K^+ and low in both Na^+ and Ca^{2+}. It is also electrically polarized by about + 80 mV with respect to perilymph, which is called the endocochlear potential (EP). The main sensory organ of the cochlea (Fig. 1C–E, and shown colored green in Fig. 1D) lies on the basilar membrane between the ELS and the perilymph of ST and is called the organ of Corti. The organ of Corti, seen here in cross section, contains one row of inner hair cells (IHC) and three rows of outer hair cells (OHC) along the spiral length of the cochlea. As shown schematically in Fig. 1F, the sensory hairs (stereocilia) of the OHC have a gradation in length, with the tallest stereocilia embedded in the gelatinous tectorial membrane (TeM) which overlies the organ of Corti in the endolymphatic space (Kimura, 1975). This arrangement allows sound-evoked displacements of the organ of Corti to be converted to a lateral displacement of OHC stereocilia. In contrast, the stereocilia of the IHC do not contact the tectorial membrane, but remain within the fluid of the subtectorial space (Kimura, 1975; Lim, 1986). Because of this difference in how the hair cell stereocilia interact with the TeM, the two types of hair cell respond differently to mechanical stimuli. At low frequencies, the IHC respond according to the velocity of basilar membrane displacement, while OHC respond to the displacement itself (Russell and Sellick, 1983; Dallos, 1984).

The two types of hair cells also contact different types of afferent nerve fibers, sending information to the brain (Spoendlin, 1972; Santi and Tsuprun, 2001). Each IHC is innervated by multiple Type I afferent fibers, with each fiber innervating only a single IHC. The Type I afferents represent the vast majority (95%) of the fibers transmitting information to the brain and as a result it is generally believed that mammals hear with their IHC (Dallos, 2008). In contrast, the OHC contact Type II afferent fibers, which are unmyelinated and make synaptic contacts with a number of OHC. Type II afferents fibers are believed to be unresponsive to sounds and may signal the static position of the organ of Corti (Brown, 1994; Robertson et al., 1999). The OHC also receive substantial efferent innervation (from the brain) while the IHC receive no direct efferent innervation (Spoendlin, 1972).

4. Mechanics of low frequency stimulation

Infrasound entering the ear through the ossicular chain is likely to have a greater effect on the structures of the inner ear than is sound generated internally. The basic principles underlying stimulation of the inner ear by low frequency sounds are illustrated in Fig. 2. Panel A shows the compartments of a simplified, uncoiled cochlea bounded by solid walls with two parallel fluid spaces representing SV and ST respectively that are separated by a distensible membrane representing the basilar membrane and organ of Corti. It is generally agreed that the differential pressure between SV and ST across the basilar membrane is the important factor driving the motion of the basilar membrane (Von Békésy, 1960; Dancer and Franke, 1980; Nakajima et al., 2008; Merchant and Rosowski, 2008). In example A, all the boundaries of the inner ear are solid and noncompliant with the exception of the stapes. In this non-physiologic situation, the stapes applies pressures to SV (indicated by the red arrows) but as the fluid can be considered incompressible, pressures are instantaneously distributed throughout both fluid spaces and pressure gradients across the basilar membrane will be small. In panel B, the round window (RW) and the cochlear aqueduct (CA) have been added to the base of ST. For frequencies below 300 Hz the RW provides compliance between perilymph and the middle ear (Nakajima et al., 2008) and the CA provides fluid communication between perilymph and the cerebrospinal fluid (CSF). Under this condition, pressures applied by the stapes induce small volume flows between the stapes and

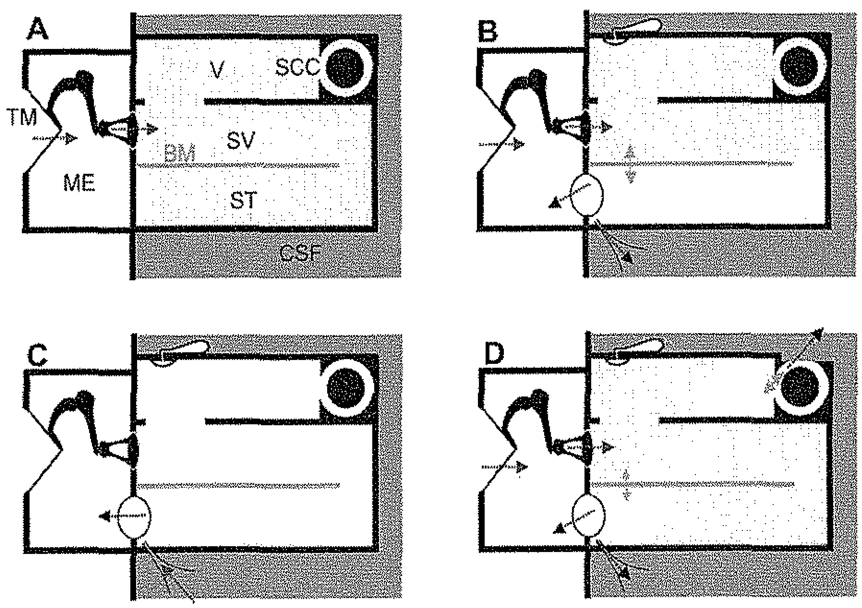

Fig. 2. Schematic representation of the uncoiled inner ear for four different mechanical conditions with low frequency stimulation. Red arrows indicate applied pressure and blue arrows indicate loss to compliant structures. A: indicates a hypothetical condition where the fluid space is rigidly bounded with no "windows" providing compliance. Sound pressure applied by the stapes causes uniform pressures (indicated by color shading) throughout the fluid space, so pressure difference across the basilar membrane and therefore stimulation is minimal. B: The normal situation with compliances provided by the round window and cochlear aqueduct at the base of scala tympani. Pressure differentials cause movement of fluid towards the compliant regions, including a pressure differential across the basilar membrane causing stimulation. C: Situation where low frequency enters scala tympani through the cochlear aqueduct. The main compliant structure is located nearby so pressure gradients across the basilar membrane are small, limiting the amount of stimulation. Infrasound entering through the cochlear aqueduct (such as from respiration and body movements) therefore does not provide the same degree of stimulation as that entering via the stapes. D: Situation with compromised otic capsule, such as superior canal dehiscence. As pressure gradients occur both along the cochlea and through the vestibule and semi-circular canal, the sensory structures in the semi-circular canal will be stimulated. Abbreviations: BM: basilar membrane; CA: cochlear aqueduct; CSF: cerebrospinal fluid; ES: endolymphatic duct and sac; ME: middle ear; RW: round window; SCC: semi-circular canal; ST: scala tympani, SV: scala vestibuli, TM: tympanic membrane; V: vestibule. The endolymphatic duct and sac is not an open pathway but is closed by the tissues of the sac, so it is not considered a significant compliance.

the site(s) of compliance (blue arrows) which requires a pressure gradient to exist along the system, as indicated by the shading. The pressure differential across the basilar membrane will displace it, causing stimulation of the IHC and OHC. This is the situation for external sounds entering the normal cochlea via the ossicular chain. In panel C the situation is compared for sounds originating in the CSF and entering the system through the CA. In this case, the compliant RW is situated close to the location of aqueduct entry, so the major fluid flows and pressure gradients occur locally between these structures. As the stapes and other boundaries in scala vestibuli and the vestibule are relatively noncompliant, pressure gradients across the basilar membrane will be lower than with an equivalent pressure applied by the stapes. For infrasonic frequencies, it was shown that responses to 1 Hz pressure oscillation applied to the fluid in the basal turn of ST were substantially increased when the wall of SV was perforated thereby providing greater compliance in that scala (Salt and DeMott, 1999).

The final condition in Fig. 2D shows the consequences of a “third window” on the SV/vestibule side of the cochlear partition. This causes an increased “air-bone gap” (i.e. an increase in sensitivity to bone conducted vibration and a decreased sensitivity to air conducted sounds, primarily at low frequencies; Merchant and Rosowski, 2008). It may also produce an abnormal sound-induced stimulation of other receptors in the inner ear, such as the hair cells in the ampulla of the semi-circular canal. This is the basis of the Tullio phenomenon, in which externally or internally generated sounds, such as voice, induce dizziness.

Receptors in other organs of the inner ear, specifically both the saccule and the utricle also respond to airborne sounds delivered by the stapes, as discussed in more detail below. The mechanism of hair cell stimulation of these organs is less certain, but is believed to be related to pressure gradients through the sensory epithelium (Sohmer, 2006).

5. Physiologic responses of the ear to low frequency stimuli

5.1. Cochlear hair cells

When airborne sounds enter the ear, to be transduced into an electrical signal by the cochlear hair cells, they are subjected to a number of mechanical and physiologic transformations, some of which vary systematically with frequency. The main processes involved were established in many studies and were summarized by Cheatham and Dallos (2001). A summary of the components is shown in Fig. 3. There are three major processes influencing the sensitivity of the ear to low frequencies. The first arises from the transmission characteristics of sounds through the ossicular structures of the middle ear, which have been shown to attenuate signals at a rate of 6 dB/octave for frequencies below 1000 Hz (Dallos, 1973). As the vibration amplitude in air increases at 6 dB/octave as frequency is lowered, this attenuation characteristic of middle ear transmission results in the displacement of middle ear structures remaining almost constant across frequency for sounds of constant pressure level. A second process attenuating low frequency sounds is the fluid shunting between ST and SV through the helicotrema. The helicotrema has been shown to attenuate frequencies below 100 Hz by 6 dB/octave (Dallos, 1970). The third filter arises from the demonstrated dependence of the IHC on stimulus velocity, rather than displacement (Dallos, 1984). This results in an attenuation of 6 dB/octave for frequencies below approximately 470 Hz for the IHC, and causes a 90° phase difference between IHC and OHC responses (Dallos, 1984). The combined results of these processes are compared with the measured sensitivity of human hearing (ISO226, 2003) in Fig. 3B. The three processes combine to produce the steep decline of sensitivity (up to

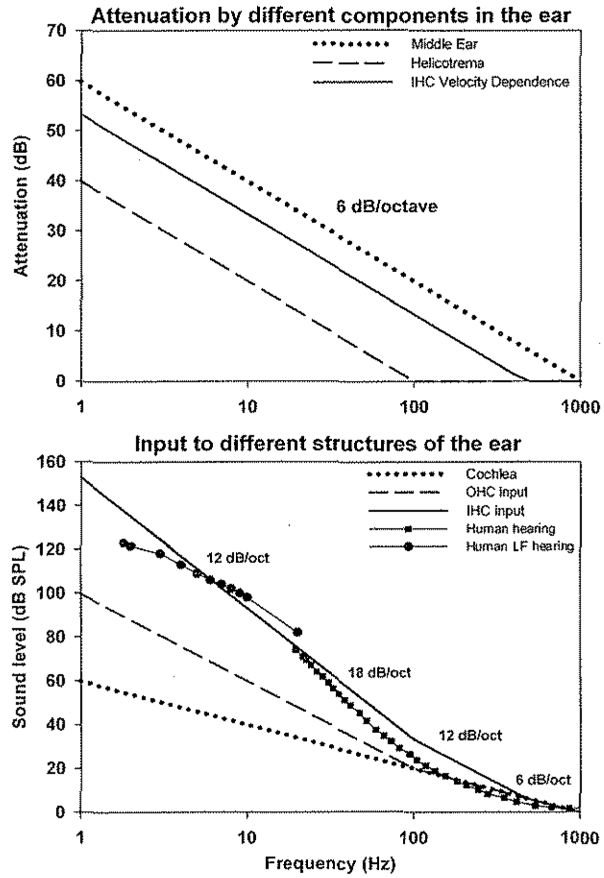

Fig. 3. Upper panel: Estimated properties of high-pass filter functions associated with cochlear signal processing (based on Cheatham and Dallos, 2001). The curves show the low frequency attenuation provided by the middle ear (6 dB/octave below 1000 Hz), by the helicotrema (6 dB/octave below 100 Hz) and by the fluid coupling of the inner hair cells (IHC) resulting in the IHC dependence on stimulus velocity (6 dB/Octave below 470 Hz). Lower panel: Combination of the three processes above into threshold curves demonstrating: input to the cochlea (dotted) as a result of middle ear attenuation; input to the outer hair cells (OHC) as a result of additional filtering by the helicotrema; and input to the IHC as a result of their velocity dependence. Shown for comparison is the sensitivity of human hearing in the audible range (ISO226, 2003) and the sensitivity of humans to infrasounds (Møller and Pederson, 2004). The summed filter functions account for the steep (18 dB/octave) decrease in sensitivity below 100 Hz.

18 dB/octave) in human hearing for frequencies between 100 and 20 Hz. This steep cutoff means that to hear a stimulus at 5 Hz it must be presented at 105 dB higher level than one at 500 Hz. This reflects the fact that the predominant, type I afferent fibers are stimulated by the IHC and that mammals hear with their IHC (Dallos, 2008). However, an important consequence of this underlying mechanism is that the OHC and IHC differ markedly in their responses to low frequency stimuli. As the OHC respond to displacement, rather than velocity, they are not subject to the 6 dB/octave attenuation seen by IHC, so at low frequencies they are stimulated by lower sound levels than the IHC. In theory, the difference between IHC and OHC responses will increase as frequency decreases (becoming over 50 dB at 1 Hz), but in practice, there is interaction between the two types of hair cells which limits the difference as discussed below.

The measured response phase of OHC, IHC and auditory nerve fibers is consistent with the above processes. The cochlear microphonics (CM) recorded in the organ of Corti with low frequency stimuli are in phase with the intracellular potentials of the OHC. This supports the view that the low frequency CM is dominated by

OHC-generated potentials, which follow the displacement of the basilar membrane (Dallos et al., 1972). In contrast, intracellular responses from the IHC lead the organ of Corti CM response by an amount which approaches 90° as frequency is reduced to 100 Hz (Dallos, 1984) corresponding to maximal basilar membrane velocity towards SV (Nuttall et al., 1981). As frequency is lowered, the intracellular potentials of IHC and afferent fiber responses show phase changes consistent with the IHC no longer responding to the increasingly attenuated velocity stimulus, but instead responding to the extracellular potentials generated by the OHC (Sellick et al., 1982; Cheatham and Dallos, 1997). A similar change of phase as frequency is lowered was reported in human psychophysical measurements (Zwicker, 1977) with masking patterns differing by approximately 90° for frequencies above and below 40 Hz. This transition from a response originating from mechanical stimulation of the IHC, to one originating from electrical stimulation of the IHC by large extracellular responses from the OHC may account for the transition of low frequency sensitivity in humans from 18 dB/octave above 20 Hz to 12 dB/octave below 10 Hz (Møller and Pederson, 2004) (Fig. 3B). Near 10 Hz the IHC transition to become primarily stimulated by the more sensitive OHC responses. It can be inferred that if extracellular voltages generated by the OHC are large enough to electrically stimulate the IHC at a specific frequency and level, then the lowest level that the OHC respond to at that frequency must be substantially lower. Based on this understanding of how the sensitivity of the ear arises, one conclusion is that at low frequencies the OHC are responding to infrasound at levels well below those that are heard. On the basis of the calculated input to OHC in Fig. 3B, it is possible that for frequencies around 5 Hz, the OHC could be stimulated at levels up to 40 dB *below* those that stimulate the IHC. Although the OHC at 1 kHz are approximately 12 dB less sensitive than IHC (Dallos, 1984), this difference declines as frequency is lowered and differences in hair cell sensitivity at very low frequencies (below 200 Hz) have not been measured.

Much of the work understanding how the ear responds to low frequency sounds is based on measurements performed in animals. Although low frequency hearing sensitivity depends on many factors including the mechanical properties of the middle ear, low frequency hearing sensitivity has been shown to be correlated with cochlear length for many species with non-specialized cochleas, including humans and guinea pigs (West, 1985; Echteler et al., 1994). The thresholds of guinea pig hearing have been measured with stimulus frequencies as low as 50 Hz, as shown in Fig. 4A. The average sensitivity at 125 Hz for five groups in four studies (Heffner et al., 1971; Miller and Murray, 1966; Walloch and Taylor-Spikes, 1976; Prosen et al., 1978; Fay, 1988) was 37.9 dB SPL, which is 17.6 dB less sensitive than the human at the same frequency and is consistent with the shorter cochlea of guinea pigs. In the absence of data to the contrary, it is therefore reasonable to assume that if low frequency responses are present in the guinea pig at a specific level, then they will be present in the human at a similar or lower stimulus level.

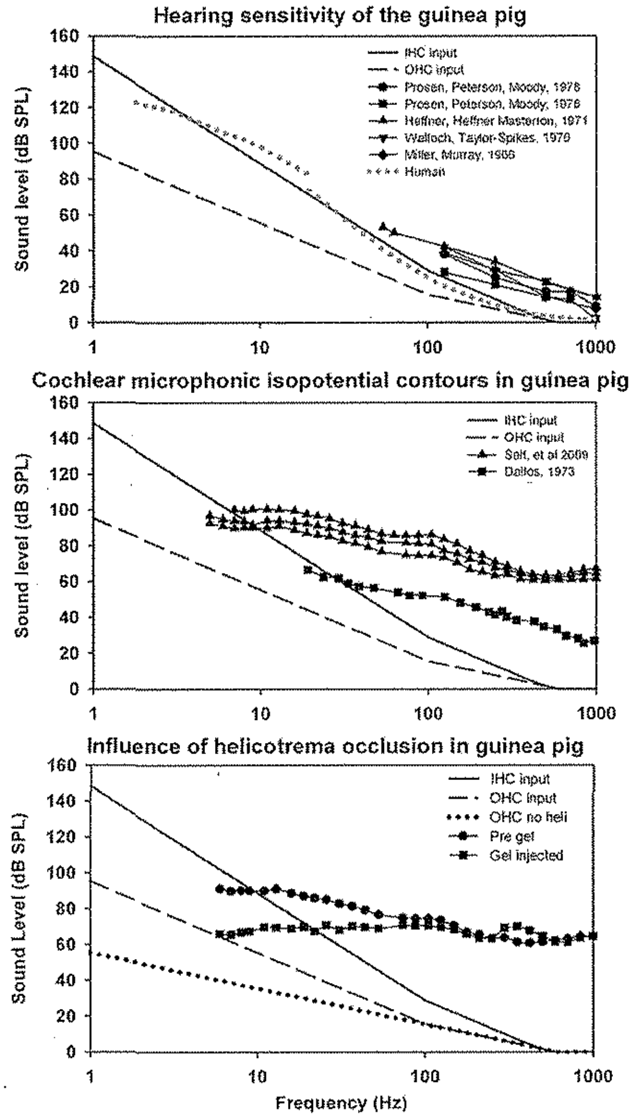

Fig. 4. Upper panel: Similar filter functions as Fig. 3, with parameters appropriate for the guinea pig, and compared with measures of guinea pig hearing. At 125 Hz the guinea pig is approximately 18 dB less sensitive than the human (shown dotted for comparison). Middle panel: Cochlear microphonic isopotential contours in the guinea pig show no steep cutoff below 100 Hz, consistent with input to the OHC being maintained at lower levels than the IHC for low frequencies. Lower panel: Influence of helicotrema occlusion in the guinea pig, produced by injecting 2 μL of hyaluronate gel into the cochlear apex, on the CM isopotential function. Also shown for comparison is the estimated input sensitivity for the OHC with the attenuation by the helicotrema excluded. CM sensitivity curves both have lower slopes than their predicted functions, but the change caused by helicotrema occlusion is comparable.

5.2. *Cochlear microphonic measurements*

Cochlear microphonics (CM) to low frequency tones originate primarily from the OHC (Dallos et al., 1972; Dallos and Cheatham, 1976). The sensitivity of CM as frequency is varied is typically shown by CM isopotential contours, made by tracking a specified CM amplitude as frequency is varied. Fig. 4B shows low frequency CM sensitivity with two different criteria (Dallos, 1973: 3 μV; Salt et al., 2009: 500 μV). The decrease in CM sensitivity as frequency is lowered notably follows a far lower slope than that of human hearing over the comparable frequency range. In the data from Salt et al. (2009), the stimulus level differences between 5 Hz and 500 Hz average only 34 dB (5.2 dB/octave), compared to the 105 dB difference (15.8 dB/octave) for human hearing over the same range. Although these are suprathreshold, extracellular responses, based on an arbitrary amplitude criterion, these findings are consistent with the OHC having a lower rate of cutoff with frequency than the IHC, and therefore responding to lower level stimuli at very low frequencies.

The measured change in CM sensitivity with frequency may include other components, such as a contribution from transducer adaptation at the level of the OHC stereocilia (Kros, 1996). Kennedy et al. (2003) have suggested that adaptation of the mechano-electrical transducer channels is common to all hair cells and contributes to driving active motion of the hair cell bundle. Based on their measurements in cells isolated from the apical turns of neonatal rats, they estimated that the adaptation caused high-pass filtering with a low frequency cutoff frequency of 2/3 of the best frequency for the cochlear location. This type of adaptation, however, does not appear to provide additional attenuation at very low frequencies, as inferred from CM sensitivity curves measured down to 5 Hz. On the contrary, the CM sensitivity curve appears to flatten below 10 Hz, a phenomenon which is currently under investigation in our laboratory.

Fig. 4C shows the influence of plugging the helicotrema with gel on CM sensitivity with frequency, recorded from the basal turn of a guinea pig with a 500 μV criterion (Salt et al., 2009). These relative sensitivity changes, combined with a 90° phase shift in responses, replicate those of Franke and Dancer (1982) and demonstrate the contribution to attenuation provided by the helicotrema for frequencies below approximately 100 Hz. This contrasts with a prior suggestion that the helicotrema of the guinea pig was less effective than that of other species (Dallos, 1970). While the above CM measurements were made with the bulla open, measurements made in both the bulla open/closed conditions with closed sound-field stimulation suggest there is no pronounced frequency dependence of the difference between these conditions below 300 Hz although there may be a level difference of 5–15 dB (Dallos, 1973; Wilson and Johnstone, 1975).

5.3. Low frequency biasing, operating point, and distortion generation

As a result of the saturating, nonlinear transducer characteristic of cochlear hair cells (Russell and Sellick, 1983; Kros, 1996), the fidelity of cochlear transduction depends highly on the so-called operating point of the cochlear transducer, which can be derived by Boltzmann analysis of the CM waveform (Patuzzi and Moleirinho, 1998; Patuzzi and O'Beirne, 1999). The operating point can be regarded as the resting position of the organ of Corti or its position during zero crossings of an applied stimulus (which may not be identical, as stimulation can itself influence operating point). Small displacements of operating point have a dramatic influence on even-order distortions generated by the cochlea ($2f$, f_2–f_1) while having little influence on odd-order distortions ($3f$, $2f_1$–f_2) until displacements are large (Frank and Kössl, 1996; Sirjani et al., 2004). Low frequency sounds (so-called bias tones) have been shown to modulate distortion generated by the ear by their displacement of the operating point of the organ of Corti (Brown et al., 2009). In normal guinea pigs, 4.8 Hz bias tones at levels of 85 dB SPL have been shown to modulate measures of operating point derived from an analysis of CM waveforms (Brown et al., 2009; Salt et al., 2009). This is a level that is substantially below the expected hearing threshold of the guinea pig at 4.8 Hz. In animals where the helicotremea was occluded by injection of gel into the perilymphatic space at the cochlear apex, even lower bias levels (down to 60 dB SPL) modulate operating point measures (Salt et al., 2009). These findings are again consistent with the OHC being the origin of the signals measured and the OHC being more responsive to low frequency sounds than the IHC. A similar hypersensitivity to 4.8 Hz bias tones was also found in animals with surgically-induced endolymphatic hydrops (Salt et al., 2009). This was thought to be related to the occlusion of the helicotrema by the displaced membranous structures bounding the hydropic endolymphatic space in the apical turn. In some cases of severe hydrops, Reissner's membrane was seen to herniate into ST. As endolymphatic hydrops is present both in patients with Meniere's disease and in a significant number of asymptomatic patients (Merchant et al., 2005), the possibility exists that some individuals may be more sensitive to infrasound due the presence of endolymphatic hydrops.

In the human ear, most studies have focused on the $2f_1$–f_2 distortion product, as even-order distortions are difficult to record in humans. The $2f_1$–f_2 component has been demonstrated to be less sensitive to operating point change (Sirjani et al., 2004; Brown et al., 2009). Using different criteria of bias-induced distortion modulation, the dependence on bias frequency was systematically studied in humans for frequencies down to 25 Hz, 6 Hz and 15 Hz respectively (Bian and Scherrer, 2007; Hensel et al., 2007; Marquardt et al., 2007). In each of these studies, the bias levels required were above those that are heard by humans, but in all of them the change of sensitivity with frequency followed a substantially lower slope than the hearing sensitivity change as shown in Fig. 5. Again this may reflect the OHC origins of acoustic emissions, possibly combined with the processes responsible for the flattening of equal loudness contours for higher level stimuli, since the acoustic emissions methods are using probe stimuli considerably above threshold. Although in some regions, slopes of 9–12 dB/octave were found, all showed slopes of 6 dB/octave around the 20 Hz region where human hearing falls most steeply at 18 dB/octave. It should also be emphasized that each of these studies selected a robust modulation criterion and was not specifically directed at establishing a threshold for the modulation response at each frequency. Indeed, in the data of Bian and Scherrer (2007) (their Fig. 3), significant modulation can be seen at levels down to 80 dB SPL at some of the test frequencies. In one of the studies (Marquardt et al., 2007) equivalent measurements were performed in guinea pigs. Although somewhat lower slopes were observed in guinea pigs it is remarkable that stimulus levels required for modulation of distortion were within 5–10 dB of each other for guinea pigs and humans across most of the frequency range. In this case the guinea pig required lower levels than the human. Although the threshold of sensitivity cannot be established from these studies, it is worth noting that for distortion product measurements in the audible range, "thresholds" typically require stimulus levels in the 35–45 dB SPL range (Lonsbury-Martin et al., 1990). In the Marquardt study, the bias tone level required at 500 Hz is over 60 dB above hearing threshold at that frequency.

5.4. Feedback mechanisms stabilizing operating point

The OHC not only transduce mechanical stimuli to electrical responses, but also respond mechanically to electrical stimulation

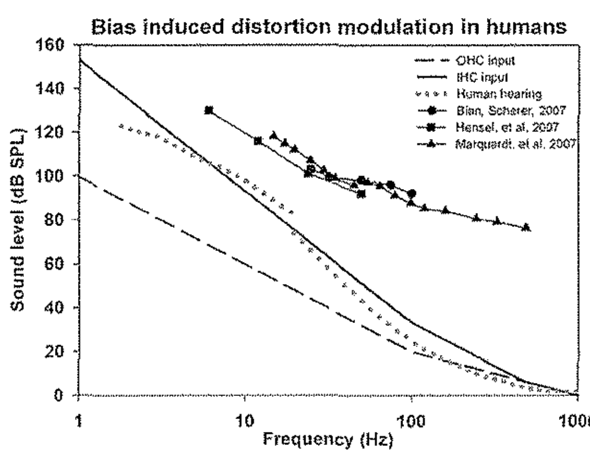

Fig. 5. Frequency dependence of low frequency bias-induced modulation of the $2f_1$–f_2 distortion product measured in the external ear canal of humans in three studies, compared with estimated input functions and human hearing sensitivity. Below 100 Hz the sensitivity to bias falls off at a much lower slope than human hearing, consistent with the response originating from OHC with a lower cutoff slope.

(reviewed by Dallos, 2008) in a manner that provides mechanical amplification. This "active tuning" primarily enhances responses to high stimulus frequencies and is thought to provide little or no active gain with stimuli below approximately 1 kHz (Sellick et al., 2006). For low frequency stimulation, however, basilar membrane modulation by the low frequency tone does have a major influence on the mechanics at the best frequency of high frequency tones i.e. on the active tuning process (Patuzzi et al., 1984). It has been suggested that slow mechanical movements of the OHC may play a part in stabilizing the operating point of the transducer (LePage, 1987, 1989) so the OHC may participate in an active cancellation of low frequency sounds. In models of the cochlear transducer, it was proposed that negative feedback occurred at low frequencies (in which the OHC opposed movements of the basilar membrane), which becomes a positive feedback at the best frequency for the region (Mountain et al., 1983). Chan and Hudspeth (2005) have also suggested OHC motility may be exploited to maintain the operating point of a fast amplifier in the hair cell bundle. However, this possibility has recently been questioned by Dallos (Ashmore et al., 2010) for a number of reasons, one of which is the somatic motor protein, prestin, has an extremely fast response capability. So the interrelationships between hair cell motility and transduction, and between OHC and IHC remain an intense focus of current research. For low frequencies, it has been shown that an out-of phase motion exists between the IHC reticular lamina and the overlying TM so that electromechanical action of the OHC may stimulate the IHC directly, without involvement of the basilar membrane (Nowotny and Gummer, 2006). The possible roles of the OHC and efferent systems are made more complex by recent findings of reciprocal synapses between OHC and their efferent terminals, seen as afferent and efferent synapses on the same fiber (Thiers et al., 2008). One explanation for this system is that the synapses may locally (without involvement of the central nervous system) coordinate the responses of the OHC population so that optimum operating point is maintained for high frequency transduction.

There is some evidence for active regulation of operating point based on the biasing of acoustic emission amplitudes by low frequency tones in which a "hysteresis" was observed (Bian et al., 2004). The hysteresis was thought to result from active motor elements, either in the stereocilia or the lateral wall of the OHC, shifting the transducer function in the direction of the bias. A similar hysteresis was also reported by Lukashkin and Russell (2005) who proposed that a feedback loop was present during the bias that keeps the operating point at its most sensitive region, shifting it in opposite directions during compression and rarefaction phase of the bias tone thereby partially counteracting its effects.

If there are systems in the cochlea to control operating point as an integral component of the amplification process, they would undoubtedly be stimulated in the presence of external infrasound.

5.5. *Vestibular function*

The otolith organs, comprising of the saccule and utricle, respond to linear accelerations of the head (Uzun-Coruhlu et al., 2007) and the semi-circular canals respond to angular acceleration. These receptors contribute to the maintenance of balance and equilibrium. In contrast to the hair cells of the cochlea, the hair cells of the vestibular organs are tuned to very low frequencies, typically below 30 Hz (Grossman et al., 1988). Frequency tuning in vestibular hair cells results from the electrochemical properties of the cell membranes (Manley, 2000; Art and Fettiplace, 1987) and may also involve active mechanical amplification of their stereociliary input (Hudspeth, 2008; Rabbitt et al., 2010). Although vestibular hair cells are maximally sensitive to low frequencies they typically do not respond to airborne infrasound. Rather, they normally respond to mechanical inputs resulting from head movements and positional changes with their output controlling muscle reflexes to maintain posture and eye position. At the level of the hair cell stereocilia, although vibrations originating from head movements and low frequency sound would be indistinguishable, the difference in sensitivity lies in the coupling between the source stimulus and the hair cell bundle. Head movements are efficiently coupled to the hair cell bundle, while acoustic stimuli are inefficiently coupled due to middle ear characteristics and the limited pressure gradients induced within the structure with sound stimuli (Sohmer, 2006).

In a similar manner to cochlear hair cells, which respond passively (i.e. without active amplification) to stimuli outside their best frequency range, vestibular hair cells respond passively to stimuli outside their best frequency range. The otolith organs have been shown to respond to higher, acoustic frequencies delivered in the form of airborne sounds or vibration. This has been demonstrated in afferent nerve fiber recordings from vestibular nerves (Young et al., 1977; McCue and Guinan, 1994; Curthoys et al., 2006) and has recently gained popularity as a clinical test of otolith function in the form of vestibular evoked myogenic potential (VEMP) testing (Todd et al., 2003; Zhou and Cox, 2004; Curthoys, 2010).These responses arise because higher frequency stimuli are more effectively coupled to the otolithic hair cells. But as sound or vibration frequency is reduced, its ability to stimulate the vestibular organs diminishes (Murofushi et al., 1999; Hullar et al., 2005; Todd et al., 2008). So for very low frequencies, even though the hair cell sensitivity is increasing as active tuning is invoked, mechanical input is being attenuated. While there have been many studies of vestibular responses to physiologic stimuli (i.e. head accelerations, rotations, etc) comprising of infrasonic frequency components, we are unaware of any studies that have directly investigated vestibular responses to airborne infrasound of similar frequency composition. As people do not become unsteady and the visual field does not blur when exposed to high-level infrasound, it can be concluded that sensitivity is extremely low.

In some pathologic conditions, coupling of external infrasound may be greater. It is known that "third window" defects, such as superior canal dehiscence increase the sensitivity of labyrinthine receptors to sounds (Wit et al., 1985; Watson et al., 2000; Carey et al., 2004), and are exhibited as the Tullio phenomenon (see earlier section). To our knowledge, the sensitivity of such patients to controlled levels of infrasound has never been evaluated. In this respect, it needs to be considered that vestibular responses to stimulation could occur at levels below those that are perceptible to the patient (Todd et al., 2008).

5.6. *Inner ear fluids changes*

Some aspects of cochlear fluids homeostasis have been shown to be sensitive to low frequency pressure fluctuations in the ear. The endolymphatic sinus is a small structure between the saccule and the endolymphatic duct which has been implicated as playing a pivotal role in endolymph volume regulation (Salt, 2005). The sinus has been shown to act as a valve, limiting the volume of endolymph driven into the endolymphatic sac by pressure differences across the endolymphatic duct (Salt and Rask-Andersen, 2004). The entrance of saccular endolymph into the endolymphatic sac can be detected either by measuring the K^+ concentration in the sac (as saccular endolymph has substantially higher K^+ concentration) or by measuring hydrostatic pressure. The application of a sustained pressure to the vestibule did not cause K^+ elevation or pressure increase in the sac, confirming that under this condition, flow was prevented by the membrane of the sinus acting as a valve. In contrast, the application of 5 cycles at 0.3 Hz to the external ear canal, caused a K^+ increase in the sac, confirming that oscillation of pressure applied to the sinus allowed pulses of endolymph to be driven from the sinus into the endolymphatic sac. The pressure changes driving these pulses was large, comparable to those produced by contractions of the tensor tympani muscle, as occurs during swallowing. Tensor tympani contractions produce displacements of the stapes towards the vestibule for a duration of approximately 0.5 s (~2 Hz), which induce large EP changes and longitudinal movements of endolymph within the cochlea (Salt and DeMott, 1999). The lowest sound level that drives endolymph movements is currently unknown.

A therapeutic device (the Meniett: www.meniett.com; Odkvist et al., 2000) that delivers infrasound to the inner ear is widely used to treat Meniere's disease in humans (a disease characterized by endolymphatic hydrops). The infrasonic stimulus (6 Hz or 9 Hz) is delivered by the device in conjunction with sustained positive pressure in the external canal. An important aspect of this therapy, however, is that a tympanostomy tube is placed in the tympanic membrane before the device is used. The tympanostomy tube provides an open perforation of the tympanic membrane which shunts pressure across the structure, so that ossicular movements (and cochlear stimulation) are minimized, and the pressures are applied directly to the round window membrane. Nevertheless, the therapeutic value of this device is based on infrasound stimulation influencing endolymph volume regulation in the ear.

As presented above, endolymphatic hydrops, by occluding the perilymph communication pathway through the helicotrema, makes the ear more sensitive to infrasound (Salt et al., 2009). It has also been shown that non-damaging low frequency sounds in the acoustic range may themselves cause a transient endolymphatic hydrops (Flock and Flock, 2000; Salt, 2004). The mechanism underlying this volume change has not been established and it has never been tested whether stimuli in the infrasound range cause endolymphatic hydrops.

Although infrasound at high levels apparently does not cause direct mechanical damage to the ear (Westin, 1975; Jauchem and Cook, 2007) in animal studies it has been found to exacerbate functional and hair cell losses resulting from high level exposures of sounds in the audible range (Harding et al., 2007). This was explained as possibly resulting from increased mixture of endolymph and perilymph around noise induced lesion sites in the presence of infrasound.

6. Wind turbine noise

Demonstrating an accurate frequency spectrum of the sound generated by wind turbines creates a number of technical problems. One major factor that makes understanding the effects of wind turbine noise on the ear more difficult is the widespread use of A-weighting to document sound levels. A-weighting shapes the measured spectrum according to the sensitivity of human hearing, corresponding to the IHC responses. As we know the sensitivity for many other elements of inner ear related to the OHC do not decline at the steep slope seen for human hearing, then A-weighting considerably underestimates the likely influence of wind turbine noise on the ear. In this respect, it is notable that in none of the physiological studies in the extensive literature reporting cochlear function at low frequencies were the sound stimuli A-weighted. This is because scientists in these fields realize that shaping sound levels according to what the brain perceives is not relevant to understanding peripheral processes in the ear. A-weighting is also performed for technical reasons, because measuring unweighted spectra of wind turbine noise is technically challenging and suitable instrumentation is not widely available. Most common approaches to document noise levels (conventional sound level meters, video cameras, devices using moving coil microphones, etc) are typically insensitive to the infrasound component. Using appropriate instrumentation, Van den Berg showed that wind turbine noise was dominated by infrasound components, with energy increasing between 1000 Hz and 1 Hz (the lowest frequency that was measured) at a rate of approximately 5.5 dB/octave, reaching levels of approximately 90 dB SPL near 1 Hz Sugimoto et al. (2008) reported a dominant spectral peak at 2 Hz with levels monitored over time reaching up to 100 dB SPL. Jung and Cheung (2008) reported a major peak near 1 Hz at a level of approximately 97 dB SPL. In most studies of wind turbine noise, this high level, low frequency noise is dismissed on the basis that the sound is not perceptible. This fails to take into account the fact that the OHC are stimulated at levels that are not heard.

7. Conclusions

The fact that some inner ear components (such as the OHC) may respond to infrasound at the frequencies and levels generated by wind turbines does not necessarily mean that they will be perceived or disturb function in any way. On the contrary though, if infrasound is affecting cells and structures at levels that cannot be heard this leads to the possibility that wind turbine noise could be influencing function or causing unfamiliar sensations. Long-term stimulation of position-stabilizing or fluid homeostasis systems could result in changes that disturb the individual in some way that remains to be established. We realize that some individuals (such as fighter pilots) can be exposed to far higher levels of infrasound without undue adverse effects. In this review, we have confined our discussion to the possible direct influence of infrasound on the body mediated by receptors or homeostatic processes in the inner ear. This does not exclude the possibility that other receptor systems, elsewhere in the body could contribute to the symptoms of some individuals.

The main points of our analysis can be summarized as follows:

1) Hearing perception, mediated by the inner hair cells of the cochlea, is remarkably insensitive to infrasound.
2) Other sensory cells or structures in the inner ear, such as the outer hair cells, are more sensitive to infrasound than the inner hair cells and can be stimulated by low frequency sounds at levels below those that are heard. The concept that an infrasonic sound that cannot be heard can have no influence on inner ear physiology is incorrect.
3) Under some clinical conditions, such as Meniere's disease, superior canal dehiscence, or even asymptomatic cases of endolymphatic hydrops, individuals may be hypersensitive to infrasound.
4) A-weighting wind turbine sounds underestimates the likely influence of the sound on the ear. A greater effort should be made to document the infrasound component of wind turbine sounds under different conditions.
5) Based on our understanding of how low frequency sound is processed in the ear, and on reports indicating that wind turbine noise causes greater annoyance than other sounds of similar level and affects the quality of life in sensitive individuals, there is an urgent need for more research directly addressing the physiologic consequences of long-term, low level infrasound exposures on humans.

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EXHIBIT
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Exposure to Magnetic Field Non-Ionizing Radiation and the Risk of Miscarriage: A Prospective Cohort Study

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Magnetic field (MF) non-ionizing radiation is widespread and everyone is exposed to some degree. This prospective cohort study of 913 pregnant women examined the association between high MF exposure and miscarriage risk. Cox (proportional hazards) regression was used to examine the association. After controlling for multiple other factors, women who were exposed to higher MF levels had 2.72 times the risk of miscarriage (hazard ratio = 2.72, 95% CI: 1.42–5.19) than those with lower MF exposure. The increased risk of miscarriage associated with high MF was consistently observed regardless of the sources of high MF. The association was much stronger if MF was measured on a typical day of participants' pregnancies. The finding also demonstrated that accurate measurement of MF exposure is vital for examining MF health effects. This study provides fresh evidence, directly from a human population, that MF non-ionizing radiation could have adverse biological impacts on human health.

Magnetic fi ld (MF) non-ionizing radiation is a ubiquitous environmental exposure and a serious looming public health challenge. MFs are emitted from both traditional sources that generate low frequency MFs (e.g., power lines, appliances, transformers, etc.) and from emerging sources that generate higher frequency MFs (e.g., wireless networks, smart meter networks, cell towers, wireless devices such as cell phones, etc.). Humans are now widely exposed to MF with ever-increasing intensity, due to the proliferation of MF-generating apparatuses.

The steep increase in MF exposure has renewed concerns about the potential health effects of this invisible, man-made environmental exposure. A recent NIEHS multi-year project conducted by the National Toxicology Program (NTP) has revealed an increased risk of cancer associated with MF non-ionizing radiation exposure[1,2]. More specifi ally, the NTP study found that the cancer risk due to MF exposure observed in their experimental animals matched the cancer cell types that had been reported in previous epidemiologic studies in human populations[1]. Th s fi ding has made it more difficult to continue to dismiss possible biological effects of MF exposure. Such outright dismissal could be especially troublesome given the high prevalence of human exposure (with almost everyone being exposed to MF non-ionizing radiation to some degree). Th s includes vulnerable populations such as pregnant women and young children. The International Agency for Research on Cancer (IARC) has classifi d MF as a possible carcinogen[3,4].

Miscarriage is one of the potential adverse health outcomes that are sensitive to MF exposure and also an endpoint that the WHO has recommended to be further studied in the context of MF health effects[5]. Over the years, a few observational studies in human populations have suggested a possible link between MF exposure during pregnancy and an increased risk of miscarriage[6–11] including two studies published in 2002 that increased the public awareness of such an association[12,13]. In addition, one study examined human embryonic tissues to assess the association between EMF exposure and embryonic growth, and observed an increased risk of impaired embryonic bud growth and apoptosis associated with exposure to higher MF level[14], providing some direct evidence of adverse biological impact of EMF exposure on embryonic development.

Nevertheless, the association between MF exposure and risk of miscarriage remains largely unknown and overlooked. We conducted this prospective cohort study among a large population of pregnant women to further examine whether exposure to MF non-ionizing radiation during pregnancy increases the risk of miscarriage.

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Materials and Methods

Th s prospective cohort study was approved by the Kaiser Permanente Northern California (KPNC) Institutional Review Board and conducted among KPNC's pregnant members in the San Francisco Bay Area, all of whom provided informed consent. The study was performed in accordance with all relevant guidelines and regulations. KPNC is an integrated health care delivery system whose members comprise 28–30% of the population in the catchment area and have consistently been shown to be representative of the underlying population[15,16].

Study population. All pregnant women, aged 18 years or older, and residing in the participating Bay Area counties, were identifi d through the KPNC electronic medical record (EMR) laboratory database based on positive pregnancy tests. At KPNC, all women suspected to be pregnant were routinely asked to have a pregnancy test done at a KPNC facility. Flyers informing women about the study were posted at the participating facilities and given to women at the time of their pregnancy test. Given that miscarriage can occur very early in pregnancy, recruiting pregnant women as early as possible in their pregnancy was crucial to ensuring as complete ascertainment of miscarriage as possible. Our identifi ation of pregnant women through positive pregnancy lab tests ensured early recruitment. To determine whether a woman's recurrent miscarriage(s), an indication of higher susceptibility to miscarriage, increases her vulnerability to MF exposure, we oversampled women with two or more prior miscarriages. The pregnant women identifi d were contacted by a trained recruiter/interviewer to determine their eligibility and willingness to participate in the study. Those who indicated their intention to carry the pregnancy to term and whose gestational age at identifi ation was less than 10 completed weeks (still at risk for miscarriage) were invited to participate in the study. Among 1,627 eligible pregnant women, 1,054 agreed to participate in the study.

Measuring magnetic field exposure during pregnancy. All participating pregnant women were asked to carry an EMDEX Lite meter (Enertech Consultants Inc.) for 24 hours during pregnancy. The EMDEX Lite meter is specifi ally designed to measure MF, which is measured in milligauss (mG).

To ensure better representation of MF exposure during pregnancy and to apply the knowledge gained from the previous study[12], we designed the MF measurement to be conducted on a typical day (a day refl cting participants' typical pattern of work and leisure activities during pregnancy). In the event that a participant's daily activities might have been altered from what was originally planned, we also verifi d with the participants, at the end of the measurement period, whether the measurement day was indeed a typical day of their pregnancy. If not, the measurement day was classifi d as non-typical.

The EMDEX Lite meter was used to measure MF exposure levels by participating pregnant women from all emitting sources. Participants were also asked to keep a diary during the 24-hour measurement period to allow the researchers to (1) identify locations of daily activities (at home, at home in bed, in transit, at work, and other), (2) verify if activities were refl ctive of a typical day, and (3) examine if locations and activities were associated with high MF exposure.

MF data together with participants' diary of activities on the measurement day were examined for quality control, including consistency and potential errors. We excluded 31 subjects who failed to carry the meter as instructed. We also excluded 107 subjects who had incomplete (<90% of their 24-hour measurements) MF measurement data. Those exclusions were made without knowledge of subjects' pregnancy outcomes.

Previous studies have found that the highest MF levels that pregnant women encounter are the most relevant to miscarriage risk[12,13], indicating a possible threshold effect at a given MF level above which developmental embryos may cease to be viable. Thus, this study focused on high levels of MF exposure. We used the 99th percentile of MF measurements during the 24-hour period to classify exposure level, balancing between the need to examine as high of MF level as possible and, at the same time, avoid using less stable indices (e.g., maximum exposure level).

To more accurately refl ct participants' true MF exposure during pregnancy, we made signifi ant efforts to separate those participants whose measurements were conducted during a typical day of their pregnancy from those whose measurements were not conducted on a typical day. Measurements obtained on a ***typical day*** are likely more representative of MF exposure during pregnancy while measurements obtained on a *non-typical* day are more subject to misrepresentation of the true MF exposure level during pregnancy, resulting in misclassifying participants into incorrect MF exposure categories. Such misclassifi ation usually reduces scientists' ability to detect an underlying association. As demonstrated in a previous study, measurements conducted on a typical day showed a stronger association between MF exposure and miscarriage risk, while measurements conducted on a non-typical day showed virtually no association due to incorrectly classifying participants into MF exposure categories[12].

Measurement of miscarriage. Using KPNC EMR data, we were able to identify participants' pregnancy immediately after a positive pregnancy test, thereby starting follow-up at an earlier gestational age than the fi st prenatal visit, the earliest time at which most other studies have been able to identify pregnant women. Th s early follow-up allowed us to ascertain early miscarriages that most other studies would have missed, making it an important strength of this study.

All participants were followed for their pregnancy outcomes from the time of their positive pregnancy test to the end of their pregnancy. In the case of miscarriage, this is, by defin tion, before 20 completed weeks of gestation. We ascertained pregnancy outcomes through the KPNC EMR databases. For participants whose outcomes were not available in the EMR, we contacted them directly. We were able to identify pregnancy outcomes for all participants except one who had moved out of the area, thus she was excluded from further analysis.

In-person interview. An *in-person* interview was conducted with all participants to ascertain extensive information on potential confounders, including pregnancy history and risk factors for miscarriage. Previous studies have shown that MF exposure level is seldom related to common socio-demographic characteristics and risk factors[12,17,18]; thus, the number of potential confounders in this study was small. Nevertheless, we still collected many factors for examination to ensure thorough control of confounders. Two participants were not able to complete the interview, thus they were excluded from the analyses.

The prospective study design also ensured that the *in-person* interview was blinded to MF exposure for both interviewers and participants, since the EMF measurement was conducted after the interview. Th s study design enhances the quality of the study fi dings.

Statistical analysis. We used the Cox Proportional Hazards regression model, with accommodation for left truncation, to examine the association between MF exposure level and miscarriage. Hazard ratios with 95% confide ce intervals were used to determine the magnitude and signifi ance of associations. Left truncation arises when study participants enter observation at a point in time (i.e. gestational age at cohort entry) after the time of origin, conception. Participants were followed until either (a) miscarriage, (b) end of pregnancy due to other outcomes (e.g., ectopic pregnancy), at which point they were censored or (c) 20 weeks of gestation, for participants who remained pregnant at that time.

We examined confounders using the change-in-estimate criterion, including the confounder if the miscarriage hazard ratio (HR) for MF changed by 10% or more. While most factors examined were not confounders due to a lack of association with MF exposure, we nevertheless included in the model commonly known risk factors for miscarriage and socio-demographic characteristics.

Given the previous fi ding that the strength of association between MF and miscarriage varied by whether the MF measurements were taken on a typical or non-typical day[12], we fi st conducted analyses separately by day type. The previous fi ding was confi med in the current study, and we therefore conducted the remaining analyses only among those whose MF exposure was measured on ***a typical day*** of their pregnancy.

Since we oversampled those with multiple prior miscarriages, we fi st stratifi d analysis by those with and without multiple prior miscarriages to determine if the MF association with miscarriage risk differed between these two groups. Once it was determined that the observed associations were largely similar, we included all participants in the analyses and adjusted for prior miscarriage in all the models.

A total of 913 subjects with valid MF measurements and pregnancy outcomes were included in the fi al analysis.

Statistical analyses were conducted using SAS 9.3.

Results

Table 1 presents the description and characteristics of participants based on their MF exposure levels (high vs. low). The low MF exposure group consisted of women whose 99th percentile of MF exposure levels was in the lowest quartile (<2.5 mG), while those in the higher three quartiles were classifi d in the high MF exposure group. There were no noticeable associations or consistent patterns between MF exposure level and most of the factors examined, including risk factors for miscarriage (Table 1).

After adjustment for maternal age, race, education, smoking during pregnancy, and prior miscarriage, overall, pregnant women who had higher MF exposure during pregnancy (higher 3 quartiles) had a 48% greater risk of miscarriage than women who had lower MF exposure (in the lowest quartile): adjusted HR = 1.48, 95% confide ce interval (CI): 1.03–2.14 (Table 2). Notably, consistent with the fi ding in a prior study[12], the observed association was much stronger among participants whose MF exposure was measured on a typical day of the pregnancy (aHR = 2.72, 1.42–5.19). In contrast, there was no observed association among those whose MF was measured on a non-typical day (Table 2). Thus, the following analyses were restricted to those whose MF was measured on a typical day of their pregnancy.

Next, we examined the association separately among women with and without multiple prior miscarriages ($\geq$2). Table 3 showed that the association was largely similar between these two groups, with the association being slightly stronger among women without multiple prior miscarriages.

Table 4 shows the possible dose-response relationship by examining the association for each quartile using the lowest quartile (2.5 mG) as the reference group. While all higher quartiles showed an increased risk of miscarriage compared to the lowest MF exposure group, there was no dose-response relationship observed. These results are similar to those of a prior study[12].

The above-observed association was consistent regardless of the source of the MF. Although we did not have information on the exact sources from which MF was generated, based on participants' diary, we were able to examine whether MF exposure was from any of the following location categories: at home, at home in bed, at work, in transit, or from other sources. The association was observed consistently, regardless of the location. In addition to the adjusted variables mentioned above, further adjustment for nausea and vomiting as well as the following variables did not change the results in Tables 2–4: maternal income, marital status, maternal nausea/vomiting, alcohol use, caffeine intake, maternal fever, vaginal bleeding, urinary tract infection, carrying loads > 10 pounds, exposure to solvents or degreasers, vitamin intake, and Jacuzzi/hot tub/steam room/sauna use during pregnancy.

Discussion

After initial reports that provided evidence of an increased risk of miscarriage associated with high MF exposure during pregnancy[12,13], the current NIEHS-funded study provides additional evidence that exposure to high MF levels in pregnancy is associated with increased risk of miscarriage. Th s fi ding is also supported by four other studies published during the past 15 years that examined the relationship between high MF exposure and the risk of miscarriage[8–11,19]. Two of those studies measured EMF both inside, and in the surrounding areas, of the

Characteristic	Total N (N = 913)[a]	99th Percentile MF Level			
		Lowest quartile (N = 219)		Higher quartiles (N = 694)	
		N	%	N	%
Maternal age					
<30	296	61	*27.9%*	235	*33.9%*
30–34	288	71	*32.4%*	217	*31.3%*
≥35	329	87	*39.7%*	242	*34.9%*
Race					
White	326	91	*41.7%*	235	*34.0%*
Black	90	16	*7.3%*	74	*10.7%*
Hispanic	226	51	*23.4%*	175	*25.3%*
Asian /Pacific Islander	202	44	*20.2%*	158	*22.8%*
Other	66	16	*7.3%*	50	*7.2%*
Education					
<High school	42	5	*2.3%*	37	*5.4%*
High school or GED	142	32	*14.7%*	110	*15.9%*
Trade/Technical school	46	5	*2.3%*	41	*5.9%*
College degree	495	128	*58.7%*	367	*53.1%*
Graduate school	184	48	*22.0%*	136	*19.7%*
Marital Status					
Single	72	12	*5.5%*	60	*8.7%*
Partnered	147	31	*14.2%*	116	*16.8%*
Married	690	175	*80.3%*	515	*74.5%*
Worked in last year					
No	183	47	*21.6%*	136	*19.7%*
Yes	727	171	*78.4%*	556	*80.3%*
Smoked since LMP					
No	807	196	*91.2%*	611	*89.3%*
Yes	92	19	*8.8%*	73	*10.7%*
Coffee intake since LMP					
0 cup/day	637	142	*64.8%*	495	*71.3%*
0–1 cup/day	201	52	*23.7%*	149	*21.5%*
>1 cups/day	75	25	*11.4%*	50	*7.2%*
Alcohol use since LMP					
No	514	127	*58.3%*	387	*55.8%*
Yes	397	91	*41.7%*	306	*44.2%*
Number of previous pregnancies					
0	94	21	*9.6%*	73	*10.5%*
1	103	18	*8.2%*	85	*12.2%*
2	140	36	*16.4%*	104	*15.0%*
≥3	576	144	*65.8%*	432	*62.2%*
Number of previous miscarriages					
0	276	60	*27.4%*	216	*31.1%*
1	79	21	*9.6%*	58	*8.4%*
2	403	101	*46.1%*	302	*43.5%*
≥3	155	37	*16.9%*	118	*17.0%*
History of subfertility					
No	633	147	*67.1%*	486	*70.0%*
Yes	280	72	*32.9%*	208	*30.0%*
Vaginal bleeding since LMP					
No	670	165	*75.7%*	505	*72.9%*
Yes	241	53	*24.3%*	188	*27.1%*
Urinary tract infection since LMP					
No	860	211	*96.8%*	649	*93.9%*
Yes	49	7	*3.2%*	42	*6.1%*
Fever since LMP					
No	851	198	*92.1%*	653	*94.8%*

Continued

Characteristic	Total N (N = 913)[a]	99th Percentile MF Level			
		Lowest quartile (N = 219)		Higher quartiles (N = 694)	
		N	%	N	%
Yes	53	17	*7.9%*	36	*5.2%*
Carry loads (>10 pounds) since LMP					
No	416	92	*42.2%*	324	*46.8%*
Yes	494	126	*57.8%*	368	*53.2%*
Used Jacuzzi/hot tub/steam room/sauna since LMP					
No	807	200	*91.7%*	607	*87.7%*
Yes	103	18	*8.3%*	85	*12.3%*
Exposure to solvents or degreasers since LMP					
No	609	148	*68.5%*	461	*67.7%*
Yes	288	68	*31.5%*	220	*32.3%*
Vitamin use since LMP					
No	91	16	*7.3%*	75	*10.8%*
Yes	820	202	*92.7%*	618	*89.2%*
Gestational age at study entry					
0–48 days	763	173	*79.0%*	590	*85.0%*
49–69 days	135	41	*18.7%*	94	*13.5%*
≥70 days	15	5	*2.3%*	10	*1.4%*

Table 1. Characteristics of the Study Population by Daily Magnetic Field Exposure Level (Lowest or Higher Quartiles of MF 99th Percentile). Abbreviation: LMP, Last menstrual period. [a]The numbers in each individual category may not sum to the total number because of missing data.

99th Percentile MF Level	Total N	Miscarriage N (%)	cHR (95% CI)	aHR[a] (95% CI)
Among all participants				
Lowest quartile	219	36 (*16.4%*)	Ref	Ref
Higher quartiles	694	164 (*23.6%*)	1.43 (1.00–2.06)	1.48 (1.03–2.14)
MF measured on *typical days*				
Lowest quartile	106	11 (*10.4%*)	Ref	Ref
Higher quartiles	347	84 (*24.2%*)	2.46 (1.31–4.62)	**2.72** (1.42–5.19)
MF measured on non-typical days				
Lowest quartile	113	25 (*22.1%*)	Ref	Ref
Higher quartiles	347	80 (*23.1%*)	1.02 (0.65–1.62)	1.08 (0.67–1.73)

Table 2. Exposure to High Magnetic Fields (MFs) During Pregnancy and the Risk of Miscarriage. cHR: crude (unadjusted) hazard ratio; aHR: adjusted hazard ratio. 95% CI: 95% Confide ce interval. [a]Adjusted for maternal age at interview, race, education, smoking since LMP and prior miscarriage. Further adjustment for the following variables did not change the results: maternal nausea/vomiting, maternal income, marital status, alcohol use, caffeine intake, maternal fever, vaginal bleeding, urinary tract infection, carrying loads > 10lbs, exposure to solvents or degreasers, vitamin intake and Jacuzzi/hot tub/steam room/sauna use during pregnancy.

residence of participating pregnant women, and observed a higher risk of miscarriage associated with higher EMF exposure levels[8,9]. Two other studies examined the impact of EMF emitted from cell phones and wireless networks, and observed that more frequent cell phone use and close proximity to wireless base stations were both associated with an increased risk of miscarriage[10,11]. Although none of these studies conducted any personal MF measurements to capture actual MF exposure from all sources, as the current study has done, all four studies reported an increased risk of miscarriage associated with high MF exposure.

One of the most challenging aspects of assessing the health impact of MF exposure is the ability to measure MF exposure accurately as well as in the relevant etiological period. Prospectively measuring MF exposure in the etiologically relevant timeframe is essential and preferable to retrospective measurements. It is especially problematic to ascertain MF exposure long after the relevant window of exposure has passed. While logistically challenging, a prospective study design with a device that captures actual MF levels from all emitting sources in an etiologically relevant period will notably improve the accuracy of MF exposure assessment in epidemiological studies in a human population. In addition, as both this study and a previous study[12] demonstrated, even with a prospective design, if measurements were not conducted on a typical day to reflect true MF exposure during pregnancy, such study design could still fail to detect any MF health risk due to misclassifi ation of MF exposure (see Table 2). Therefore, to ensure accurate exposure assessment, MF measurements need to be conducted prospectively during an etiologically relevant window *and* to refl ct a participant's typical MF exposure patterns. The

99th Percentile MF Level	Total N	Miscarriage N (%)	cHR (95% CI)	aHR[a] (95% CI)
≤1 prior miscarriages				
Lowest quartile	39	3 (*7.7%*)	Ref	Ref
Higher quartiles	143	27 (*18.9%*)	**2.69** (0.82–8.87)	**3.76** (1.07–13.18)
≥2 prior miscarriages				
Lowest quartile	67	8 (*11.9%*)	Ref	Ref
Higher quartiles	204	57 (*27.9%*)	**2.43** (1.16–5.11)	**2.56** (1.19–5.50)

Table 3. Exposure to High Magnetic Fields (MFs) During Pregnancy and the Risk of Miscarriage, Stratified by Number of Prior Miscarriages, *MF Measured on Typical Days Only*. cHR: crude (unadjusted) hazard ratio; aHR: adjusted hazard ratio. 95% CI: 95% Confidence interval. [a]Adjusted for maternal age at interview, race, education, smoking since LMP, and gravidity. Further adjustment for the following variables did not change the results: maternal nausea/vomiting, maternal income, marital status, alcohol use, caffeine intake, maternal fever, vaginal bleeding, urinary tract infection, carrying loads > 10lbs, exposure to solvents or degreasers, vitamin intake and Jacuzzi/hot tub/steam room/sauna use during pregnancy.

99th Percentile MF Level	Total N	Miscarriage N (%)	cHR (95% CI)	aHR[a] (95% CI)
1st quartile (<2.5 mG)	106	11 (*10.4%*)	Ref	Ref
2nd quartile (2.5–3.6 mG)	116	32 (*27.6%*)	2.87 (1.45–5.70)	3.29 (1.59–6.79)
3rd quartile (3.7–6.2 mG)	119	31 (*26.1%*)	2.70 (1.36–5.39)	3.01 (1.48–6.12)
4th quartile (≥6.3 mG)	112	21 (*18.8%*)	1.83 (0.88–3.79)	2.02 (0.95–4.28)

Table 4. Exposure to High Magnetic Fields (MFs) During Pregnancy and the Risk of Miscarriage – Assessing Dose-Response, *MF Measured on Typical Days Only*. cHR: crude (unadjusted) hazard ratio; aHR: adjusted hazard ratio. 95% CI: 95% Confidence interval. [a]Adjusted for maternal age at interview, race, education, smoking since LMP, and prior miscarriage. Further adjustment for the following variables did not change the results: maternal nausea/vomiting, maternal income, marital status, alcohol use, caffeine intake, maternal fever, vaginal bleeding, urinary tract infection, carrying loads > 10lbs, exposure to solvents or degreasers, vitamin intake and Jacuzzi/hot tub/steam room/sauna use during pregnancy.

determination of whether the activity pattern was typical needs to be verified after measurement is complete since planned activities can change during the measurement day. It is clear that, if MF exposure is measured subjectively (e.g., interview based on participants' recall) or based on surrogate measures (e.g., wire codes, distance from power lines, job matrix, spot measurement at home, etc.), it would be very difficult for such studies to detect any MF health effect in epidemiological studies due to gross inaccuracies in measuring actual MF exposure levels. By definition, inaccurate MF measures lead to misclassification of MF exposure, which generally result in null findings. Unfortunately, the vast majority of epidemiological studies on MF health effects in the literature so far have been based on subjective and unreliable MF measurements. Thus, it is not surprising that many of the past studies failed to detect MF health effects. In addition, the focus on studying MF effects on cancer has exacerbated the problem, since the development of cancer usually has a long latency period between exposure and outcome that could span several decades. This has made accurately measure MF exposure in the etiologically relevant period (decades before the diagnosis of cancer) almost impossible. Those "null findings" have left a false impression of the "safety" of MF exposure.

The strength of this current study is that, in addition to using an objective measuring device (EMDEX Lite meter), we examined an outcome (miscarriage) with a short latency period (days or weeks rather than years or decades as in the case of cancers or autoimmune diseases). Thus, we were able to measure MF exposure prospectively in the relevant time period (during pregnancy). Furthermore, at the end of the measurement day, we ascertained whether activity patterns on that day reflected a typical day, which allowed us to identify participants with MF exposure measurements that more accurately reflected MF exposure during their pregnancies.

In this study, we found an almost three-fold increased risk of miscarriage if a pregnant woman was exposed to higher MF levels compared to women with lower MF exposure. The association was independent of any specific MF exposure sources or locations, thus removing the concern that other factors connected to the sources of the exposure might account for the observed associations. While nausea and vomiting were hypothesized to be potential confounders, adjustment for both nausea and vomiting did not change the results in this study or in a previous study[20]. Although we did not observe a dose-response relationship for MF exposure above 2.5 mG, this could be due to a threshold effect of MF exposure in which MF levels at or above 2.5 mG could lead to fetal demise, thus examining further higher levels of MF exposure were not able to confer additional risk.

Given the ubiquitous nature of exposure to this non-ionizing radiation, a small increased risk due to MF exposure could lead to unacceptable health consequences to pregnant women. Although the number of epidemiological studies examining the adverse impact of MF exposure in humans remains limited, the findings of this study should bring attention to this potentially important environmental hazard to pregnant women, at least in the context of miscarriage risk, and stimulate much needed additional research.

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Author Contributions

De-Kun Li conceived the concept, designed the study, obtained funding, oversaw the data gathering and analyses, and is responsible for the interpretation of results, and drafting and fi alizing the manuscript. Jeannette Ferber and Hong Chen were responsible for data management. Hong Chen was involved in data analysis and interpretation of the results. Roxana Odouli was involved in the study management and preparation of the manuscript. Charles Quesenberry was involved in interpretation of results and preparation of the manuscript. De-Kun Li is the guarantor of this paper who took full responsibility for the conduct of the study, had access to the data, and controlled the decision to publish.

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EXHIBIT
25

Public Health Impacts of Wind Turbines

Prepared by:
Minnesota Department of Health
Environmental Health Division

In response to a request from:
Minnesota Department of Commerce
Office of Energy Security

May 22, 2009

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I. Introduction

In late February 2009 the Minnesota Department of Health (MDH) received a request from the Office of Energy Security (OES) in the Minnesota Department of Commerce, for a "white paper" evaluating possible health effects associated with low frequency vibrations and sound arising from large wind energy conversion systems (LWECS). The OES noted that there was a request for a Contested Case Hearing before the Minnesota Public Utilities Commission (PUC) on the proposed Bent Tree Wind Project in Freeborn County Minnesota; further, the OES had received a long comment letter from a citizen regarding a second project proposal, the Lakeswind Wind Power Plant in Clay, Becker and Ottertail Counties, Minnesota. This same commenter also wrote to the Commissioner of MDH to ask for an evaluation of health issues related to exposure to low frequency sound energy generated by wind turbines. The OES informed MDH that a white paper would have more general application and usefulness in guiding decision-making for future wind projects than a Contested Case Hearing on a particular project. (Note: A Contested Case Hearing is an evidentiary hearing before an Administrative Law Judge, and may be ordered by regulatory authorities, in this case the PUC, in order to make a determination on disputed issues of material fact. The OES advises the PUC on need and permitting issues related to large energy facilities.)

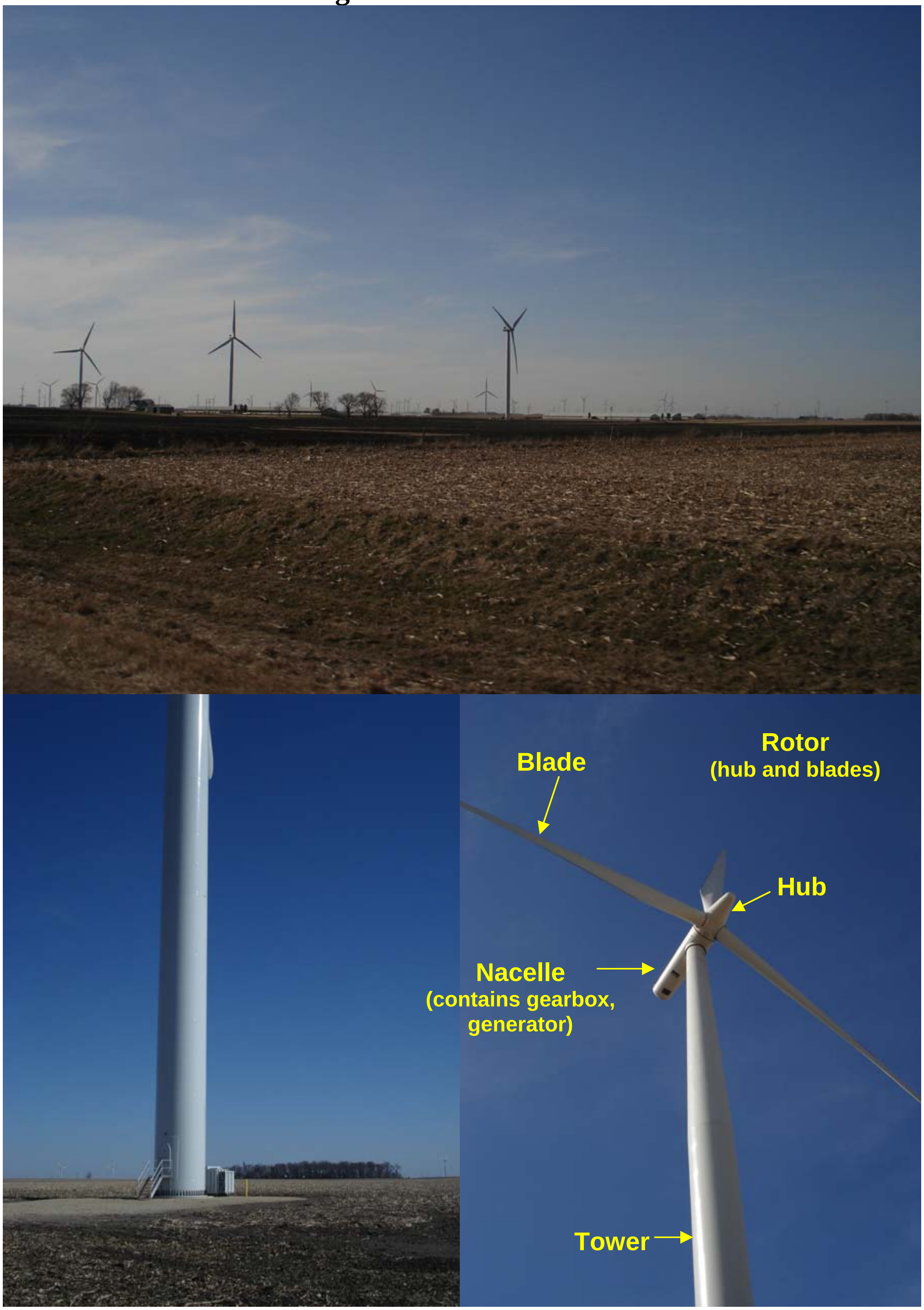
In early March 2009, MDH agreed to evaluate health impacts from wind turbine noise and low frequency vibrations. In discussion with OES, MDH also proposed to examine experiences and policies of other states and countries. MDH staff appeared at a hearing before the PUC on March 19, 2009, and explained the purpose and use of the health evaluation. The Commissioner replied to the citizen letter, affirming that MDH would perform the requested review.

A brief description of the two proposed wind power projects, and a brief discussion of health issues to be addressed in this report appear below.

A. Site Proposals

Wind turbines are huge and expensive machines requiring large capitol investment. Figure 1 shows some existing wind turbines in Minnesota. Large projects require control of extensive land area in order to optimize spacing of turbines to minimize turbulence at downwind turbines. Towers range up to 80 to 100 meters (260 to 325 feet), and blades can be up to 50 meters long (160 feet) (see Tetra Tech, 2008; WPL, 2008). Turbines are expected to be in place for 25-30 years.

Figure 1: Wind turbines



1. Bent Tree Wind Project in Freeborn County

This is a proposal by the Wisconsin Power and Light Company (WPL) for a 400 megawatt (MW) project in two phases of 200 MW each (requiring between 80 and 130 wind turbines). The cost of the first phase is estimated at $497 million. The project site area would occupy approximately 40 square miles located 4 miles north and west of the city of Albert Lea, approximately 95 miles south of Minneapolis (Figure 2) (WPL, 2008). The Project is a LWECS and a Certificate of Need (CON) from the PUC is required (*Minnesota Statutes 216B.243)*. The PUC uses the CON process to determine the basic type of facility (if any) to be constructed, the size of the facility, and when the project will be in service. The CON process involves a public hearing and preparation of an Environmental Report by the OES. The CON process generally takes a year, and is required before a facility can be permitted.

WPL is required to develop a site layout that optimizes wind resources. Accordingly, project developers are required to control areas at least 5 rotor diameters in the prevailing (north-south) wind directions (between about 1300 and 1700 feet for the 1.5 to 2.5 MW turbines under consideration for the project) and 3 rotor diameters in the crosswind (east-west) directions (between about 800 and 1000 feet). Thus, these are minimum setback distances from properties in the area for which easements have not been obtained. Further, noise rules promulgated by the Minnesota Pollution Control Agency (MPCA; *Minnesota Rules* Section 7030), specify a maximum nighttime noise in residential areas of 50 A-weighted decibels (dB(A). WPL has proposed a minimum setback of 1,000 feet from occupied structures in order to comply with the noise rule.

2. Noble Flat Hill Wind Park in Clay, Becker and Ottertail Counties

This is a LWECS proposed by Noble Flat Hill Windpark I (Noble), a subsidiary of Noble Environmental Power, based in Connecticut. The proposal is for a 201 MW project located 12 miles east of the City of Moorhead, about 230 miles northwest of Minneapolis (Figure 3) (Tetra Tech, 2008). The cost of the project is estimated to be between $382 million and $442 million. One hundred thirty-four GE 1.5 MW wind turbines are planned for an area of 11,000 acres (about 17 square miles); the site boundary encompasses approximately 20,000 acres. Setback distances of a minimum of 700 feet are planned to comply with the 50 dB(A) noise limit. However, rotor diameters will be 77 meters (250 feet). Therefore, setback distances in the prevailing wind direction of 1,300 feet are planned for properties where owners have not granted easements. Setbacks of 800 feet are planned in the crosswind direction.

Figure 2: Bent Tree Wind Project, Freeborn County

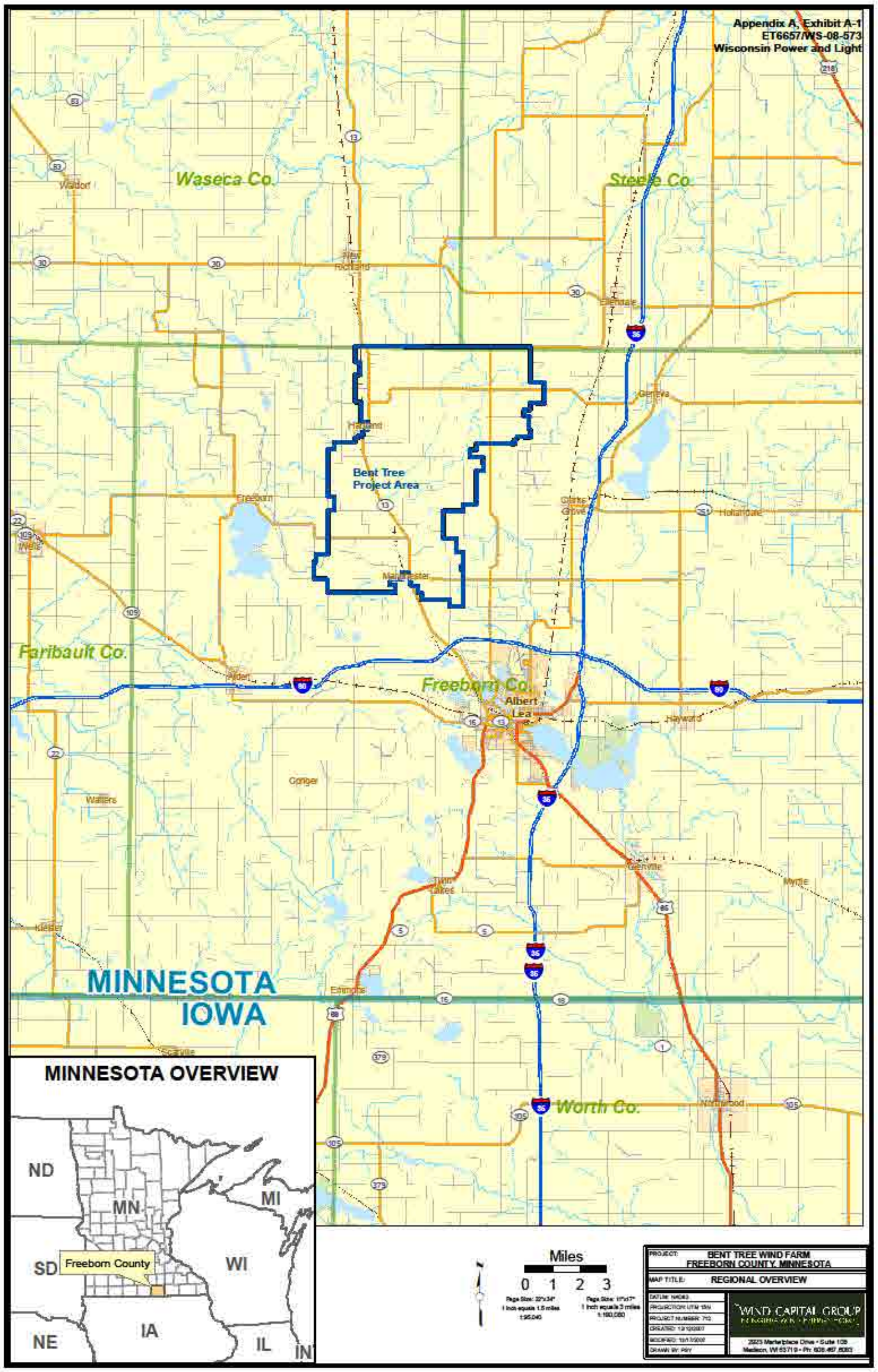
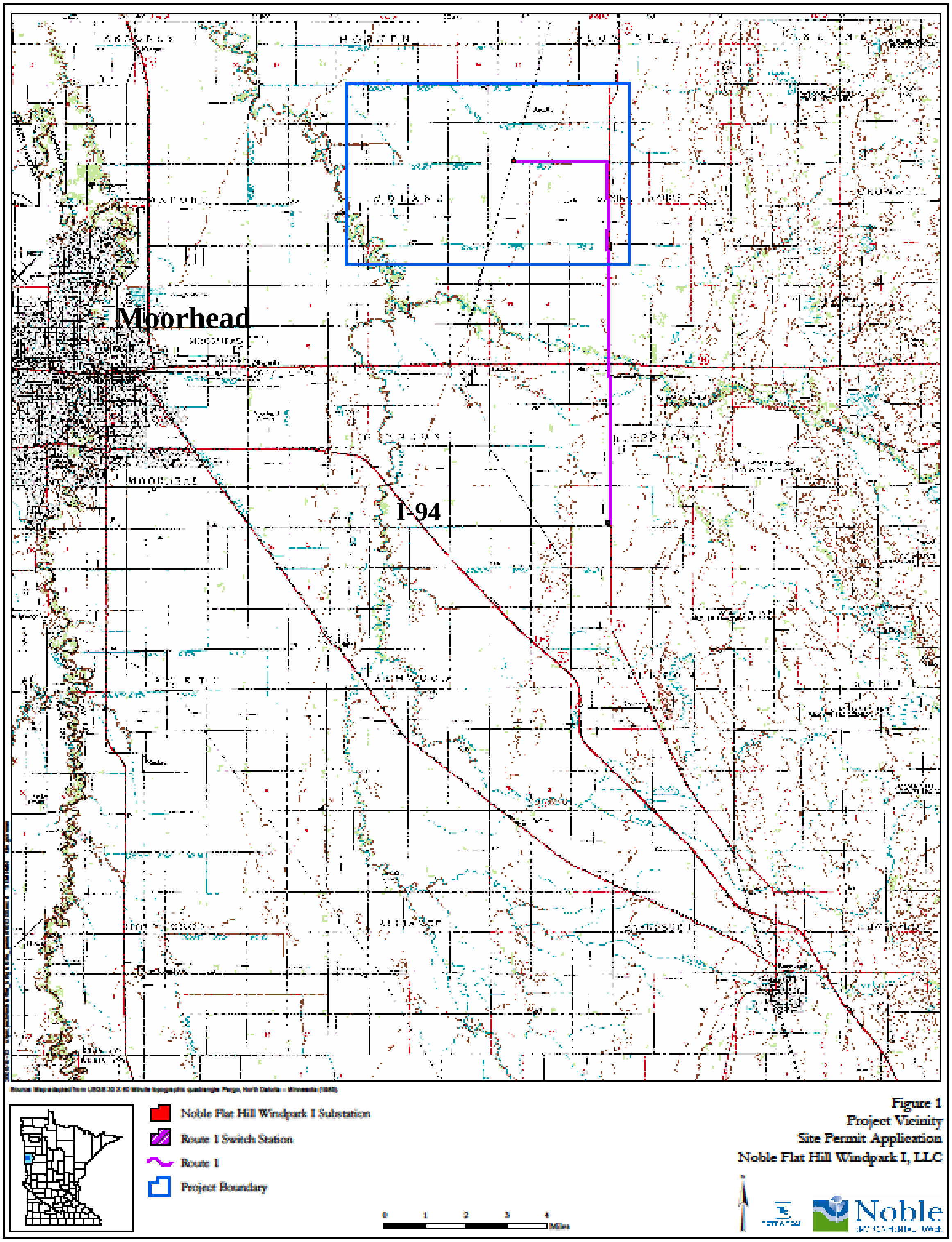


Figure 3: Noble Flat Hill Wind Park, Clay, Becker, Ottertail Counties



B. Health Issues

The National Research Council of the National Academies (NRC, 2007) has reviewed impacts of wind energy projects on human health and well-being. The NRC begins by observing that wind projects, just as other projects, create benefits and burdens, and that concern about impacts is natural when the source is near one's home. Further, the NRC notes that different people have different values and levels of sensitivity. Impacts noted by the NRC that may have the most effect on health include noise and low frequency vibration, and shadow flicker. While noise and vibration are the main focus of this paper, shadow flicker (casting of moving shadows on the ground as wind turbine blades rotate) will also be briefly discussed.

Noise originates from mechanical equipment inside the nacelles of the turbines (gears, generators, etc.) and from interaction of turbine blades with wind. Newer wind turbines generate minimal noise from mechanical equipment. The most problematic wind turbine noise is a broadband "whooshing" sound produced by interaction of turbine blades with the wind. Newer turbines have upwind rotor blades, minimizing low frequency "infrasound" (i.e., air pressure changes at frequencies below 20-100 Hz that are inaudible). However, the NRC notes that during quiet conditions at night, low frequency modulation of higher frequency sounds, such as are produced by turbine blades, is possible. The NRC also notes that effects of low frequency (infrasound) vibration (less than 20 Hz) on humans are not well understood, but have been asserted to disturb some people.

Finally, the NRC concludes that noise produced by wind turbines is generally not a major concern beyond a half mile. Issues raised by the NRC report and factors that may affect distances within which wind turbine noise may be problematic are discussed more extensively below.

II. Elementary Characteristics of Sensory Systems and Sound

A. Sensory Systems

1. Hearing

Sensory systems respond to a huge dynamic range of physical stimuli within a relatively narrow dynamic range of mechanical, chemical and/or neuronal (electrophysiological) output. Compression of the dynamic range is accomplished by systems that respond to logarithmic increases in intensity of physical stimuli with arithmetically increasing sensory responses. This general property is true for hearing, and has been recognized since at least the mid-19th century (see e.g., Woodworth and Schlosberg, 1964). "Loudness" is the sensory/perceptual correlate of the physical intensity of air pressure changes to which the electro-mechanical transducers in the ear and associated neuronal pathways are sensitive. Loudness increases as the logarithm of air pressure, and it is convenient to relate loudness to a reference air pressure (in dyne/cm^2 or pascals) in tenths of logarithmic units (decibels; dB). Further, the ear is sensitive to only a relatively narrow frequency range of air pressure changes: those between approximately 20 and 20,000 cycles per second or Herz (Hz). In fact, sensitivity varies within this range, so that the sound pressure level relative to a reference value that is audible in the middle of the range (near 1,000 Hz) is about 4 orders of magnitude smaller than it is at 20 Hz and about 2 orders of magnitude smaller than at 20,000 Hz (Fig. 3). Accordingly, measurements of loudness in dB generally employ filters to equalize the loudness of sounds at different frequencies or "pitch." To approximate the sensitivity of the ear, A-weighted filters weigh sound pressure changes at frequencies in the mid-range more than those at higher or lower frequencies. When an A-weighted filter is used, loudness is measured in dB(A). This is explained in greater detail in Section B below.

The ear accomplishes transduction of sound through a series of complex mechanisms (Guyton, 1991). Briefly, sound waves move the eardrum (tympanic membrane), which is in turn connected to 2 small bones (ossicles) in the middle ear (the malleus and incus). A muscle connected to the malleus keeps the tympanic membrane tensed, allowing efficient transmission to the malleus of vibrations on the membrane. Ossicle muscles can also relax tension and attenuate transmission. Relaxation of muscle tension on the tympanic membrane protects the ear from very loud sounds and also masks low frequency sounds, or much background noise. The malleus and incus move a third bone (stapes). The stapes in turn applies pressure to the fluid of the cochlea, a snail-shaped structure imbedded in temporal bone. The cochlea is a complex structure, but for present purposes it is sufficient to note that pressure changes or waves of different frequencies in cochlear fluid result in bending of specialized hair cells in regions of the cochlea most sensitive to different frequencies or pitch. Hair cells are directly connected to nerve fibers in the vestibulocochlear nerve (VIII cranial nerve).

Transmission of sound can also occur directly through bone to the cochlea. This is a very inefficient means of sound transmission, unless a device (e.g. a tuning fork or hearing aid) is directly applied to bone (Guyton, 1991).

2. Vestibular System

The vestibular system reacts to changes in head and body orientation in space, and is necessary for maintenance of equilibrium and postural reflexes, for performance of rapid and intricate body movements, and for stabilizing visual images (via the vestibulo-ocular reflex) as the direction of movement changes (Guyton, 1991).

The vestibular apparatus, like the cochlea, is imbedded in temporal bone, and also like the cochlea, hair cells, bathed in vestibular gels, react to pressure changes and transmit signals to nerve fibers in the vestibulocochlear nerve. Two organs, the utricle and saccule, called otolith organs, integrate information about the orientation of the head with respect to gravity. Otoliths are tiny stone-like crystals, embedded in the gels of the utricle and saccule, that float as the head changes position within the gravitational field. This movement is translated to hair cells. Three semi-circular canals, oriented at right angles to each other, detect head rotation. Stimulation of the vestibular apparatus is not directly detected, but results in activation of motor reflexes as noted above (Guyton, 1991).

Like the cochlea, the vestibular apparatus reacts to pressure changes at a range of frequencies; optimal frequencies are lower than for hearing. These pressure changes can be caused by body movements, or by direct bone conduction (as for hearing, above) when vibration is applied directly to the temporal bone (Todd et al., 2008). These investigators found maximal sensitivity at 100 Hz, with some sensitivity down to 12.5 Hz. The saccule, located in temporal bone just under the footplate of the stapes, is the most sound-sensitive of the vestibular organs (Halmagyi et al., 2004). It is known that brief loud clicks (90-95 dB) are detected by the vestibular system, even in deaf people. However, we do not know what the sensitivity of this system is through the entire range of sound stimuli.

While vestibular system activation is not directly felt, activation may give rise to a variety of sensations: vertigo, as the eye muscles make compensatory adjustments to rapid angular motion, and a variety of unpleasant sensations related to internal organs. In fact, the vestibular system interacts extensively with the “autonomic” nervous system, which regulates internal body organs (Balaban and Yates, 2004). Sensations and effects correlated with intense vestibular activation include nausea and vomiting and cardiac arrhythmia, blood pressure changes and breathing changes.

While these effects are induced by relatively intense stimulation, it is also true that A-weighted sound measurements attuned to auditory sensitivity, will underweight low frequencies for which the vestibular system is much more sensitive (Todd et al., 2008). Nevertheless, activation of the vestibular system *per se* obviously need not give rise to unpleasant sensations. It is not known what stimulus intensities are generally required for for autonomic activation at relatively low frequencies, and it is likely that there is considerable human variability and capacity to adapt to vestibular challenges.

B. Sound

1. Introduction

Sound is carried through air in compression waves of measurable frequency and amplitude. Sound can be tonal, predominating at a few frequencies, or it can contain a random mix of a broad range of frequencies and lack any tonal quality (white noise). Sound that is unwanted is called noise.

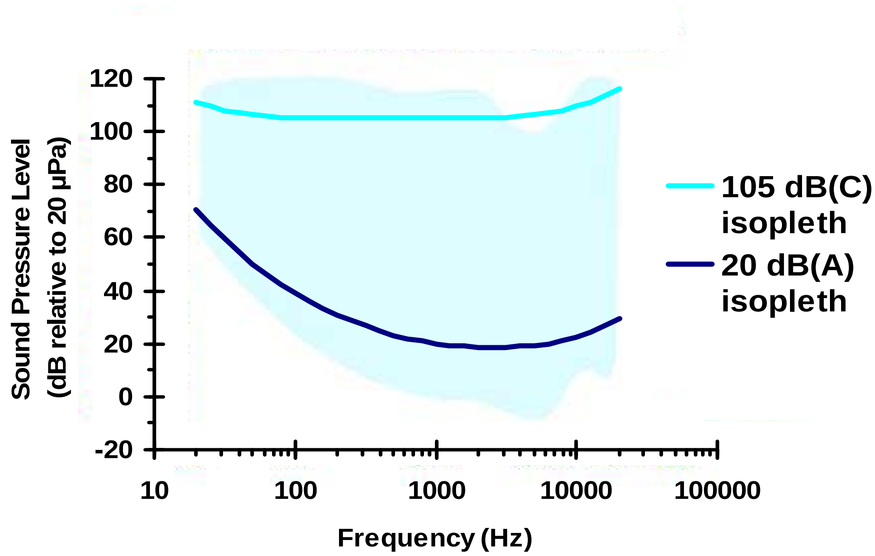
Audible Frequency Sound

Besides frequency sensitivity (between 20 and 20,000 Hz), humans are also sensitive to changes in the amplitude of the signal (compression waves) within this audible range of frequencies. Increasing amplitude, or increasing sound pressure, is perceived as increasing volume or loudness. The sound pressure level in air (SPL) is measured in micro Pascals (μPa). SPLs are typically converted in measuring instruments and reported as decibels (dB) which is a log scale, relative unit (see above). When used as the unit for sound, dBs are reported relative to a SPL of 20 μPa. Twenty μPa is used because it is the approximate threshold of human hearing sensitivity at about 1000 Hz. Decibels relative to 20 μPa are calculated from the following equation:

$$\text{Loudness (dB)} = \text{Log}\left(\left(\text{SPL} / 20\ \mu\text{Pa}\right)^2\right) * 10$$

Figure 4 shows the audible range of normal human hearing. Note that while the threshold sensitivity varies over the frequency range, at high SPLs sensitivity is relatively consistent over audible frequencies.

Figure 4: Audible Range of Human Hearing



Equivalence curves for different frequencies, when sound meter readings in dB are taken with A or C-weighting filters. (Adapted from EPD Hong Kong SAR, 2009)

Sub-Audible Frequency Sound

Sub-audible frequency sound is often called infrasound. It may be sensed by people, similar to audible sound, in the cochlear apparatus in the ear; it may be sensed by the vestibular system which is responsible for balance and physical equilibrium; or it may be sensed as vibration.

Resonance and modulation

Sound can be attenuated as it passes through a physical structure. However, because the wavelength of low frequency sound is very long (the wavelength of 40 Hz in air at sea level and room temperature is 8.6 meters or 28 ft), low frequencies are not effectively attenuated by walls and windows of most homes or vehicles. (For example, one can typically hear the bass, low frequency music from a neighboring car at a stoplight, but not the higher frequencies.) In fact, it is possible that there are rooms within buildings exposed to low frequency sound or noise where some frequencies may be amplified by resonance (e.g. ½ wavelength, ¼ wavelength) within the structure. In addition, low frequency sound can cause vibrations within a building at higher, more audible frequencies as well as throbbing or rumbling.

Sounds that we hear generally are a mixture of different frequencies. In most instances these frequencies are added together. However, if the source of the sound is not constant, but changes over time, the effect can be re-occurring pulses of sound or low frequency modulation of sound. This is the type of sound that occurs from a steam engine, a jack hammer, music and motor vehicle traffic. Rhythmic, low frequency pulsing of higher frequency noise (like the sound of an amplified heart beat) is one type of sound that can be caused by wind turbine blades under some conditions.

2. Human Response to Low Frequency Stimulation

There is no consensus whether sensitivity below 20 Hz is by a similar or different mechanism than sensitivity and hearing above 20 Hz (Reviewed by Møller and Pedersen, 2004). Possible mechanisms of sensation caused by low frequencies include bone conduction at the applied frequencies, as well as amplification of the base frequency and/or harmonics by the auditory apparatus (eardrum and ossicles) in the ear. Sensory thresholds are relatively continuous, suggesting (but not proving) a similar mechanism above and below 20 Hz. However, it is clear that cochlear sensitivity to infrasound (< 20 Hz) is considerably less than cochlear sensitivity to audible frequencies.

Møller and Pedersen (2004) reviewed human sensitivity at low and infrasonic frequencies. The following findings are of interest:

- When whole-body pressure-field sensitivity is compared with ear-only (earphone) sensitivity, the results are very similar. These data suggest that the threshold sensitivity for low frequency is through the ear and not vestibular.
- Some individuals have extraordinary sensitivity at low frequencies, up to 25 dB more sensitive than the presumed thresholds at some low frequencies.
- While population average sensitivity over the low frequency range is smooth, sound pressure thresholds of response for individuals do not vary smoothly but are inconsistent, with peaks and valleys or “microstructures”. Therefore the sensitivity response of individuals to different low frequency stimulation may be difficult to predict.
- Studies of equal-loudness-levels demonstrate that as stimulus frequency decreases through the low frequencies, equal-loudness lines compress in the dB scale. (See Figure 4 as an example of the relatively small difference in auditory SPL range between soft and loud sound at low frequencies).
- The hearing threshold for pure tones is different than the hearing threshold for white noise at the same total sound pressure.

3. Sound Measurements

Sound measurements are taken by instruments that record sound pressure or the pressure of the compression wave in the air. Because the loudness of a sound to people is usually the primary interest in measuring sound, normalization schemes or filters have been applied to absolute measurements. dB(A) scaling of sound pressure measurements was intended to normalize readings to equal loudness over the audible range of frequencies at low loudness. For example, a 5,000 Hz (5 kHz) and 20 dB(A) tone is expected to have the same intensity or loudness as a 100 Hz, 20 dB(A) tone. However, note that the absolute sound pressures would be about 200 μPa and 2000 μPa, respectively, or about a difference of 20 dB (relative to 20 μPa), or as it is sometimes written 20 dB(linear).

Most sound is not a single tone, but is a mixture of frequencies within the audible range. A sound meter can add the total SPLs for all frequencies; in other words, the dB readings over the entire spectrum of audible sound can be added to give a single loudness metric. If sound is reported as A-weighted, or dB(A), it is a summation of the dB(A) scaled sound pressure from 20 Hz to 20 kHz.

In conjunction with the dB(A) scale, the dB(B) scale was developed to approximate equal loudness to people across audible frequencies at medium loudness, and dB(C) was developed to approximate equal-loudness for loud environments. Figure 4 shows isopleths for 20 dB(A) and 105 dB(C). While dB(A), dB(B), dB(C) were developed from empirical data at the middle frequencies, at the ends of the curves these scales were extrapolated, or sketched in, and are not based on experimental or observational data (Berglund et al., 1996). As a result, data in the low frequency range (and probably the highest audible frequencies as well) cannot be reliably interpreted using these scales. The World Health Organization (WHO, 1999) suggests that A-weighting noise that has a large low frequency component is not reliable assessment of loudness.

The source of the noise, or the noise signature, may be important in developing equal-loudness schemes at low frequencies. C-weighting has been recommended for artillery noise, but a linear, unweighted scale may be even better at predicting a reaction (Berglund et al., 1996). A linear or equal energy rating also appears to be the most effective predictor of reaction to low frequency noise in other situations, including blast noise from mining. The implication of the analysis presented by Berglund et al. (1996) is that annoyance from non-tonal noise should not be estimated from a dB(A) scale, but may be better evaluated using dB(C), or a linear non-transformed scale.

However, as will be discussed below, a number of schemes use a modified dB(A) scale to evaluate low frequency noise. These schemes differ from a typical use of the dB(A) scale by addressing a limited frequency range below 250 Hz, where auditory sensitivity is rapidly changing as a function of frequency (see Figure 4).

III. Exposures of Interest

A. Noise From Wind Turbines

1. Mechanical noise

Mechanical noise from a wind turbine is sound that originates in the generator, gearbox, yaw motors (that intermittently turn the nacelle and blades to face the wind), tower ventilation system and transformer. Generally, these sounds are controlled in newer wind turbines so that they are a fraction of the aerodynamic noise. Mechanical noise from the turbine or gearbox should only be heard above aerodynamic noise when they are not functioning properly.

2. Aerodynamic noise

Aerodynamic noise is caused by wind passing over the blade of the wind turbine. The tip of a 40-50 meter blade travels at speeds of over 140 miles per hour under normal operating conditions. As the wind passes over the moving blade, the blade interrupts the laminar flow of air, causing turbulence and noise. Current blade designs minimize the amount of turbulence and noise caused by wind, but it is not possible to eliminate turbulence or noise.

Aerodynamic noise from a wind turbine may be underestimated during planning. One source of error is that most meteorological wind speed measurements noted in wind farm literature are taken at 10 meters above the ground. Wind speed above this elevation, in the area of the wind turbine rotor, is then calculated using established modeling relationships. In one study (van den Berg, 2004) it was determined that the wind speeds at the hub at night were up to 2.6 times higher than modeled. Subsequently, it was found that noise levels were 15 dB higher than anticipated.

Unexpectedly high aerodynamic noise can also be caused by improper blade angle or improper alignment of the rotor to the wind. These are correctable and are usually adjusted during the turbine break-in period.

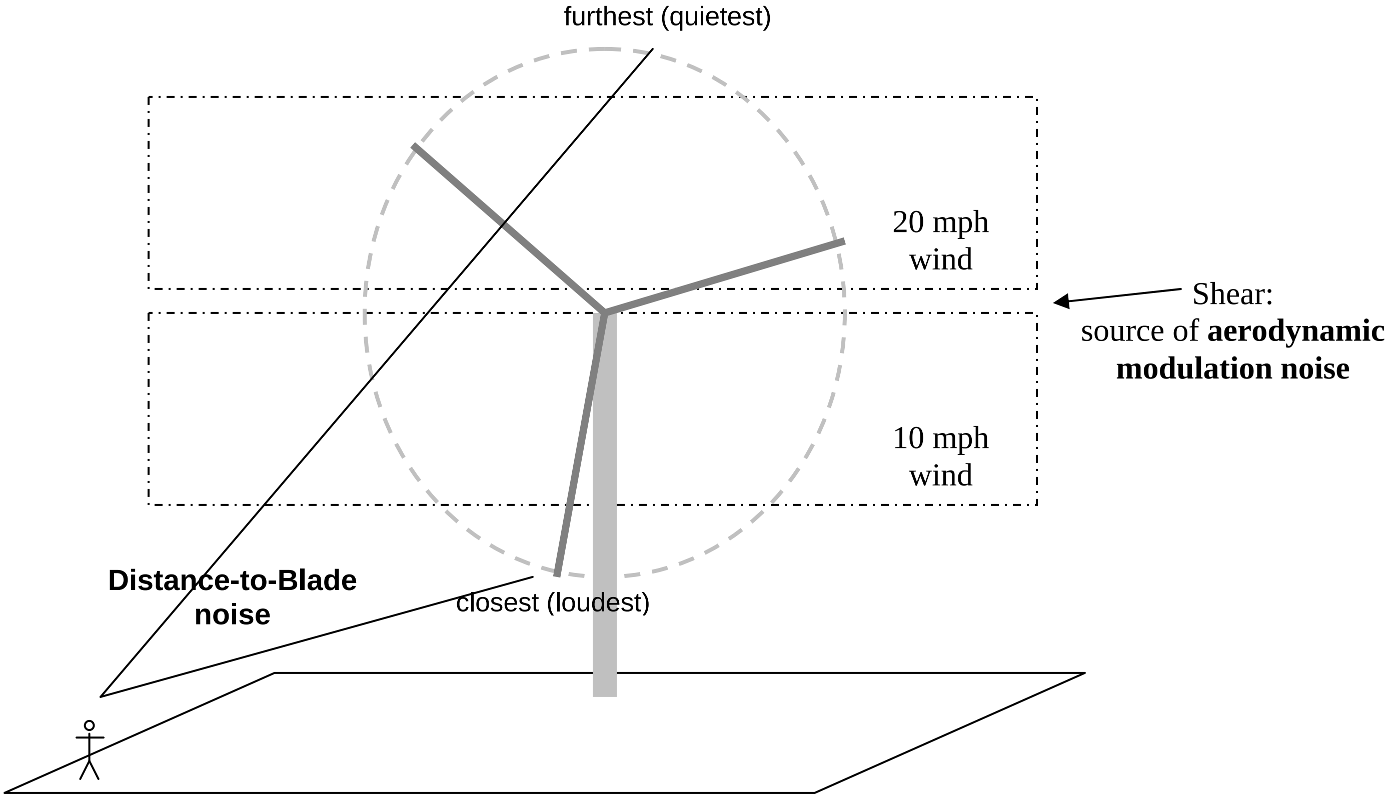
3. Modulation of aerodynamic noise

Rhythmic modulation of noise, especially low frequency noise, has been found to be more annoying than steady noise (Bradley, 1994; Holmberg et al., 1997). One form of rhythmic modulation of aerodynamic noise that can be noticeable very near to a wind turbine is a distance-to-blade effect. To a receptor on the ground in front of the wind turbine, the detected blade noise is loudest as the blade passes, and quietest when the blade is at the top of its rotation. For a modern 3-blade turbine, this distance-to-blade effect can cause a pulsing of the blade noise at about once per second (1 Hz). On the ground, about 500 feet directly downwind from the turbine, the distance-to-blade can cause a difference in sound pressure of about 2 dB between the *tip* of the blade at its farthest point and the *tip* of the blade at its nearest point (48 meter blades, 70 meter tower). Figure 5 demonstrates why the loudness of blade noise (aerodynamic noise) pulses as the distance-to-blade varies for individuals close to a turbine.

If the receptor is 500 feet from the turbine base, in line with the blade rotation or up to 60° off line, the difference in sound pressure from the *tip* of the blade at its farthest and nearest point can be about 4-5 dB, an audible difference. The tip travels faster than the rest of the blade and is closer to (and then farther away from) the receptor than other parts of the blade. As a result, noise from other parts of the blade will be modulated less than noise from the tip. Further, blade design can also affect the noise signature of a blade. The distance-to-blade effect diminishes as receptor distance increases because the relative difference in distance from the receptor to the top or to the bottom of the blade becomes smaller. Thus, moving away from the tower, distance-to-blade noise gradually appears to be more steady.

Another source of rhythmic modulation may occur if the wind through the rotor is not uniform. Blade angle, or pitch, is adjusted for different wind speeds to maximize power and to minimize noise. A blade angle that is not properly tuned to the wind speed (or wind direction) will make more noise than a properly tuned blade. Horizontal layers with different wind speeds or directions can form in the atmosphere. This wind condition is called shear. If the winds at the top and bottom of the blade rotation are different, blade noise will vary between the top and bottom of blade rotation, causing modulation of aerodynamic noise. This noise, associated with the blades passing through areas of different air-wind speeds, has been called aerodynamic modulation and is demonstrated in Figure 5.

Figure 5: Sources of noise modulation or pulsing



In some terrains and under some atmospheric conditions wind aloft, near the top of the wind turbine, can be moving faster than wind near the ground. Wind turbulence or even wakes from adjacent turbines can create non-uniform wind conditions as well. As a result of aerodynamic modulation a rhythmic noise pattern or pulsing will occur as each blade passes through areas with different wind speed. Furthermore, additional noise, or thumping, may occur as each blade passes through the transition between different wind speed (or wind direction) areas.

Wind shear caused by terrain or structures on the ground (e.g. trees, buildings) can be modeled relatively easily. Wind shear in areas of flat terrain is not as easily understood. During the daytime wind in the lower atmosphere is strongly affected by thermal convection which causes mixing of layers. Distinct layers do not easily form. However, in the nighttime the atmosphere can stabilize (vertically), and layers form. A paper by G.P. van den Berg (2008) included data from a study on wind shear at Cabauw, The Netherlands (flat terrain). Annual average wind speeds at different elevations above ground was reported. The annual average wind speed at noon was about 5.75 meters per second (m/s; approximately 12.9 miles per hour(mph)) at 20 m above ground, and about 7.6 m/s (17 mph) at 140 m. At midnight, the annual averages were about 4.3 m/s (9.6 mph) and 8.8 m/s (19.7 mph) for 20m and 140 m, respectively, above ground. The data show that while the average windspeed (between 20m and 140m) is very similar at noon and midnight at Cabauw, the windspeed difference between elevations during the day is much less than the difference at night (1.85 m/s (4.1 mph) and 4.5 m/s (10 mph), respectively). As a result one would expect that the blade angle can be better tuned to the wind speed during the daytime. Consequently, blade noise would be greater at night.

A number of reports have included discussion of aerodynamic modulation (van den Berg, 2005; UK Department of Transport and Industry, 2006; UK Department for Business Enterprise and Regulatory Reform, 2007; van den Berg, 2008). They suggest that aerodynamic modulation is typically underestimated when noise estimates are calculated. In addition, they suggest that detailed modeling of wind, terrain, land use and structures may be used to predict whether modulation of aerodynamic noise will be a problem at a proposed wind turbine site.

4. Wind farm noise

The noise from multiple turbines similarly distant from a residence can be noticeably louder than a lone turbine simply through the addition of multiple noise sources. Under steady wind conditions noise from a wind turbine farm may be greater than noise from the nearest turbine due to synchrony between noise from more than one turbine (van den Berg, 2005). Furthermore, if the dominant frequencies (including aerodynamic modulation) of different turbines vary by small amounts, an audible beat or dissonance may be heard when wind conditions are stable.

B. Shadow Flicker

Rhythmic light flicker from the blades of a wind turbine casting intermittent shadows has been reported to be annoying in many locations (NRC, 2007; Large Wind Turbine Citizens Committee, 2008). (Note: Flashing light at frequencies around 1 Hz is too slow to trigger an epileptic response.)

Modeling conducted by the Minnesota Department of Health suggests that a receptor 300 meters perpendicular to, and in the shadow of the blades of a wind turbine, can be in the flicker shadow of the rotating blade for almost 1½ hour a day. At this distance a blade may completely obscure the sun each time it passes between the receptor and the sun. With current wind turbine designs, flicker should not be an issue at distances over 10 rotational diameters (~1000 meters or 1 km (0.6 mi) for most current wind turbines). This distance has been recommended by the Wind Energy Handbook (Burton et al., 2001) as a minimum setback distance in directions that flicker may occur, and has been noted in the Bent Tree Permit Application (WPL, 2008).

Shadow flicker is a potential issue in the mornings and evenings, when turbine noise may be masked by ambient sounds. While low frequency noise is typically an issue indoors, shadow flicker can be an issue both indoors and outdoors when the sun is low in the sky. Therefore, shadow flicker may be an issue in locations other than the home.

Ireland recommends wind turbines setbacks of at least 300 meters from a road to decrease driver distraction (Michigan State University, 2004). The NRC (2007) recommends that shadow flicker is addressed during the preliminary planning stages of a wind turbine project.

IV. Impacts of Wind Turbine Noise

A. Potential Adverse Reaction to Sound

Human sensitivity to sound, especially to low frequency sound, is variable. Individuals have different ranges of frequency sensitivity to audible sound; different thresholds for each frequency of audible sound; different vestibular sensitivities and reactions to vestibular activation; and different sensitivity to vibration.

Further, sounds, such as repetitive but low intensity noise, can evoke different responses from individuals. People will exhibit variable levels of annoyance and tolerance for different frequencies. Some people can dismiss and ignore the signal, while for others, the signal will grow and become more apparent and unpleasant over time (Moreira and Bryan, 1972; Bryan and Tempest, 1973). These reactions may have little relationship to will or intent, and more to do with previous exposure history and personality.

Stress and annoyance from noise often do not correlate with loudness. This may suggest, in some circumstances, other factors impact an individual's reaction to noise. A number of reports, cited in Staples (1997), suggest that individuals with an interest in a project and individuals who have some control over an environmental noise are less likely to find a noise annoying or stressful.

Berglund et al. (1996) reviewed reported health effects from low frequency noise. Loud noise from any source can interfere with verbal communication and possibly with the development of language skills. Noise may also impact mental health. However, there are no studies that have looked specifically at the impact of low frequency noise on communication, development of language skills and mental health. Cardiovascular and endocrine effects have been demonstrated in studies that have looked at exposures to airplane and highway noise. In addition, possible effects of noise on performance and cognition have also been investigated, but these health studies have not generally looked at impacts specifically from low frequency noise. Noise has also been shown to impact sleep and sleep patterns, and one study demonstrated impacts from low frequency noise in the range of 72 to 85 dB(A) on chronic insomnia (Nagai et al., 1989 as reported in Berglund et al., 1996).

Case studies have suggested that health can be impacted by relatively low levels of low frequency noise. But it is difficult to draw general conclusions from case studies. Feldmann and Pitten (2004)) describe a family exposed during the winter to low frequency noise from a nearby heating plant. Reported health impacts were: "indisposition, decrease in performance, sleep disturbance, headache, ear pressure, crawl parästhesy [crawling, tingling or numbness sensation on the skin] or shortness of breath."

Annoyance, unpleasant sounds, and complaints

Reported health effects from low frequency stimulation are closely associated with annoyance from audible noise. "There is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects" (WHO, 1999). It has not been shown whether annoyance is a symptom or an accessory in the causation of health impacts from low frequency noise. Studies have been conducted on some aspects of low frequency noise that can cause annoyance.

Noise complaints are usually a reasonable measure of annoyance with low frequency environmental noise. Leventhall (2004) has reviewed noise complaints and offers the following conclusions:

> “ The problems arose in quiet rural or suburban environments
> The noise was often close to inaudibility and heard by a minority of people
> The noise was typically audible indoors and not outdoors
> The noise was more audible at night than day
> The noise had a throb or rumble characteristic
> The main complaints came from the 55-70 years age group
> The complainants had normal hearing.
> Medical examination excluded tinnitus.
>
> “ These are now recognised as classic descriptors of low frequency noise problems.”

These observations are consistent with what we know about the propagation of low intensity, low frequency noise. Some people are more sensitive to low frequency noise. The difference, in dB, between soft (acceptable) and loud (annoying) noise is much less at low frequency (see Figure 4 audible range compression). Furthermore, during the daytime, and especially outdoors, annoying low frequency noise can be masked by high frequency noise.

The observation that “the noise was typically audible indoors and not outdoors” is not particularly intuitive. However, as noted in a previous section, low frequencies are not well attenuated when they pass through walls and windows. Higher frequencies (especially above 1000 Hz) can be efficiently attenuated by walls and windows. In addition, low frequency sounds may be amplified by resonance within rooms and halls of a building. Resonance is often characterized by a throbbing or a rumbling, which has also been associated with many low frequency noise complaints.

Low frequency noise, unlike higher frequency noise, can also be accompanied by shaking, vibration and rattling. In addition, throbbing and rumbling may be apparent in some low frequency noise. While these noise features may not be easily characterized, numerous studies have shown that their presence dramatically lowers tolerance for low frequency noise (Berglund et al., 1996).

As reviewed in Leventhall (2003), a study of industrial exposure to low frequency noise found that fluctuations in total noise averaged over 0.5, 1.0 and 2.0 seconds correlated with annoyance (Holmberg et al., 1997). This association was noted elsewhere and led (Broner and Leventhall, 1983) to propose a 3dB “penalty” be added to evaluations of annoyance in cases where low frequency noise fluctuated.

In another laboratory study with test subjects controlling loudness, 0.5 – 4 Hz modulation of low frequency noise was found to be more annoying than non-modulated low frequency noise. On average test subjects found modulated noise to be similarly annoying as a constant tone 12.9 dB louder (Bradley, 1994).

B. Studies of Wind Turbine Noise Impacts on People

1. Swedish Studies

Two studies in Sweden collected information by questionnaires from 341 and 754 individuals (representing response rates of 68% and 58%, respectively), and correlated responses to calculated exposure to noise from wind farms (Pedersen and Waye, 2004; Pedersen, 2007; Pedersen and Persson, 2007). Both studies showed that the number of respondents perceiving the noise from the wind turbines increased as the calculated noise levels at their homes increased from less than 32.5 dB(A) to greater than 40 dB(A). Annoyance appeared to correlate or trend with calculated noise levels. Combining the data from the two studies, when noise measurements were greater than 40 dB(A), about 50% of the people surveyed (22 of 45 people) reported annoyance. When noise measurements were between 35 and 40 dB(A) about 24% reported annoyance (67 of 276 people). Noise annoyance was more likely in areas that were rated as quiet and in areas where turbines were visible. In one of the studies, 64% respondents who reported noise annoyance also reported sleep disturbance; 15% of respondents reported sleep disturbance without annoyance.

2. United Kingdom Study

Moorhouse et al. (UK Department for Business Enterprise and Regulatory Reform, 2007) evaluated complaints about wind farms. They found that 27 of 133 operating wind farms in the UK received formal complaints between 1991 and 2007. There were a total of 53 complainants for 16 of the sites for which good records were available. The authors of the report considered that many complaints in the early years were for generator and gearbox noise. However, subjective analyses of reports about noise ("like a train that never gets there", "distant helicopter", "thumping", "thudding", "pulsating", "thumping", "rhythmical beating", and "beating") suggested that aerodynamic modulation was the likely cause of complaints at 4 wind farms. The complaints from 8 other wind farms may have had "marginal" association with aerodynamic modulation noise.

Four wind farms that generated complaints possibly associated with aerodynamic modulation were evaluated further. These wind farms were commissioned between 1999 and 2002. Wind direction, speed and times of complaints were associated for 2 of the sites and suggested that aerodynamic modulation noise may be a problem between 7% and 25% of the time. Complaints at 2 of the farms have stopped and at one farm steps to mitigate aerodynamic modulation (operational shutdown under certain meteorological conditions) have been instituted.

3. Netherlands Study

F. van den Berg et al. (2008) conducted a postal survey of a group selected from all residents in the Netherlands within 2.5 kilometers (km) of a wind turbine. In all, 725 residents responded (37%). Respondents were exposed to sound between 24 and 54 dB(A). The percentage of respondents annoyed by sound increased from 2% at levels of 30 dB(A) or less, up to 25% at between 40 and 45 dB. Annoyance decreased above 45 dB. Most residents exposed above 45 dB(A) reported economic benefits from the turbines. However, at greater than 45 dB(A) more respondents reported sleep interruption. Respondents tended to report more annoyance when they also noted a negative effect on landscape, and ability to see the turbines was strongly related to the probability of annoyance.

4. Case Reports

A number of un-reviewed reports have catalogued complaints of annoyance and some more severe health impacts associated with wind farms. These reports do not contain measurements of noise levels, and do not represent random samples of people living near wind turbines, so they cannot assess prevalence of complaints. They do generally show that in the people surveyed, complaints are more likely the closer people are to the turbines. The most common complaint is decreased quality of life, followed by sleep loss and headache. Complaints seem to be either from individuals with homes quite close to turbines, or individuals who live in areas subject to aerodynamic modulation and, possibly, enhanced sound propagation which can occur in hilly or mountainous terrain. In some of the cases described, people with noise complaints also mention aesthetic issues, concern for ecological effects, and shadow flicker concerns. Not all complaints are primarily about health.

Harry (2007) describes a meeting with a couple in Cornwall, U.K. who live 400 meters from a wind turbine, and complained of poor sleep, headaches, stress and anxiety. Harry subsequently investigated 42 people in various locations in the U.K. living between 300 meters and 2 kilometers (1000 feet to 1.2 miles) from the nearest wind turbine. The most frequent complaint (39 of 42 people) was that their quality of life was affected. Headaches were reported by 27 people and sleep disturbance by 28 people. Some people complained of palpitations, migraines, tinnitus, anxiety and depression. She also mentions correspondence and complaints from people in New Zealand, Australia, France, Germany, Netherlands and the U.S.

Phipps (2007) discusses a survey of 619 households living up to 10 kilometers (km; 6 miles) from wind farms in mountainous areas of New Zealand. Most respondents lived between 2 and 2.5 km from the turbines (over 350 households). Most respondents (519) said they could see the turbines from their homes, and 80% of these considered the turbines intrusive, and 73% considered them unattractive. Nine percent said they were affected by flicker. Over 50% of households located between 2 and 2.5 km and between 5 and 9.5 km reported being able to hear the turbines. In contrast, fewer people living between 3 and 4.5 km away could hear the turbines. Ninety-two households said that their quality of life was affected by turbine noise. Sixty-eight households reported sleep disturbances: 42 of the households reported occasional sleep disturbances, 21 reported frequent sleep disturbances and 5 reported sleep disturbances most of the time.

The Large Wind Turbine Citizens Committee for the Town of Union (2008) documents complaints from people living near wind turbines in Wisconsin communities and other places in the U.S. and U.K. Contained in this report is an older report prepared by the Wisconsin Public Service Corporation in 2001 in response to complaints in Lincoln County, Wisconsin. The report found essentially no exceedances of the 50 dB(A) requirement in the conditional use permit. The report did measure spectral data accumulated over very short intervals (1 minute) in 1/3 octave bands at several sites while the wind turbines were functioning, and it is of interest that at these sites the sound pressure level at the lower frequencies (below 125 Hz) were at or near 50 dB(A).

Pierpont (2009) postulates wind turbine syndrome, consisting of a constellation of symptoms including headache, tinnitus, ear pressure, vertigo, nausea, visual blurring, tachycardia, irritability, cognitive problems and panic episodes associated with sensations of internal pulsation. She studied 38 people in 10 families living between 1000 feet and slightly under 1 mile from newer wind turbines. She proposes that the mechanism for these effects is disturbance of balance due to "discordant" stimulation of the vestibular system, along with visceral sensations, sensations of vibration in the chest and other locations in the body, and stimulation of the visual system by moving shadows. Pierpont does report that her study subjects maintain that their problems are caused by noise and vibration, and the most common symptoms reported are sleep disturbances and headache. However, 16 of the people she studied report symptoms consistent with (but not necessarily caused by) disturbance of equilibrium.

V. Noise Assessment and Regulation

1. Minnesota noise regulation

The Minnesota Noise Pollution Control Rule is accessible online at: https://www.revisor.leg.state.mn.us/rules/?id=7030 . A summary of the Minnesota Pollution Control Agency (MPCA) noise guidance can be found online at: http://www.pca.state.mn.us/programs/noise.html . The MPCA standards require A-weighting measurements of noise; background noise must be at least 10 dB lower than the noise source being measured. Different standards are specified for day and night, as well as standards that may not be exceeded for more than 10 percent of the time during any hour (L10) and 50 percent of the time during any hour (L50). Household units, including farm houses, are Classification 1 land use. The following are the Class 1 noise limits:

Table 1: Minnesota Class 1 Land Use Noise Limits

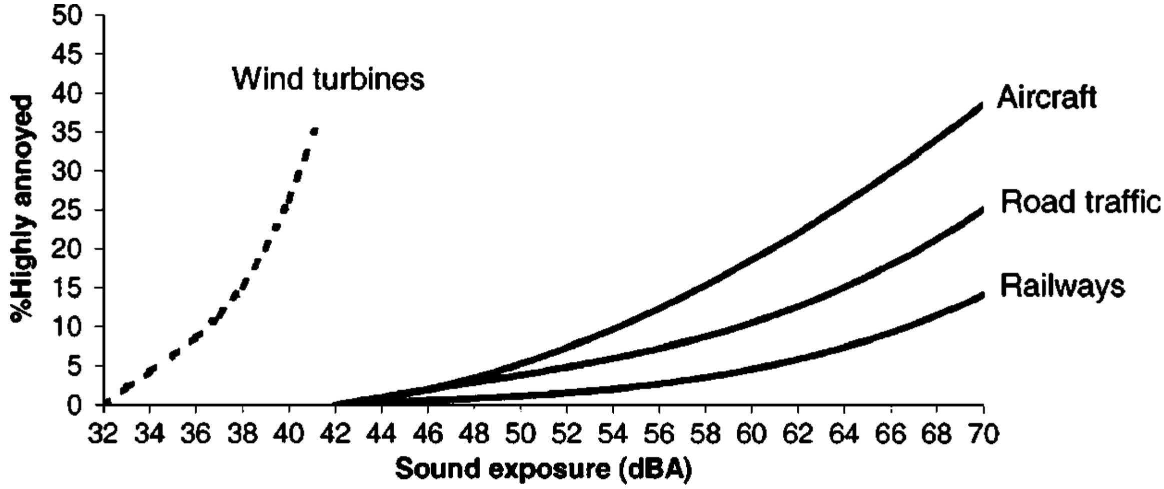
Daytime		Nighttime	
L50	L10	L50	L10
60 dB(A)	65 dB(A)	50 dB(A)	55 dB(A)

These noise limits are single number limits that rely on the measuring instrument to apply an A-weighting filter over the entire presumed audible spectrum of frequencies (20 Hz to 20 KHz) and then integrating that signal. The result is a single number that characterizes the audible spectrum noise intensity.

2. Low frequency noise assessment and regulation

Pedersen and Waye (2004) looked at the relationship between total dB(A) sound pressure and the annoyance of those who are environmentally exposed to noise from different sources. Figure 6 demonstrates the difficulty in using total dB(A) to evaluate annoyance. Note how lower noise levels (dB(A)) from wind turbines engenders annoyance similar to much higher levels of noise exposure from aircraft, road traffic and railroads. Sound impulsiveness, low frequency noise and persistence of the noise, as well as demographic characteristics may explain some of the difference.

Figure 6: Annoyance associated with exposure to different environmental noises



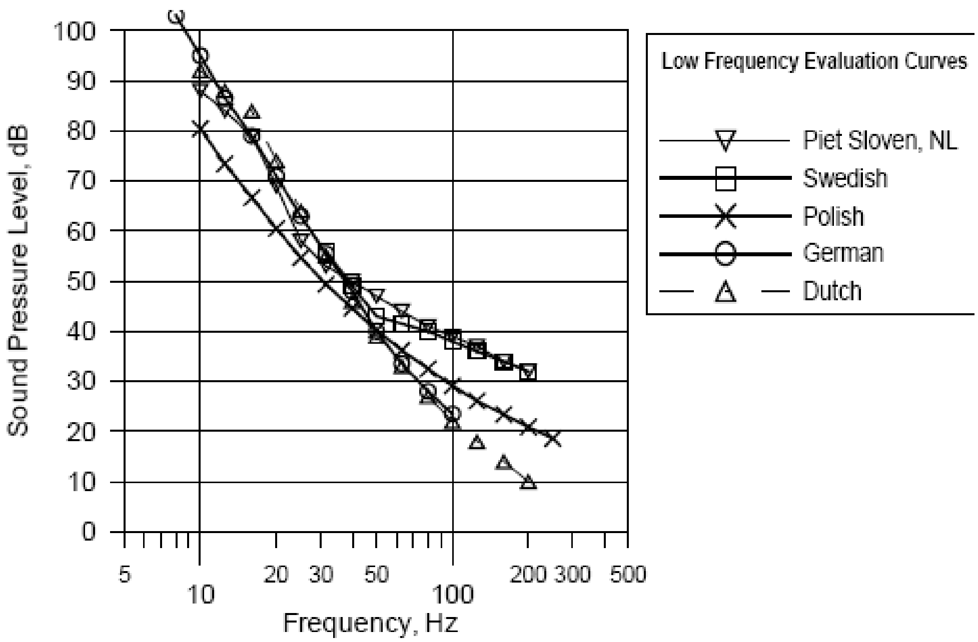
Reprinted with permission from Pedersen, E. and K.P. Waye (2004). Perception and annoyance due to wind turbine noise—a dose–response relationship. The Journal of the Acoustical Society of America 116: 3460. Copyright 2004, Acoustical Society of America.

Kjellberg et al. (1997) looked at the ability of different full spectrum weighting schemes to predict annoyance caused by low frequency audio noise. They found that dB(A) is the worst predictor of annoyance of available scales. However, if 6 dB ("penalty") is added to dB(A) when dB(C) – dB(A) is greater than 15 dB, about 71% of the predictions of annoyance are correct. It is important to remember that integrated, transformed measurements of SPL (e.g. dB(A), dB(C)) do not measure frequencies below 20 Hz. While people detect stimuli below 20 Hz, as discussed in above sections, these frequencies are not measured using an A-weighted or C-weighted meter.

The World Health Organization (WHO) recommends that if dB(C) is greater than 10 dB more than dB(A), the low frequency components of the noise may be important and should be evaluated separately. In addition, WHO says "[i]t should be noted that a large proportion of low-frequency components in noise may increase considerably the adverse effects on health." (WHO, 1999)

Many governments that regulate low frequency noise look at noise within bands of frequencies instead of summing the entire spectrum. A study by Poulsen and Mortensen (Danish Environmental Protection Agency, 2002) included a summary of low frequency noise guidelines. German, Swedish, Polish, and Dutch low frequency evaluation curves were compared (see Figure 7). While there are distinctions in how the evaluation curves are described, generally, these curves are sound pressure criterion levels for 1/3 octaves from about 8 Hz to 250 Hz. Exceedance in any 1/3 octave measurement suggests that the noise may be annoying. However, note that regulations associated with low frequency noise can be quite complex and the regulatory evaluations associated with individual curves can be somewhat different.

Figure 7: 1/3 Octave Sound Pressure Level Low frequency Noise Evaluation Curves



(Danish Environmental Protection Agency, 2002)

The Danish low frequency evaluation requires measuring noise indoors with windows closed; SPL measurements are obtained in 1/3 octave bands and transformed using the A-weighting algorithm for all frequencies between 10 and 160 Hz. These values are then summed into a single metric called $L_{pA,LF}$. A 5 dB “penalty” is added to any noise that is “impulsive”. Danish regulations require that 20 dB $L_{pA,LF}$ is not exceeded during the evening and night, and that 25 dB $L_{pA,LF}$ is not exceeded during the day.

Swedish guidance recommends analyzing 1/3 octave bands between 31.5 and 200 Hz inside a home, and comparing the values to a Swedish assessment curve. The Swedish curve is equal to the United Kingdom (UK) Department of Environment, Food and Rural Affairs (DEFRA) low frequency noise criterion curve for overlapping frequencies (31.5 – 160 Hz).

The German “A-level” method sums the A-weighted equivalent levels of 1/3 octave bands that exceed the hearing threshold from 10 – 80 Hz. If the noise is not tonal, the measurements are added. The total cannot exceed 25 dB at night and 35 dB during the day. A frequency-dependent adjustment is applied if the noise is tonal.

In the Poulsen and Mortensen, Danish EPA study (2002), 18 individuals reported annoyance levels when they were exposed through earphones in a controlled environment to a wide range of low frequency environmental noises, all attenuated down to 35 dB, as depicted in Table 2. Noise was simulated as if being heard indoors, filtering out noise at higher frequencies and effectively eliminating all frequencies above 1600 Hz. Noise levels in 1/3 octave SPLs from 8 Hz to 1600 Hz were measured and low frequencies (below 250 Hz) were used to predict annoyance using 7 different methods (Danish, German A-level, German tonal, Swedish, Polish, Sloven, and C-level). Predictions of annoyance were compared with the subjective annoyance evaluations. Correlation coefficients for these analyses ranged from 0.64 to 0.94, with the best correlation in comparison with the Danish low frequency noise evaluation methods.

As would be expected, at 35 dB nominal (full spectrum) loudness, every low frequency noise source tested exceeded all of the regulatory standards noted in the Danish EPA report. Table 2 shows the Danish and Swedish regulatory exceedances of the different 35 dB nominal (full spectrum) noise.

Table 2: 35 dB(A) (nominal, 8 Hz-20KHz) Indoor Noise from Various Outdoor Environmental Sources

	Traffic Noise	Drop Forge	Gas Turbine	Fast Ferry	Steel Factory	Generator	Cooling Compressor	Discotheque
Noise	67.6 dB(lin)	71.1 dB(lin)	78.4 dB(lin)	64.5 dB(lin)	72.7 dB(lin)	60.2 dB(lin)	60.3 dB(lin)	67.0 dB(lin)
Noise ≥ 20 Hz	35.2 dB(A)	36.6 dB(A)	35.0 dB(A)	35.1 dB(A)	33.6 dB(A)	36.2 dB(A)	36.6 dB(A)	33.6 dB(A)
	62.9 dB(C)	67.3 dB(C)	73.7 dB(C)	61.7 dB(C)	66.0 dB(C)	58.6 dB(C)	59.0 dB(C)	57.8 dB(C)
Danish Environmental Protection Agency	14.5 dB	21.5 dB *	14.8 dB	15.0 dB	13.1 dB	16.1 dB	14.0 dB	18.0 dB *
Swedish National Board of Health and Welfare	14.1 dB	19.7 dB	15.9 dB	16.8 dB	15.5 dB	18.3 dB	16.0 dB	10.0 dB
* includes 5 dB "penalty"								

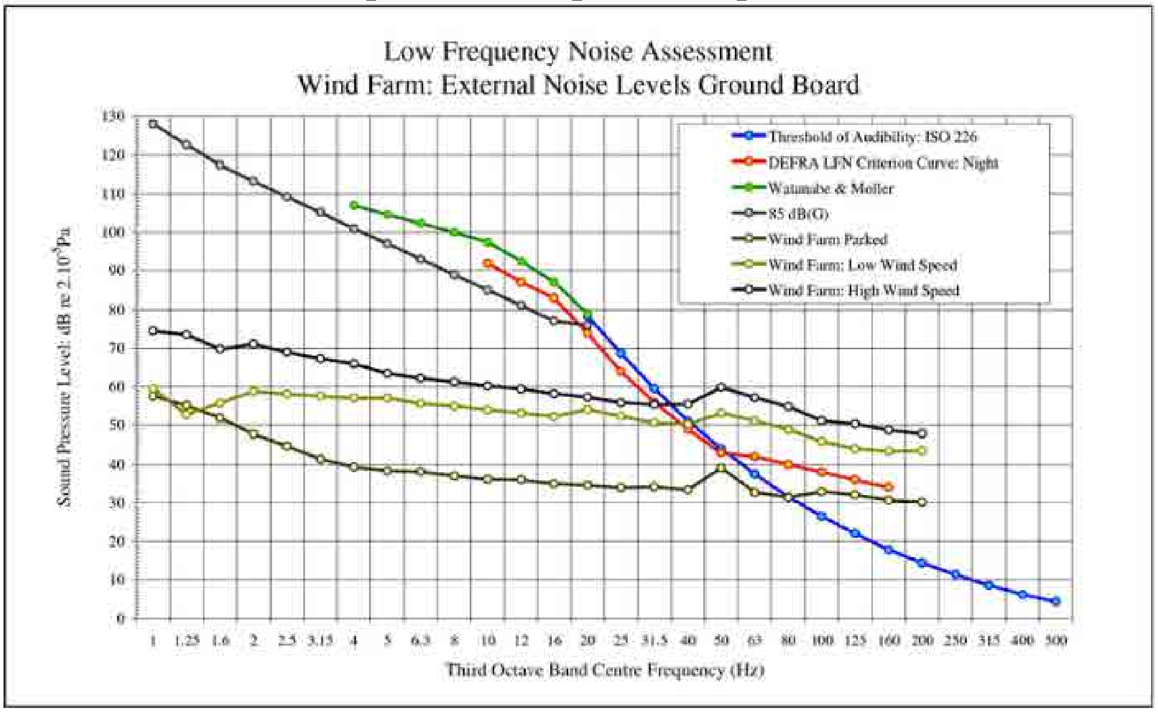
Noise adjusted to dB(lin), dB(A), dB(C) scales. Calculated exceedances of Danish and Swedish indoor criteria. (data from Danish Environmental Protection Agency, 2002)

In their noise guidance, the WHO (1999) recommends 30 dB(A) as a limit for “a good night’s sleep”. However, they also suggest that guidance for noise with predominating low frequencies be less than 30 dB(A).

3. Wind turbine sound measurements

Figure 8 shows examples of the SPLs at different frequencies from a representative wind turbine in the United Kingdom. Sound pressure level measurements are reported for a Nordex N-80 turbine at 200 meters (UK Department of Transport and Industry, 2006) when parked, at low wind speeds, and at high wind speeds. Figure 8 also includes, for reference, 3 sound threshold curves (ISO 226, Watanabe & Moller, 85 dB(G)) and the DEFRA Low Frequency Noise Criterion Curve (nighttime).

Figure 8: Low Frequency Noise from Wind Farm: Parked, Low Wind Speed, and High Wind Speed

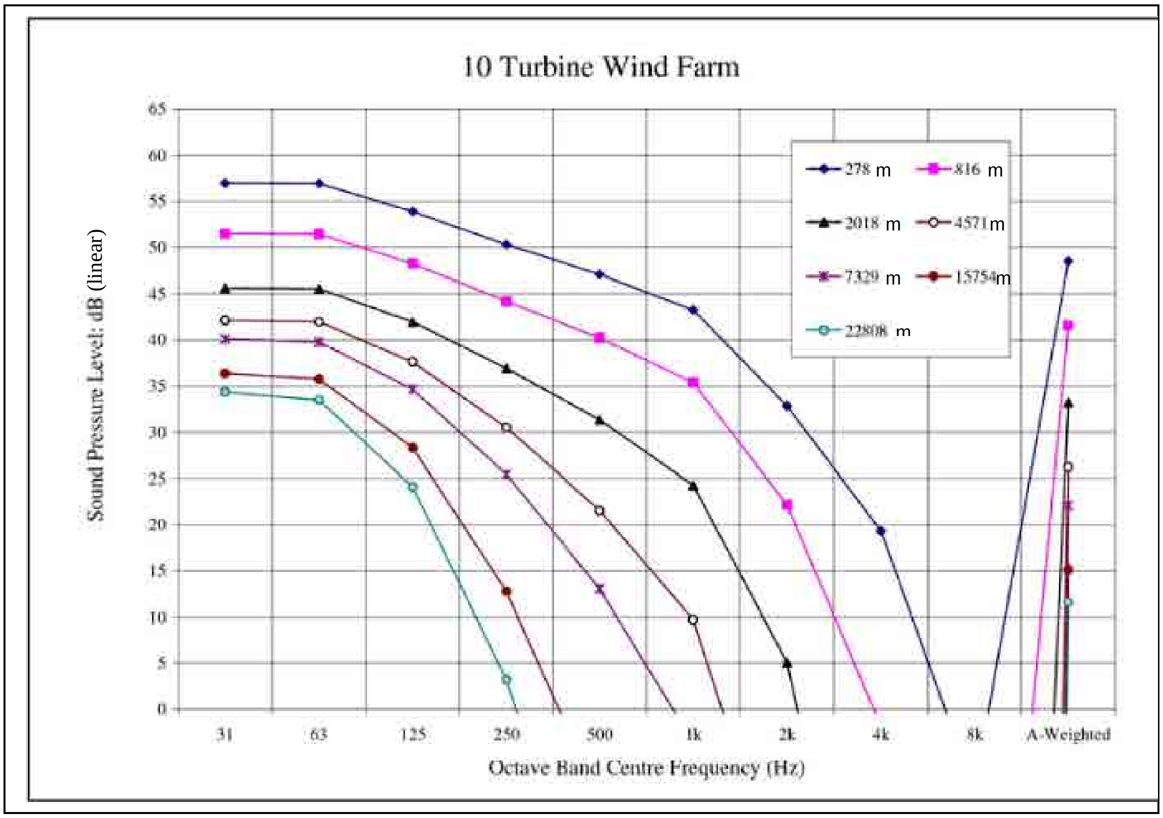


(UK Department of Transport and Industry, 2006)

In general, sound tends to propagate as if by spherical dispersion. This creates amplitude decay at a rate of about -6 dB per doubling of distance. However, low frequency noise from a wind turbine has been shown to follow more of a cylindrical decay at long distances, about -3 dB per doubling of distance in the downwind direction (Shepherd and Hubbard, 1991). This is thought to be the result of the lack of attenuation of low frequency sound waves by air and the atmospheric refraction of the low frequency sound waves over medium to long distances (Hawkins, 1987).

Figure 9 shows the calculated change in spectrum for a wind farm from 278 meters to 22,808 meters distant. As one moves away from the noise source, loudness at higher frequencies decreases more rapidly (and extinguishes faster) than at lower frequencies. Measurement of A-weighted decibels, shown at the right of the figure, obscures this finding.

Figure 9: Change in Noise Spectrum as Distance from Wind Farm Changes



(UK Department of Transport and Industry, 2006)

Thus, although noise from an upwind blade wind turbine is generally broad spectrum, without a tonal quality, high frequencies are efficiently attenuated by both the atmosphere, and by walls and windows of structures, as noted above. As a result, as one moves away from a wind turbine, the low frequency component of the noise becomes more pronounced.

Kamperman and James (2008) modeled indoor noise from outdoor wind turbine noise measurements, assuming a typical vinyl siding covered 2X4 wood frame construction. The wind turbine noise inside was calculated to be 5 dB less than the noise outside. Model data suggested that the sound of a single 2.5 MW wind turbine at 1000 feet will likely be heard in a house with the windows sealed. They note that models used for siting turbines often incorporate structure attenuation of 15dB. In addition, Kamperman and James demonstrate that sound from 10 2.5 MW turbines (acoustically) centered 2 km (1¼ mile) away and with the nearest turbine 1 mile away will only be 6.3 dB below the sound of a single turbine at 1000 feet (0.19 mile).

4. Wind turbine regulatory noise limits

Ramakrishnan (2007) has reported different noise criteria developed for wind farm planning. These criteria include common practices (if available) within each jurisdiction for estimating background SPLs, turbine SPLs, minimum setbacks and methods used to assess impacts. Reported US wind turbine noise criteria range from: ambient + 10 dB(A) where ambient is assumed to be 26 dB(A) (Oregon); to 55 dB(A) or "background" + 5 dB(A) (Michigan). European criteria range from 35 dB(A) to 45 dB(A), at the property. US setbacks range from 1.1 times the full height of the turbine (consenting) and 5 times the hub height (non-consenting; Pennsylvania); to 350 m (consenting) and 1000 m (non-consenting; Oregon). European minimum setbacks are not noted.

VI. Conclusions

Wind turbines generate a broad spectrum of low-intensity noise. At typical setback distances higher frequencies are attenuated. In addition, walls and windows of homes attenuate high frequencies, but their effect on low frequencies is limited. Low frequency noise is primarily a problem that may affect some people in their homes, especially at night. It is not generally a problem for businesses, public buildings, or for people outdoors.

The most common complaint in various studies of wind turbine effects on people is annoyance or an impact on quality of life. Sleeplessness and headache are the most common health complaints and are highly correlated (but not perfectly correlated) with annoyance complaints. Complaints are more likely when turbines are visible or when shadow flicker occurs. Most available evidence suggests that reported health effects are related to audible low frequency noise. Complaints appear to rise with increasing outside noise levels above 35 dB(A). It has been hypothesized that direct activation of the vestibular and autonomic nervous system may be responsible for less common complaints, but evidence is scant.

The Minnesota nighttime standard of 50 dB(A) not to be exceeded more than 50% of the time in a given hour, appears to underweight penetration of low frequency noise into dwellings. Different schemes for evaluating low frequency noise, and/or lower noise standards, have been developed in a number of countries.

For some projects, wind velocity for a wind turbine project is measured at 10 m and then modeled to the height of the rotor. These models may under-predict wind speed that will be encountered when the turbine is erected. Higher wind speed will result in noise exceeding model predictions.

Low frequency noise from a wind turbine is generally not easily perceived beyond ½ mile. However, if a turbine is subject to aerodynamic modulation because of shear caused by terrain (mountains, trees, buildings) or different wind conditions through the rotor plane, turbine noise may be heard at greater distances.

Unlike low frequency noise, shadow flicker can affect individuals outdoors as well as indoors, and may be noticeable inside any building. Flicker can be eliminated by placement of wind turbines outside of the path of the sun as viewed from areas of concern, or by appropriate setbacks.

Prediction of complaint likelihood during project planning depends on: 1) good noise modeling including characterization of potential sources of aerodynamic modulation noise and characterization of nighttime wind conditions and noise; 2) shadow flicker modeling; 3) visibility of the wind turbines; and 4) interests of nearby residents and community.

VII. Recommendations

To assure informed decisions:

- Wind turbine noise estimates should include cumulative impacts (40-50 dB(A) isopleths) of all wind turbines.
- Isopleths for dB(C) - dB(A) greater than 10 dB should also be determined to evaluate the low frequency noise component.
- Potential impacts from shadow flicker and turbine visibility should be evaluated.

Any noise criteria beyond current state standards used for placement of wind turbines should reflect priorities and attitudes of the community.

VIII. Preparers of the Report:

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EXHIBIT 26

Correction

ECOLOGY, SUSTAINABILITY SCIENCE

Correction for "Solar energy development impacts on land cover change and protected areas," by Rebecca R. Hernandez, Madison K. Hoffacker, Michelle L. Murphy-Mariscal, Grace C. Wu, and Michael F. Allen, which appeared in issue 44, November 3, 2015, of *Proc Natl Acad Sci USA* (112:13579–13584; first published October 19, 2015; 10.1073/pnas.1517656112).

The authors note that on page 13579, right column, first full paragraph, lines 12–16, the following statement published incorrectly: "If up to 500 GW of USSE may be required to meet United States-wide reduction of 80% of 1990 greenhouse gas emissions by 2050, 71,428 km^2 of land may be required (roughly the land area of the state of South Carolina) assuming a capacity factor of 0.20 (an average capacity factor for PV; Table S1)." The statement should instead appear as: "For example, up to 500 GW of USSE may be required to meet United States-wide reduction of 80% of 1990 greenhouse gas emissions by 2050 (33). This requires about 14,285 km^2 of land [roughly the area of the state of Connecticut, (9)], underscoring the possible vast area requirements for energy needs in the United States." Additionally, the authors note ref. 33 was omitted from the published article. The full reference appears below.

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www.pnas.org/cgi/doi/10.1073/pnas.1602975113

Solar energy development impacts on land cover change and protected areas

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Decisions determining the use of land for energy are of exigent concern as land scarcity, the need for ecosystem services, and demands for energy generation have concomitantly increased globally. Utility-scale solar energy (USSE) [i.e., ≥1 megawatt (MW)] development requires large quantities of space and land; however, studies quantifying the effect of USSE on land cover change and protected areas are limited. We assessed siting impacts of >160 USSE installations by technology type [photovoltaic (PV) vs. concentrating solar power (CSP)], area (in square kilometers), and capacity (in MW) within the global solar hot spot of the state of California (United States). Additionally, we used the Carnegie Energy and Environmental Compatibility model, a multiple criteria model, to quantify each installation according to environmental and technical compatibility. Last, we evaluated installations according to their proximity to protected areas, including inventoried roadless areas, endangered and threatened species habitat, and federally protected areas. We found the plurality of USSE (6,995 MW) in California is sited in shrublands and scrublands, comprising 375 km^2 of land cover change. Twenty-eight percent of USSE installations are located in croplands and pastures, comprising 155 km^2 of change. Less than 15% of USSE installations are sited in "Compatible" areas. The majority of "Incompatible" USSE power plants are sited far from existing transmission infrastructure, and all USSE installations average at most 7 and 5 km from protected areas, for PV and CSP, respectively. Where energy, food, and conservation goals intersect, environmental compatibility can be achieved when resource opportunities, constraints, and trade-offs are integrated into siting decisions.

concentrating solar power | conservation | greenhouse gas emissions | land use | photovoltaics

The need to mitigate climate change, safeguard energy security, and increase the sustainability of human activities is prompting the need for a rapid transition from carbon-intensive fuels to renewable energy (1). Among renewable energy systems, solar energy has one of the greatest climate change mitigation potentials with life cycle emissions as low as 14 g CO_2-eq·kW·h^{-1} [compare this to 608 g CO_2-eq·kW·h^{-1} for natural gas (2)]. Solar energy embodies diverse technologies able to capture the sun's thermal energy, such as concentrating solar power (CSP) systems, and photons using photovoltaics (PV). In general, CSP is economically optimal where direct normal irradiance (DNI) is 6 kW·h·m^{-2}·d^{-1} or greater, whereas PV, able to use both diffuse and DNI, is economically optimal where such solar resources are 4 kW·h·m^{-2}·d^{-1} or greater. Solar energy systems are highly modular ranging from small-scale deployments (≤1 MW; e.g., residential rooftop modules, portable battlefield systems, solar water heaters) to centralized, utility-scale solar energy (USSE) installations (≥1 MW) where a large economy of scale can meet greater energy demands. Nonetheless, the diffuse nature of solar energy necessitates that large swaths of space or land be used to collect and concentrate solar energy into forms usable for human consumption, increasing concern over potential adverse impacts on natural ecosystems, their services, and biodiversity therein (2–5).

Given the wide range of siting options for USSE projects, maximizing land use efficiency and minimizing land cover change is a growing environmental challenge (6–8). Land use efficiency describes how much power or energy a system generates by area (e.g., watts per square meter, watt-hours per square meter, respectively). For example, USSE installations have an average land use efficiency of 35 W·m^{-2} based on nameplate capacity under ideal conditions (9). The ratio of the realized generation of an installation to maximum generation under ideal conditions over a period is the capacity factor. Using these two terms, we can quantify land requirements for USSE at larger spatial scales. If up to 500 GW of USSE may be required to meet United States-wide reduction of 80% of 1990 greenhouse gas emissions by 2050, 71,428 km^2 of land may be required (roughly the land area of the state of South Carolina) assuming a capacity factor of 0.20 (an average capacity factor for PV; Table S1). This underscores the possible vast area requirements for meeting energy needs in the United States and elsewhere. Increasing the land use efficiency of each installation—e.g., decreasing space between rows of PV modules or CSP mirrors—and prudent siting decisions that incorporate the weighting of environmental trade-offs and synergies can reduce land cover change impacts broadly (10).

Land cover change owing to solar energy has received increasing attention over concerns related to conflicts with biodiversity goals (2–4) and greenhouse gas emissions, which are released when

Significance

Decisions humans make about how much land to use, where, and for what end use, can inform innovation and policies directing sustainable pathways of land use for energy. Using the state of California (United States) as a model system, our study shows that the majority of utility-scale solar energy (USSE) installations are sited in natural environments, namely shrublands and scrublands, and agricultural land cover types, and near (<10 km) protected areas. "Compatible" (≤15%) USSE installations are sited in developed areas, whereas "Incompatible" installations (19%) are classified as such owing to, predominantly, lengthier distances to existing transmission. Our results suggest a dynamic landscape where land for energy, food, and conservation goals overlap and where environmental cobenefit opportunities should be explored.

Author contributions: R.R.H. designed research; R.R.H. and M.K.H. performed research; R.R.H. and M.K.H. contributed new reagents/analytic tools; R.R.H. and M.K.H. analyzed data; and R.R.H., M.K.H., M.L.M.-M., G.C.W., and M.F.A. wrote the paper.

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biomass, including soil, is disturbed or removed during the lifetime of a power plant (11, 12). Siting USSE installations in places already impacted by humans (e.g., parking lots, rooftops) reduces the likelihood that adverse environmental impacts will occur and can exceed generation demands for renewable energy goals in places with moderate- to high-quality solar resources (8, 10, 13), including California. When sites within the built environment are inaccessible, siting that minimizes land use and land cover change within areas acting as carbon sinks, avoids extirpation of biodiversity, and does not obstruct the flow of ecosystem services to residents, firms, and communities, can serve to mitigate adverse environmental impacts (2, 3, 9, 10, 14, 15). Siting within the built environment also reduces the need for complex decision making dictating the use of land for food or energy (16).

Recent studies have underscored the role that proximity of threats to protected areas plays in meeting conservation goals (16–20). Protected areas may preclude habitat loss within boundaries; however, a prevailing cause of degradation within protected areas is land use and land cover change in surrounding areas. Specifically, protected areas are effective when land use nearby does not obstruct corridor use, dispersion capabilities, nor facilitate invasions of nonnative species through habitat loss, fragmentation, and isolation—including those caused by renewable energy development. Quantifying both internal and external threats is necessary for assessing vulnerability of individual protected areas to conversion and landscape sustainability overall. Siting decisions can be optimized with decision support tools (10, 14) that differentiate areas where direct (e.g., land cover change) and proximate effects (e.g., habitat fragmentation) are lowest on the landscape.

Several studies have made predictions regarding which specific land cover types may be impacted by solar energy development (7, 21); however, few studies have evaluated actual siting decisions and their potential or realized impact on land cover change (9, 11). In this study, our objectives were to (*i*) evaluate potential land cover change owing to development of utility-scale PV and CSP within the state of California (United States) and describe relationships among land cover type and the number of installations, capacity, and technology type of USSE; (*ii*) use the decision support tool, the Carnegie Energy and Environmental Compatibility (CEEC) model (10), to develop a three-tiered spatial environmental and technical compatibility index (hereafter called Compatibility Index; "Compatible," "Potentially Compatible," and "Incompatible") for California that identifies environmentally low-conflict areas using resource constraints and opportunities; and (*iii*) compare utility-scale PV and CSP installation locations with the Compatibility Index and their proximity to protected areas to quantify solar energy development decisions and their impact on land cover change (see *Supporting Information* for details).

We selected the state of California as a model system owing to its relatively early, rapid, and ambitious deployment of solar energy systems, 400,000 km^2 of land area (greater than Germany and 188 other countries), large human population and energy demands, diverse ecosystems comprising 90% of the California Floristic Province biodiversity hot spot, and its long-standing use in elucidating the interrelationship between land and energy (9, 10, 22, 23).

Results

We identified 161 planned, under construction, and operating USSE installations throughout 10 land cover types (Figs. 1 and 2) among 16 total in the state of California (Table S2). Broadly, PV installations are concentrated particularly in the Central Valley and the interior of southern California, whereas CSP power plants are sited exclusively in inland southern California (Figs. 1 and 2). For all technology types, the plurality of capacity (6,995 MW) is found in shrubland and scrubland land cover type, necessitating 375 km^2 of land (Table 1). This area is approximately two times greater than USSE development occurring within cultivated croplands, representing 4,103 MW of capacity within 118 km^2. Over 2,000 MW of existing or proposed USSE capacity is sited within the built environment, particularly within relatively lower density areas.

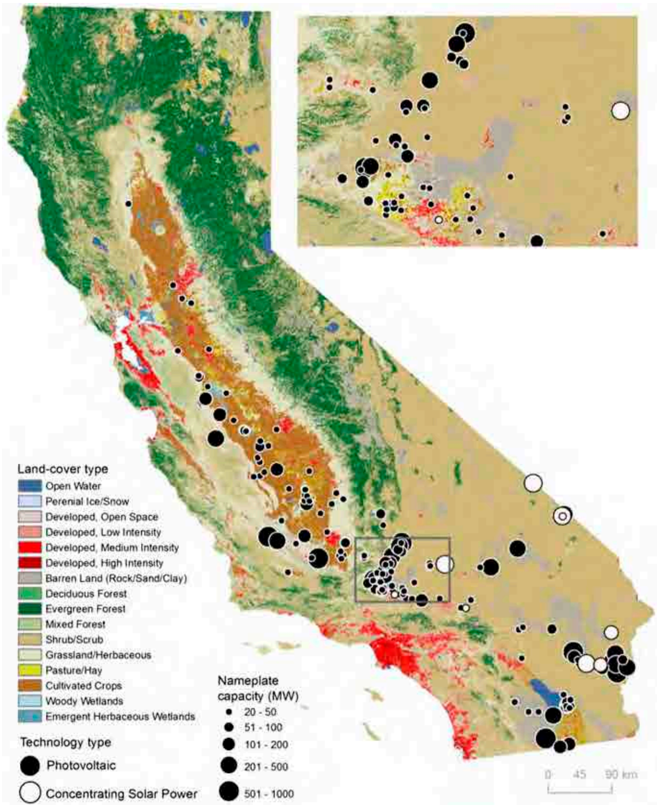

Fig. 1. Map showing land cover types across California and the size and location of USSE installations.

PV power plants are found in 10 land cover types; the plurality of capacity is sited within shrubland/scrublands (6,251 MW; Table 1), representing 26.0% of all PV installations (Fig. 2). Capacity for utility-scale PV installations is also represented within cultivated croplands (3,823 MW), barren land (2,102 MW), developed (2,039 MW), and grassland/herbaceous (1,483 MW) land cover types. Within the developed land cover types, open space is most used (1,205 MW) for utility-scale PV capacity. For CSP, 1,000 MW are located within 34 km^2 of barren land land cover types, and conjointly within shrubland/scrublands (744 MW, 32 km^2).

Using the decision support tool, CEEC (Fig. 3), we identified 22,028 and 77,761 km^2 of Compatible and Potentially Compatible area, respectively, in California for developing PV (Fig. S1). Generation-based potential within Compatible areas—comprising 5.4% of California's area—is 8,565 TW·h·y^{-1} for fixed-tilt modules and up to 11,744 TW·h·y^{-1} for dual-axis modules. For CSP technologies, we found 6,274 and 33,489 km^2 of Compatible and Potentially Compatible area. Generation-based potential for CSP within Compatible areas—comprising 1.5% of California's area—is 5,947 TW·h·y^{-1}.

USSE installations vary in the environmental compatibility of their actual or proposed site (Fig. 4 *A* and *B*). The majority (71.7%) of PV USSE installations are in Potentially Compatible areas, whereas 11.2% are located in Compatible areas. PV installations classified as Incompatible are due to distances from existing transmission infrastructure exceeding 10 km (45.9%), slope exceeding the recommended threshold (41.9%), and to a

Table 1. USSE installations and land cover type

	Nameplate capacity, MWdc				Area, km^2			
Land cover type	PV	%	CSP	%	PV	%	CSP	%
Barren land (rock/sand/clay)	2,102	12	**1,000**	**48**	77	11	**34**	**45**
Cultivated crops	3,823	22	280	14	110	15	8	11
Developed (all)	2,039	12	50	2	70	10	1	1
Developed, high intensity	50	0	0	0	1	0	0	0
Developed, medium intensity	624	4	0	0	17	2	0	0
Developed, low intensity	160	1	0	0	9	1	0	0
Developed, open space	1,205	7	50	2	43	6	1	1
Emergent herbaceous wetlands	60	0	0	0	1	0	0	0
Grass/herbaceous	1,483	9	0	0	72	10	0	0
Pasture/hay	1,397	8	0	0	37	5	0	0
Shrubland/scrubland	**6,251**	**36**	744	36	**343**	**48**	32	43

The nameplate capacity [in megawatts (MWdc)], footprint (in square kilometers), and number of photovoltaic (PV) and concentrating solar power (CSP) USSE installations (>20 MW) in California (in planning, under construction, operating) by land cover type. Bold data represent the greatest value among all land cover types.

lesser degree, owing to development on endangered and threatened species habitat (9.7%) and federally preserved land (3.2%; Fig. 4 *A* and *B*). For CSP installations, 55.5% are located in either Compatible or Potentially Compatible areas. Siting incompatibilities for CSP were either due to slope (25.0%) or distance from transmission lines (75.0%). PV and CSP installations on Compatible areas range in capacity between 20 and 200 MW, and are located within the Central Valley and inland southern California regions, excepting one PV facility in Yolo County (Fig. 4*A*). PV facilities on Incompatible land are found throughout all of California and, excepting one facility (250 MW; San Luis Obispo County), are 200 MW in capacity or less.

PV and CSP USSE installations average 7.2 ± 0.9 and 5.3 ± 2.3 km, respectively, from the closest protected area (Fig. 5). Federally protected areas are the nearest protected area type (7.8 ± 1.0) to land use and land cover change for PV development, whereas both endangered and threatened species habitat (5.7 ± 2.4) and federally protected areas (5.3 ± 2.3) are nearest for CSP development. Of PV installations, 73.7% were less than 10 km and 47.4% were less than 5 km away from the nearest protected area. Of CSP installations, 90.0% were less than 10 km away and 60.0% were less than 5 km away from the nearest protected area.

Discussion

Evaluation of siting decisions for USSE is increasingly relevant in a world of mounting land scarcity and in which siting decisions are as diverse as their deployment worldwide. For example, China has emphasized utility-scale, ground-mounted PV and residential, small-scale solar water heating installations (24), whereas Germany is notable for achieving up to 90% development within the built environment (25). In California, a large portion of USSE installations is sited far from existing transmission infrastructure. New transmission extensions are expensive, difficult to site due to social and environmental concerns, and require many years of planning and construction. Such transmission-related siting incompatibilities not only necessitate additional land cover change but also stand in the way of cost-efficient and rapid renewable energy deployment.

Environmental regulations and laws, which vary drastically from one administrative area to the next, may also cause incongruities in siting decisions. Inherent ambiguities of such policies allows for further inconsistencies. A study in southern Italy (11) found that two-thirds of authorizations for USSE were within environmentally "unsuitable" areas as defined by municipal and international criteria (e.g., United Nations Educational, Scientific and Cultural Organization sites), with adverse implications for land cover change-related CO_2 emissions. Studies (7, 21) including our own reveal that regulations and policies to date have deemphasized USSE development in California, the United States, and North America, respectively, within the built environment and near population centers in favor of development within shrublands and scrublands. California's shrublands and scrublands comprise, in part, the California Floristic Province, a biodiversity hot spot known for high levels of species richness and endemism and where 70% or more of the original extent of vegetation has been lost due to global environmental change-type threats, including land cover change (26, 27). In biologically rich areas like this, land cover change has the potential to greatly impact ecological value and function. Globally, the extent of shrubland and scrubland is vast; therefore, in areas where biodiversity is low, goods and services of shrublands may include diverse recreational opportunities, culturally and historically significant landscapes, movement corridors for wildlife, groundwater as a drinking source, and carbon (sequestration), which may also be adversely impacted by land cover conversion (28).

Proximity impacts result from the fragmentation and degradation of land near and between protected areas, reducing ecological flows of energy, organisms, and goods (16–20). In a study of 57

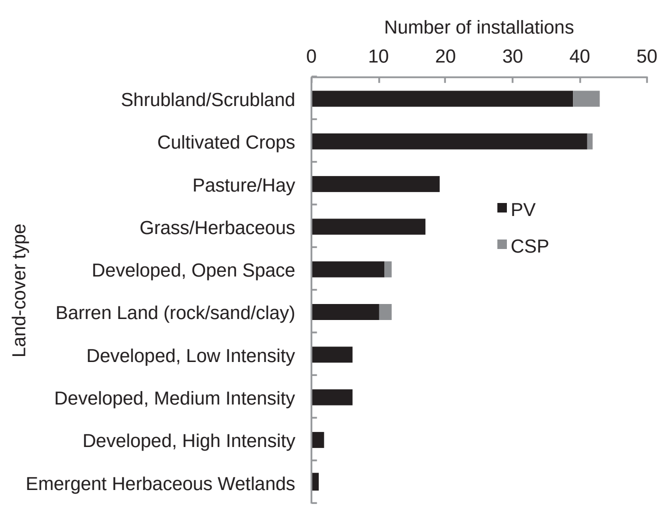

Fig. 2. Number of photovoltaic (PV) and concentrating solar power (CSP) installations (planned, under construction, operating) by land cover type in California; represented in order of most installations to least for both technologies.

ECOLOGY

SUSTAINABILITY SCIENCE

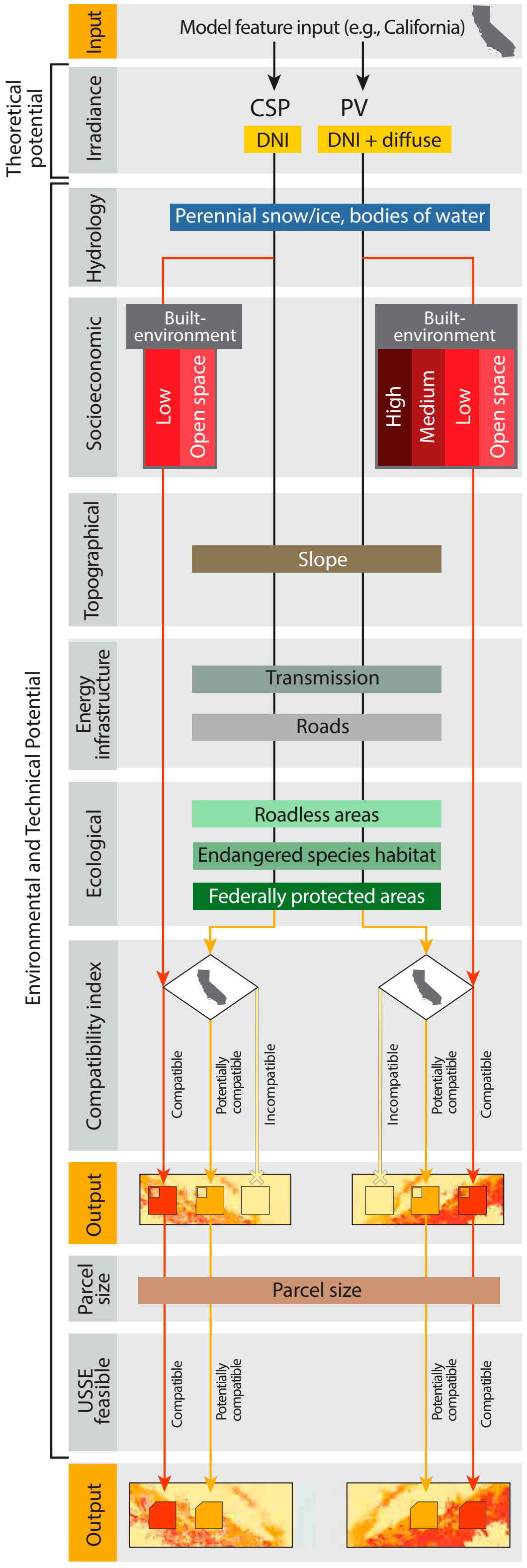

Fig. 3. Workflow of the Carnegie Energy and Environmental Compatibility (CEEC) model, a decision support tool, showing model inputs (resource opportunities and constraints), Environmental and Technical Compatibility Index, and model outputs.

US protected areas, Hansen et al. (16) found such zones extended an average of 18 times (in area) beyond the park area (e.g., Mojave National Preserve, three times protected area, i.e., ∼30 km radially beyond preserve boundary). Additionally, Hamilton et al. (17) used distances of 5, 25, and 75 km from all US protected area boundaries to represent three spatial scales (i.e., buffers) of proximity impacts owing to US land cover and land use change. Last, the US Fish and Wildlife Service's Partners for Fish and Wildlife Program, seeks to reduce adverse proximity impacts by augmenting protected areas with private land restoration, targeting land within a maximum distance of 75 km from existing protected areas. Thus, our results confirm USSE development in California engenders important proximity impacts, for example, encompassing all three spatial scales from Hamilton et al. (17) and decreasing land available for US Fish and Wildlife Service partner restoration programs.

Industrial sectors—including energy and agriculture—are increasingly responsible for decisions affecting biodiversity. Concomitantly, target-driven conservation planning metrics (e.g., percentage of remaining extant habitat does not fall below 40%), geospatial products (e.g., decision support tools), and the monetization of carbon and ecosystem services are increasing and may be effective in compensating for the lack of target-driven regulation observed in policy (29).

Last, development decisions may overlook environmental resources unprotected by policies but valued by interest groups [e.g., important bird areas, essential connectivity areas, vulnerability of caliche (i.e., mineralized carbon) in desert soils, biodiversity hot spots, percent habitat loss]. Several elements of the environment providing ecosystem services that humans depend upon remain widely unprotected by laws and regulations and vastly understudied. By integrating land conservation value earlier in the electricity procurement and planning process, preemptive transmission upgrades or expansions to low-impact regions could improve the incentive to develop in designated zones, avoiding future incompatible development. However, zones themselves must also be carefully designated. The landscape-scale Desert Renewable Energy Conservation Plan initially provided a siting framework—including incidental take authorizations of endangered and threatened species—for streamlining solar energy development within the 91,000 km^2 of mostly desert habitat in public and private lands and designated as the Development Focus Area (DFA). After accounting for unprotected environmental attributes like biodiversity, Cameron et al. (14) identified ∼7,400 km^2 of relatively low-value conservation land within the Mojave Desert Ecoregion (United States) that can meet California's 33% renewable portfolio standard for electricity sales seven times over. Since this publication, the Desert Renewable Energy Conservation Plan's DFA has now been restricted to only public lands, which some argue to be more intact, and to the ire of certain local interest groups and government agencies. Hernandez et al. (10) developed a satellite-based decision support tool, the CEEC model, that showed that generation-based technical potential of PV and CSP within the built environment could meet California's total energy demand 4.8 and 2.7 times over, respectively. Development decisions may also overlook synergistic environmental cobenefit opportunities. Environmental cobenefit opportunities include the utilization of degraded or contaminated lands, colocation of solar and agriculture, hybrid power systems, and building-integrated PV (2).

This study found that nearly 30% of all USSE installations are sited in croplands and pastures; signifying perhaps an increasing affinity for using agricultural lands for renewable energy, specifically within the Central Valley of California, renowned for agricultural productivity globally. The growing demand for food, affordable housing, water, and electricity puts considerable pressure on available land resources, making recent land use decisions in this region a noteworthy case study for understanding the food–energy–water nexus that should be explored. Opportunities to minimize land use change include colocating renewable energy systems with food production and converting degraded and salt-contaminated lands, unsuitable for agriculture, to sites for

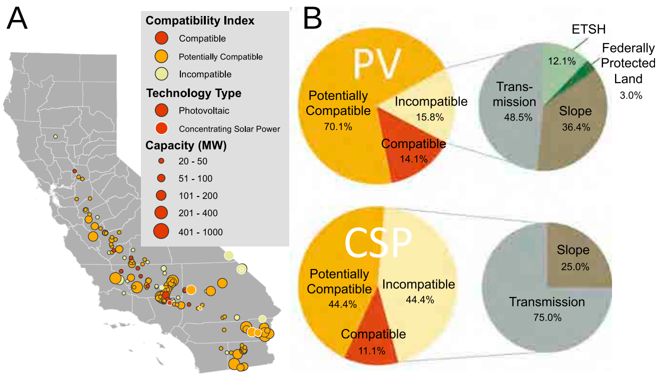

Fig. 4. (*A*) Map of California showing utility-scale solar energy (USSE) (planned, under construction, operating) installations' compatibility by technology [i.e., photovoltaic (PV), concentrating solar power (CSP)], site, and capacity (in megawatts). (*B*) Percentage of USSE installations sited in Compatible, Potentially Compatible, and Incompatible areas. For USSE installations in incompatible sites, we provide the percentage of each incompatibility type.

renewable energy production. Using unoccupied spaces such as adjacent to and on top of barns, parking lots, and distribution centers in agricultural areas is another win–win scenario. In sub-Saharan Africa, integrating solar energy into a drip irrigation system has enhanced food security by conserving water, enhancing reliability of power, and conserving land and space (30). As the development of renewable energy and the production of food are expected to grow, so will the need to understand and evaluate their interactions with the land supporting this expansion in other landscapes.

Conclusion

A growing body of studies underscores the vast potential of solar energy development in places that minimize adverse environmental impacts and confer environmental cobenefits (2, 10, 14, 15, 21). Our study of California reveals that USSE development is a source of land cover change and, based on its proximity to protected areas, may exacerbate habitat fragmentation resulting in direct and indirect ecological consequences. These impacts may include increased isolation and nonnative species invasions, and compromised movement potential of species tracking habitat shifts in response to environmental disturbances, such as climate change. Furthermore, we have shown that USSE development within California comprises siting decisions that lead to the alteration of natural ecosystems within and close to protected areas in lieu of land already impacted by humans (7, 21). Land use policies and electricity planning that emphasizes the use of human-impacted places, complies with existing environmental regulations at the federal, state, and municipal level, and considers environmental concerns over local resource constraints and opportunities, including those of communities, firms, and residents, may prove an effective approach for avoiding deleterious land cover change. Empirical analyses using decision support tools, like CEEC, can help guide development practices toward greater environmental compatibility through improved understanding of the impacts of policy and regulatory processes to date.

Methods

To achieve our objectives, we (*i*) created a multiinstitution dataset of 161 USSE installations in the state of California and compared these data to land cover data; (*ii*) developed a spatial Compatibility Index (i.e., Compatible, Potentially Compatible, and Incompatible) for California using the CEEC model that identifies environmentally low-conflict areas for development, integrating environmental and technical resource constraints and opportunities; (*iii*) compared USSE installation locations with the Compatibility Index to enumerate the number of installations sited within each area type; and (*iv*) compared USSE installation locations with their proximity to protected areas, including Inventoried Roadless Areas, Endangered and Threatened Species Habitat, and Federally Protected Areas (*Supporting Information*). All analyses were conducted using ArcGIS (10.x) and R (R: A Language and Environment for Statistical Computing).

To evaluate land cover change owing to USSE development, we collected data on PV and CSP USSE installations in California that vary in development stage (i.e., planned, under construction, operating) and range in nameplate capacity, selecting a subset of all USSE that range from 20 to 873 MW, 20 MW being a legislative capacity threshold for transmission connection affecting development action. Data for each installation included nameplate capacity under standard test conditions (in megawatts), land footprint (in square kilometers), technology type, and point location (latitude, longitude). Data were collected exclusively from official government documents and records (see *Supporting Information* for details). We define the land footprint as the area directly affected during the construction, operation, and decommissioning phases of the entire power plant facility, excluding existing transmission corridors, land needed for raw material acquisition, and land for generation of energy required for manufacturing. Installations that did not meet data quality criteria (e.g., lacking exact location) were excluded, resulting in a total of 161 USSE installations (see *Supporting Information* for details). Data were collected beginning in 2010 and updated until May 2014. Installations in our dataset vary in their development stage and therefore include installations that may change in attribute or may never reach full operation. Given that we are interested in decisions regarding siting, we included siting data for planned installations, despite their potential uncertainty, as these reflect the most current siting practices that may not be fully represented in decisions for installations that are already under construction or operating.

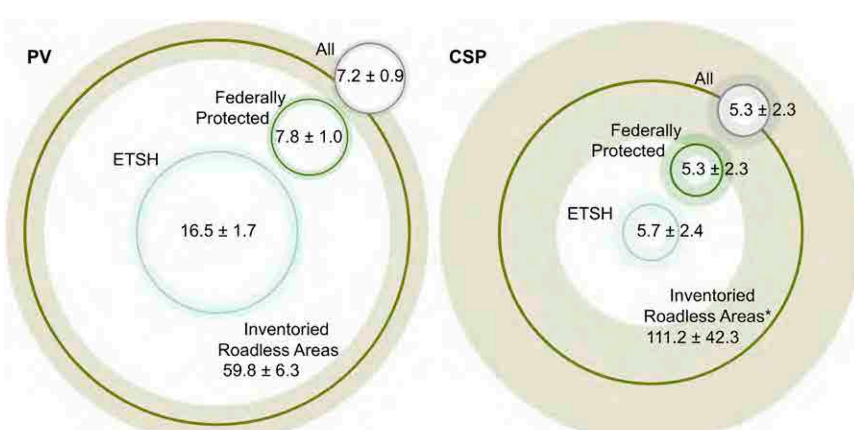

Fig. 5. Proximity of PV and CSP USSE installations to Endangered and Threatened Species Habitat, Federally Protected Areas, Inventoried Roadless Areas, and the closest for all protected area types. Circles are to scale, relatively (with the exception of Inventoried Roadless Areas for CSP), showing 95% confidence intervals (shaded area).

ECOLOGY

SUSTAINABILITY SCIENCE

To evaluate land cover change by USSE development, we compared the point location of each USSE power plant from our dataset (by their latitude and longitude) to the land cover type according to the National Land Cover Dataset (NLCD) (30-m resolution) and allocated the reported total footprint of the installation as land cover change within this land cover type. All 16 land cover types, as described by the NLCD, are represented in California, including developed areas within the built environment (Table S3). Developed areas are further classified according to imperviousness of surfaces: open-space developed (<20% disturbed surface cover; e.g., large-lot single-family housing units, golf courses, parks), low-intensity developed (20–49% disturbed cover), medium-intensity developed (50–79% disturbed cover), and high-intensity developed (80–100% disturbed cover; e.g., apartment complexes, row houses, commercial and industrial facilities).

The CEEC model (10) is a decision support tool used to calculate the technical potential of solar electricity generation and characterize site suitability by incorporating user-specified resource opportunities and constraints (Fig. 3 and Tables S2–S5). The CEEC model uses the National Renewable Energy Laboratory's satellite-based diffuse/direct normal radiation and direct normal radiation models, which estimate average daily insolation (in kilowatt-hours per square meter per day) over 0.1° surface cells (~10 km in size), to identify areas with annual average solar resources adequate for PV ($\geq$4 $kW \cdot h \cdot m^{-2} \cdot d^{-1}$) and CSP ($\geq$6 $kW \cdot h \cdot m^{-2} \cdot d^{-1}$) technologies, respectively (Table S1).

Among these areas, bodies of open water and perennial ice and snow were excluded as potential sites. We indexed the resulting area for solar energy infrastructure—independently for PV and CSP—as follows: Compatible, Potentially Compatible, and Incompatible (*Supporting Information*). Because solar energy potential within California's developed areas can meet the state's current energy consumptive demand 2.7 times over, decrease or eliminate land cover change, and reduce environmental impacts (10), we defined all four developed land cover classes as Compatible, excepting CSP in high and medium intensity as, to date, CSP technologies have not been deployed there owing to the relatively lower modularity of CSP.

Potentially Compatible areas augment site selections beyond Compatible areas. As slopes of 3% and 5% or less are most suitable for CSP and PV installations, respectively—owing to reduced costs and impact associated with surface grading—we used the National Elevation Dataset (varies from 3- to 30-m resolution; US Geological Survey) to exclude areas without these criteria. To minimize costs and impacts linked to new construction activities and materials, Potentially Compatible areas were also restricted to areas within 10 and 5 km of transmission lines (California Energy Commission) and roads (TIGER), respectively (*Supporting Information*, Fig. 3, and Table S4). We excluded areas where road construction is prohibited ("Federal Roadless Areas"; US Department of Forest and Agriculture), critical habitat of threatened and endangered species (US Fish and Wildlife Service), and federally protected areas (i.e., GAP Statuses 1 and 2, Protected Areas Database of the United States, US Geological Survey; Table S1). We reported generation-based potential for PV and CSP at the utility-scale, i.e., within areas identified as Compatible and Potentially Compatible and within areas meeting a minimum parcel size as needed for a 1-MW installation. Incompatible areas are not classified as Compatible and Potentially Compatible areas. To quantify impacts of solar energy development decisions, we spatially characterized the number, capacity, technology type, and footprint of USSE power plants dataset within the Compatibility Index and analyzed the reasons for incompatibility.

To quantify impact of proximity to protected areas from USSE development, we calculated the distance between each USSE facility data point (by technology type) to the nearest protected area by type (i.e., inventoried roadless areas, critical habitat of threatened and endangered species, and federally protected areas) using the "Near (Analysis)" in ArcGIS, and subsequently calculated the average of all distances (by protected area type) and 95% confidence intervals. For "all" protected area types, we used the shortest distance between each USSE facility data point and the three protected area types, and subsequently calculated the average of these shortest distances and 95% confidence intervals.

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EXHIBIT 27

Environmental Science & Technology

Article

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Land-Sparing Opportunities for Solar Energy Development in Agricultural Landscapes: A Case Study of the Great Central Valley, CA, United States

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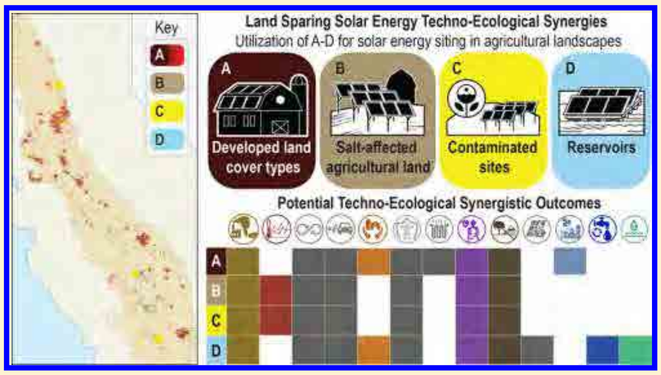
Supporting Information

ABSTRACT: Land-cover change from energy development, including solar energy, presents trade-offs for land used for the production of food and the conservation of ecosystems. Solar energy plays a critical role in contributing to the alternative energy mix to mitigate climate change and meet policy milestones; however, the extent that solar energy development on nonconventional surfaces can mitigate land scarcity is understudied. Here, we evaluate the land sparing potential of solar energy development across four nonconventional land-cover types: the built environment, salt-affected land, contaminated land, and water reservoirs (as floatovoltaics), within the Great Central Valley (CV, CA), a globally significant agricultural region where land for food production, urban development, and conservation collide. Furthermore, we calculate the technical potential (TWh year^{-1}) of these land sparing sites and test the degree to which projected electricity needs for the state of California can be met therein. In total, the CV encompasses 15% of CA, 8415 km^2 of which was identified as potentially land-sparing for solar energy development. These areas comprise a capacity-based energy potential of at least 17 348 TWh year^{-1} for photovoltaic (PV) and 2213 TWh year^{-1} for concentrating solar power (CSP). Accounting for technology efficiencies, this exceeds California's 2025 projected electricity demands up to 13 and 2 times for PV and CSP, respectively. Our study underscores the potential of strategic renewable energy siting to mitigate environmental trade-offs typically coupled with energy sprawl in agricultural landscapes.



INTRODUCTION

In the 21st century, agricultural landscapes are a complex nexus in which land, energy, and water are increasingly limited and interconnected.[1−4] Food production is intrinsically dependent on the diminishing supply of fresh water and viable land.[5,6] The pumping of water for irrigation, dependent on declining aquifers,[7] and other agricultural activities necessitates vast amounts of energy.[8] In the United States, the most agriculturally productive country globally, expenses related to energy (e.g., fertilizer production and equipment manufacture and use) are one of the primary limitations of food production, while U.S. dependency on foreign energy imports imposes additional limitations.[4] Additionally, organic emissions and those from carbon-intensive energy sources pose serious health and environmental risks to farming communities and geographically nested urban population centers.[9−12] In response to such limitations and risks,[4] solar energy is increasingly adopted by farmers and other agricultural stakeholders in ways that may spare land (e.g., building integrated photovoltaics [PVs]) for food and fiber production or, conversely, place additional pressure on arable land by displacing such land for energy production.[13,14]

Unlike conventional energy sources, solar energy can be integrated into pre-existing agricultural infrastructure and under-utilized spaces without adversely affecting commodity production or space required for such activities (e.g., edges of fields, corners of center pivot irrigation fields, and barn rooftops).[13,15,16] Farms require energy to support machinery, electric fencing, pumping and water filtration for irrigation,

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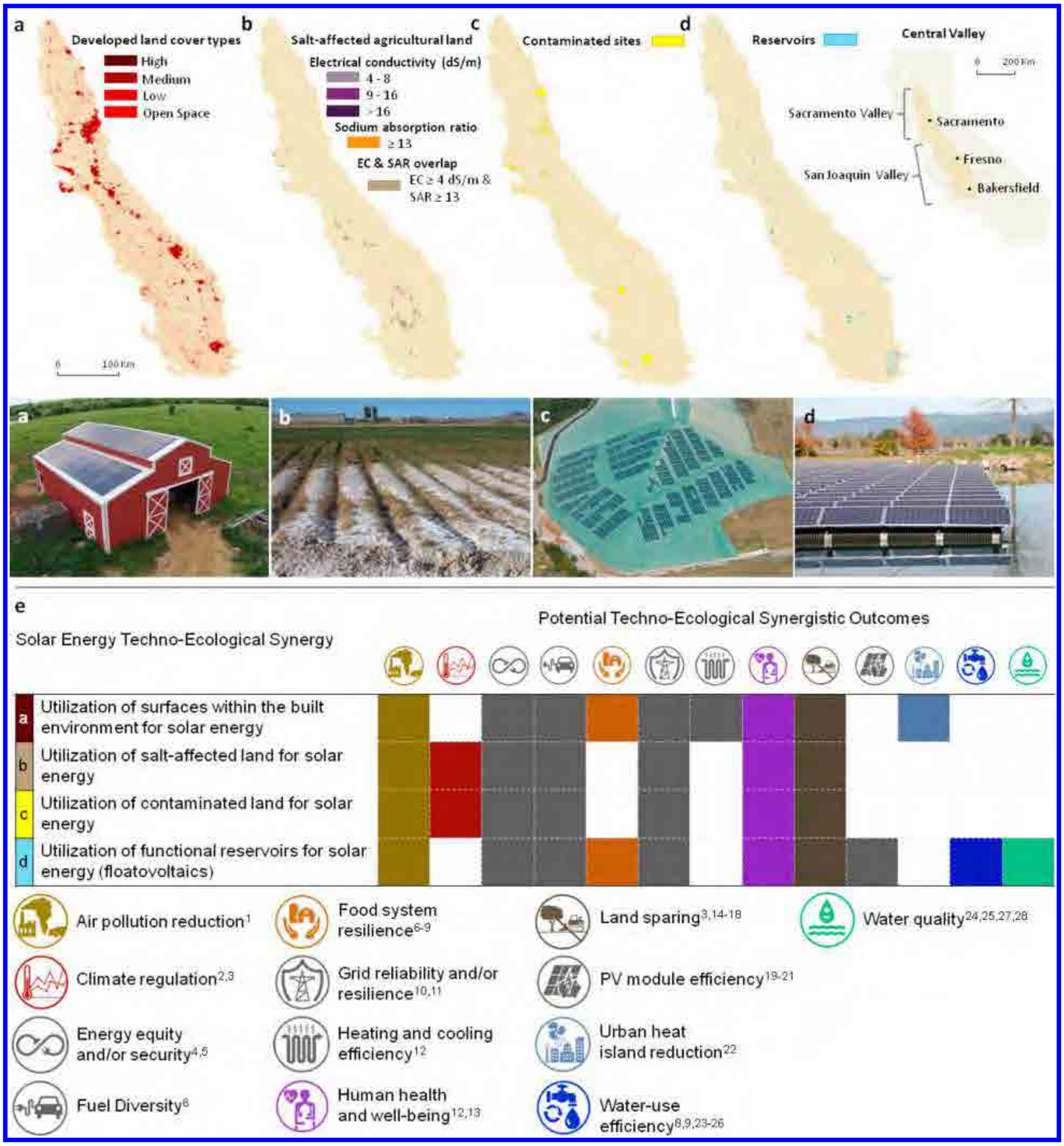

Figure 1. Land sparing solar energy siting opportunities within a 21st century agricultural landscape, i.e., California's Central Valley including within and over (a) the built environment, (b) salt-affected soils, (c) contaminated land, and (d) reservoirs. Contaminated sites are shown accurately according to their actual area but not shape. We posit that these land-sparing siting opportunities for solar energy development may also function individually (e) as a techno-ecological synergy (TES), a framework for engineering mutually beneficial relationships between technological and ecological systems that engender both techno-centric outcomes (gray icons) as well as support for sustainable flows of ecosystem goods and services (colored icons). Numbers refer to citations that provide justification for all potential techno-ecological synergistic outcomes. Larger versions of the map images are available in Figure S4. Photograph credit from left to right: (a) Cromwell Solar in Lawrence, Kansas by Aron Cromwell; (b) Donald Suarez, USDA Salinity Laboratory; (c) Carlisle Energy; (d) Far Niente Winery. All photographs are used with permission. Maps were made using ESRI ArcGIS Desktop (version 10.4) software.

drying and storing crops, lighting, powering heaters, and cooling livestock farmhouses. Previous studies have shown that on-farm solar schemes can provide farmers with reduced electricity pricing while requiring minimal water inputs (relative to other energy sources), thereby improving overall food availability and affordability.[2,13,14]

However, when large solar industrial complexes are developed on natural or prime agricultural lands, nontrivial land-use and land-cover change (LULCC) may result.[17−19] In California, Hernandez et al. (2015) found 110 km^2 of cultivated cropland and 37 km^2 of pasture was converted into use for ground-mounted utility-scale solar energy (USSE, ≥ 1 megawatt [MW]). In the municipality of Leece, Italy; De

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Marco et al. (2014) found that 51% of solar energy installations greater than 20 kW in capacity (n = 42) are sited in unsuitable areas, notably natural and agricultural areas, including century-old olive grooves.[19] Reversion of a site used for solar energy generation back to agriculture is typically unlikely, complicated by long-term application of herbicides, stabilizers, gravel, chemical suppressants, and soil compaction from power plant construction and maintenance activities. Further, land lease agreements and payback periods often exceed 15 years.[20]

The sustainability of energy, food, and water resources and the preservation of natural ecosystems are determined, in part, by how efficiently humans utilize land.[21] While most research has focused on the negative environmental impacts of ground-mounted USSE installations,[17,22] there is increasing attention on the design and enterprise of solar energy that produce both technological outcomes favorable for humans (e.g., energy security and fuel diversity) and benefits supporting ecosystem goods and services, including land sparing.[23] In this study, we define land sparing as siting decisions for solar energy infrastructure that obviate the need for LULCC that may have otherwise occurred within prime agricultural land and natural environments, respectively, including intermediates between these land-cover types. We posit that this framework, known techno-ecological synergy (TES), proposed by Bakshi et al. (2015),[24] and other studies suggest that several potential techno-ecological outcomes may be concomitantly achieved when nonconventional surfaces within agricultural landscapes are used for siting solar energy. Specifically, the utilization of geographically nested (1) urban population centers, i.e., the built environment (i.e., developed areas characterized by impermeable surfaces and human occupation), (2) land with salt-affected soils, (3) contaminated land, and (4) reservoirs may serve as recipient environments for solar energy infrastructure. These sites may also confer techno-ecological outcomes necessary for meeting sustainability goals in landscapes characterized by complex, coupled human and natural systems, such as those within agricultural landscapes. We explore these potential techno-ecological outcomes first, emphasizing the critical role these recipient environments may play in land sparing, which is the focus of our analysis (Figure 1).

Built Environments for Synergistic Solar Energy Development. Modern agricultural landscapes span 40% of Earth's surface[25] and are characterized by complex, heterogeneous mosaics in which natural, agricultural, and built-up elements, infrastructure, and policies intersect.[19,26,27] Areas characterized as the built environment within agricultural landscapes have considerable potential to accommodate solar energy development: a TES that may spare land for agricultural production and conservation locally,[17,21,28] reduce urban heat island effects,[29] and enhance human health and well-being, energy efficiency, and cost savings to consumers[30] (Figure 1). In the state of California (CA), installing small solar energy technology and USSE, including photovoltaic (PV) and concentrating solar power (CSP) technologies, throughout the built environment could meet the state's projected 2020 energy needs 3 to 5 times over.[17] Integrated PV (e.g., on rooftops, vertical walls, and over parking lots) has the lowest land footprint relative to all other energy sources (0 ha [ha]/TWh/year), incurring no LULCC, thus making developed areas environmentally optimal for PV systems. Additionally, solar panels within urban areas may lower local temperatures from increased surface albedo.[29] Integrating solar energy installations within such human-dominated environments generates cost savings directly from generation but also precludes energy losses from transmission and additional construction (e.g., grading, roads, and transmission) and raw material needs (e.g., grid connections, office facilities, and concrete) required for displacive ground-mounted USSE systems. For example, innovative ways of integrating PV technology, such as panels on or alongside transportation corridors (e.g., solar road panels[31] and photovoltaic noise barriers) and clear modules replacing windows will only increase its appeal within the built environment.[15,16,32,33]

Salt-Affected Lands for Synergistic Solar Energy Development. Naturally occurring high concentrations of salt (saline soils; Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, $SO_4{}^{2-}$, and $HCO_3{}^{-}$) or sodium (sodic soils; Na^{+}, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, $HCO_3{}^{-}$, $CO_3{}^{-}$, Cl^{-}, and $SO_4{}^{2-}$) combined with poor irrigation and farming practices can lead to dramatic losses in crop yield and, in severe cases, the cessation of agricultural productivity. An excess quantity of dissolved salt or sodium minerals in soil and water inhibits food production, threatens water quality, and facilitates sedimentation problems and soil erosion. Plant growth is limited by salinity due to the osmotic effect in which excess salts (e.g., chloride [Cl^{-}] and sulfate [$SO_4{}^{2-}$]) tightly attach to water molecules, inhibiting plant roots from absorbing "available" water due to the high passage resistance of the electric current. Different salts can affect growth uniquely where plant success is dependent on both the salt compound makeup and the individual plant's tolerance. A high sodium ratio (proportion of sodium [Na^{+}] relative to calcium [Ca^{2+}] and magnesium [Mg^{2+}]) is related to soil dispersion influenced by an excess of cations (Na^{+}) attaching to clay particles causing soil swelling and expansion. Overtime, sodic soils begin to solidify and lose their structure as they fluctuate between dry and moist periods, reducing soil permeability. Salinization impacts about 19.5% (45 million ha) of irrigated land, 2.1% (32 million ha) of dryland agriculture globally,[34] and costs the United States approximately $12 billion a year.[35] Developing solar energy on salt-affected land may reduce air pollution (e.g., when substituted for carbon-intensive energy sources), while a concomitant restoration of biophysical capacity of salt-affected land (e.g., composted municipal solar waste amendments[36] and native halophytic vegetation out-planting) may support climate regulation. Techno-centric outcomes of solar energy on salt-affected land may include energy equity, fuel diversity, and grid reliability.[37−39] Heckler[40] estimates soil lost to salt degradation will continue to increase at a yearly rate of about 0.8−16%, underscoring the potential long-term opportunity of salt-affected land as a potential land-sparing TES of solar energy (Figure 1).

Contaminated Land for Synergistic Solar Energy Development. Reclaiming land to provide sustainable energy has numerous potential techno-ecological outcomes including addressing public health risks, supporting climate regulation (e.g., following reclamation activities), and mitigating air pollution when solar energy generation is substituted for carbon-intensive sources of energy (Figure 1). Contaminated lands include brownfields, federal or nonfederal superfunds, and lands identified by the Resource Conservation and Recovery Act (RCRA), the Abandoned Mine Lands Program, and the Landfill Methane Outreach Program. Brownfields are areas previously designated for industrial or commercial use in which there are remnants of hazardous substances, pollutants, or contaminants. Superfund sites involve the most severely

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hazardous wastes requiring federal or state government attention. The RCRA ensures toxic waste storage facility sites responsibly and properly treat, store, or dispose of hazardous waste where cleanup expectations and requirements are determined by individual state governments. Once responsibly reclaimed, a process typically facilitated by government efforts, the land can be repurposed for commercial or industrial development. Contaminated sites typically left idle for extended periods of time, have low economic value, and are challenging to cultivate,[41,42] none of which undermine their potential for solar energy development. Examples of toxic wastelands that have been repurposed for solar energy development projects include sites formerly involving chemical and explosive manufacturing, steel production, tar and chemical processing, geothermal heating and cooling, and garbage disposal.[43] In the United States, the RE-Powering Initiative encourages renewable energy development on contaminated lands, and since the inception of the program, 1124 MW of renewable energy capacity is produced on 171 contaminated land sites.[44]

Floatovoltaics for Synergistic Solar Energy Development. Irrigation is the largest source of water consumption globally.[45,46] Brauman et al. (2013) found extensive variability in crop water productivity within global climatic zones indicating that irrigated croplands have significant potential to be intensified (i.e., food produced [kcal] per unit of water [L]) through improved water management.[47] The siting of solar energy panels that float on the surface of water bodies, such as reservoirs and irrigation canals, may minimize evaporation, reduce algae growth, cool water temperatures, and improve energy efficiency by reducing PV temperatures through evaporative cooling (Figure 1). There are vast opportunities for floatovoltaic deployment; collectively, lakes, ponds, and impoundments (water bodies formed by dams) cover more than 3% of the earth's surface area.[48] Reservoirs allow for relatively seamless solar energy integration compared with natural bodies of water, such as rivers, because their surfaces are relatively placid. This reduces the likelihood that panels will collide with each other or drift and break apart, allowing for easy maintenance. Additionally, unlike rivers and lakes, reservoirs are often located where energy demands are relatively high. Floatovoltaics integrate well into agricultural systems by allaying competition with land resources and providing energy and water savings. Farmers increasingly rely on agricultural ponds as water storage for irrigation, livestock, and aquaculture.[48] On-farm reservoirs are often wide but shallow making them more susceptible to water loss through evaporation.[49] Algae growth, a nutrient pollutant, is another costly nuisance for irrigation ponds that can clog pumps, block filters, and produce odors,[50] conditions attributed to further water losses that can be expensive and challenging for farmers to address. Solar panels reduce light exposure and lower water temperatures, minimizing algae growth and the need to filter water.[51−53] Finally, when solar panels are placed over cool water instead of land, PV module efficiency may increase 8−10%[54] where increased thermal transfer limits resistance on the circuit allow the electrical current to move faster.[55,56]

The Central Valley: A Model System for Land-Energy Interactions. The Central Valley (CV) is an ideal region in which to study land sparing benefits of solar energy TESs and to inform on broader issues related to the intersection between energy and land.[57] Located in one of the world's five mediterranean climate regions, California is valued as the largest agricultural producer within the United States, responsible for over half of the country's fruits and nuts, and is productive year-round.[58,59] This region also includes, in part, the California Floristic Province, an area supporting high concentrations of native and endemic species.[60] Over the last 150 years, the CV has experienced expansive LULCC owing to agricultural and urban development, which has accelerated habitat loss and fragmentation in areas of native prairies, marshes, vernal pools, oak woodlands, and alkali sink scrublands.[61] Within the last 30 years, LULCC has also occurred within agricultural land owing to energy development and urbanization, a large percent of which were considered prime farmlands.[61]

To date, there are few studies assessing the potential of solar energy within agricultural landscapes in ways that may concomitantly facilitate synergistic outcomes on technological and ecological systems beyond avoided emissions.[62,63] In this study, we sought to (1) evaluate the land sparing potential of solar energy development across four nonconventional land-cover types: the built environment, salt-affected land, contaminated land, and water reservoirs, as floatovoltaics, within the Great Central Valley (CV, CA) and (2) quantify the theoretical and technical (i.e., generation-based) potential of PV and CSP technologies within the CV and across these potential solar energy TESs to determine where technical potential for development is greatest geographically. Further, we sought to (3) determine the spatial relationship of land sparing areas with natural areas, protected areas, and agricultural regions designated as important to determine the proximity of these opportunities to essential landscapes that may have otherwise be selected for energy siting and development. Next, we (4) analyze the spatial density of contaminated sites within 10 km of the most populated CV cities to elucidate relationships between attributes (number and size) of nearby contaminated sites potentially favorable for solar energy generation and urban development centers because urban density is an explicative factor determining electricity consumption for cities.[64] Lastly, we (5) test the degree to which current and projected (2025) electricity needs for the state of California can be met across all four potential land sparing opportunities.

■ METHODS

Theoretical and Technical Solar Energy Potential for PV and CSP Technologies. The theoretical, or capacity-based, solar energy potential is the radiation incident on Earth's surfaces that can be utilized for energy production, including solar energy.[65] We used two satellite-based radiation models developed by the National Renewable Energy Laboratory (NREL) and Perez et al.[66] to estimate the theoretical solar energy potential of PV and CSP technologies operating at their full, nominal capacity over 0.1° surface cells (~10 km in size).

Photovoltaic technologies use both direct and indirect radiation, while CSP uses only direct-beam radiation. Therefore, the radiation model we used for CSP capacity-based energy estimates is representative of direct normal irradiance (DNI) only, whereas the PV model incorporates both DNI and diffuse irradiance. Areas with DNI values of less than 6 kWh m^{-2} day^{-1} were not considered economically adequate for CSP deployment and therefore excluded from solar potential estimates (Figure S1).

To evaluate the technical, or generation-based, solar energy potential within identified areas for land-sparing PV development, we multiplied the theoretical potential by a capacity

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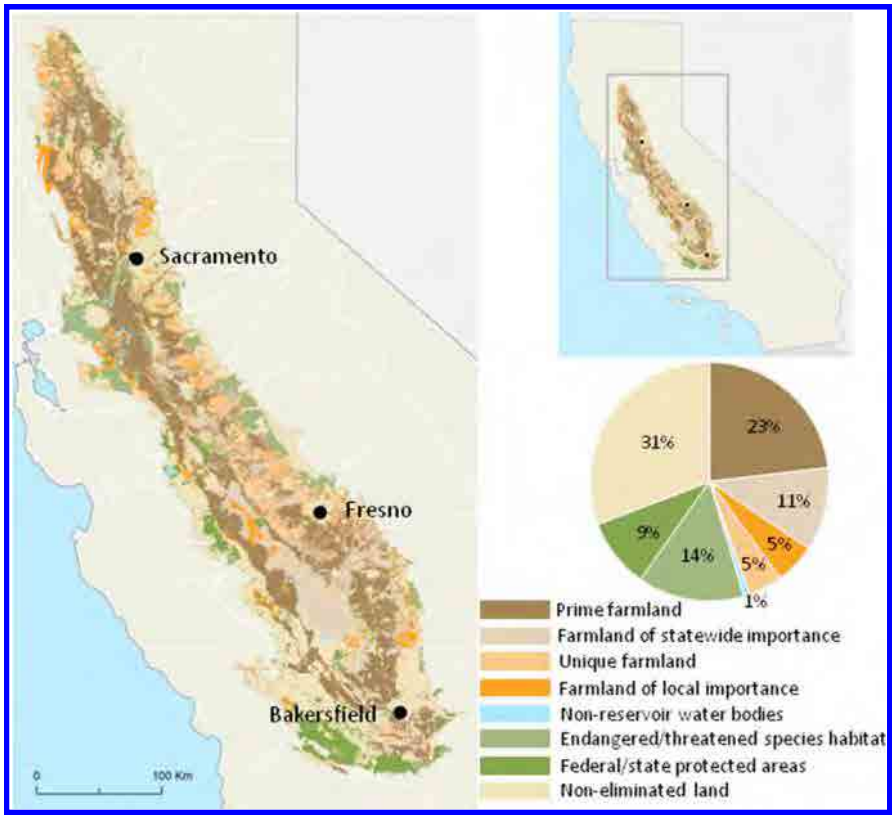

Figure 2. Map of California showing land-cover types eliminated when identifying solar energy potential over salt-affected soil. The pie graph depicts the relative proportion of area that each land cover type makes up within the Central Valley, which is not visible in the map due to overlap (e.g., areas identified as both endangered species habitat and state-protected). Land-cover types include: important farmlands (prime, unique, and of state-wide or local importance), nonreservoir bodies of water, endangered and threatened species habitat, federally and state-protected land, and non-eliminated land that was further evaluated for solar energy potential. The map was made using ESRI ArcGIS Desktop (version 10.4) software.

factor. The capacity factor values are derived from a satellite-based, spatially explicit capacity factor model[67] that has identical cells as the radiation models described above. The PV capacity factor model comprises estimates for three primary technology subtypes including fixed mount, south facing with a 25° tilt (TILT25); one-axis tracking, rotating east−west with a ± 45° maximum tracking angle (AX1FLAT); and two-axis tracking, rotating east−west and north−south of the sun across the horizon (AX2). For CSP generation-based calculations, we incorporated a five DNI class value scheme resembling estimates for a trough system.[68] Full details are provided in the Supplementary Methods.

Next, we calculated solar energy potential for both small and large-scale solar energy projects, where a minimum parcel size of 28 490 m^2 and 29 500 m^2 were required for PV and CSP facilities, respectively, producing 1 MW or more. These values are based on the average USSE land-use efficiency of 35.1 and 33.9 W m^{-2} for PV and CSP, respectively.[69] All CSP installations are utility-scale, and therefore, only these data are reported.

Solar Energy Potential of Land Sparing Opportunities in the Central Valley. We delineated the CV (58 815 km^2) based on the Great Central Valley Region[70] (Figure 1), composed of the geographic subdivisions of the Sacramento Valley, San Joaquin Valley, and all Outer South Coast Ranges encompassed within the San Joaquin Valley polygon. We overlaid the PV and CSP radiation models with the four land sparing land-cover types within the CV and calculated total area (km^2) and solar energy potentials (TWh $year^{-1}$). Across the salt-affected land solar energy TESs, we eliminated lands protected at the federal and state levels and threatened and endangered species habitats (Figure 2). Furthermore, all water bodies (e.g., wetlands and rivers), occurring in salt affected areas, with the exception of reservoirs, were removed as they may function as essential habitats for birds and other wildlife. Salt-affected soils within farmlands identified as primary, unique, or of state-wide or local importance[71] were also not included in the final estimates for solar energy potential. See the Supplementary Methods for explicit details on data and analysis for each land-cover type.

Spatial Relationships between Synergies and across Land-Cover Types. To ensure that energy potentials were not double-counted (e.g., salt-affected lands within the built environment), we calculated the spatial overlap across three solar energy TESs. Specifically, we observed overlap of land sparing potential among the built environment, salt-affected regions, and reservoirs. We did not include Environmental Protection Agency (EPA) contaminated sites because such data is not absolutely spatially explicit, but instead, each site is modeled circularly, in known total area, outward from a centroid based on known latitude and longitude coordinates, which may not represent each site's actual boundaries. Overlap between contaminated sites and land classified as salt-affected may be the most unlikely as most actions at these sites focus on preventing human contact.[41] Nonetheless, we did count 17 (189.5 km^2), 3 (2.5 km^2), and 740 (332.8 km^2) contaminated sites that may potentially overlap with salt-affected land, reservoirs, and the built environment, respectively, but we did

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Table 1. Contaminated Site Attributes across the Ten Most-Populated Cities Within the Central Valley, CA

city	city population	city area (km^2)	contaminated sites within city	contaminated sites within 10 km of city	contaminated site area within 10 km (km^2)
Fresno	494 665	112	38	58	21
Sacramento	466 488	98	83	140	47
Bakersfield	347 483	142	10	32	8
Stockton	291 707	62	53	95	35
Modesto	201 165	37	19	55	28
Elk Grove	153 015	42	27	71	52
Visalia	124 442	36	36	46	9
Concord	122 067	31	9	60	107
Roseville	118 788	5	8	60	75
Fairfield	105 321	37	10	26	34

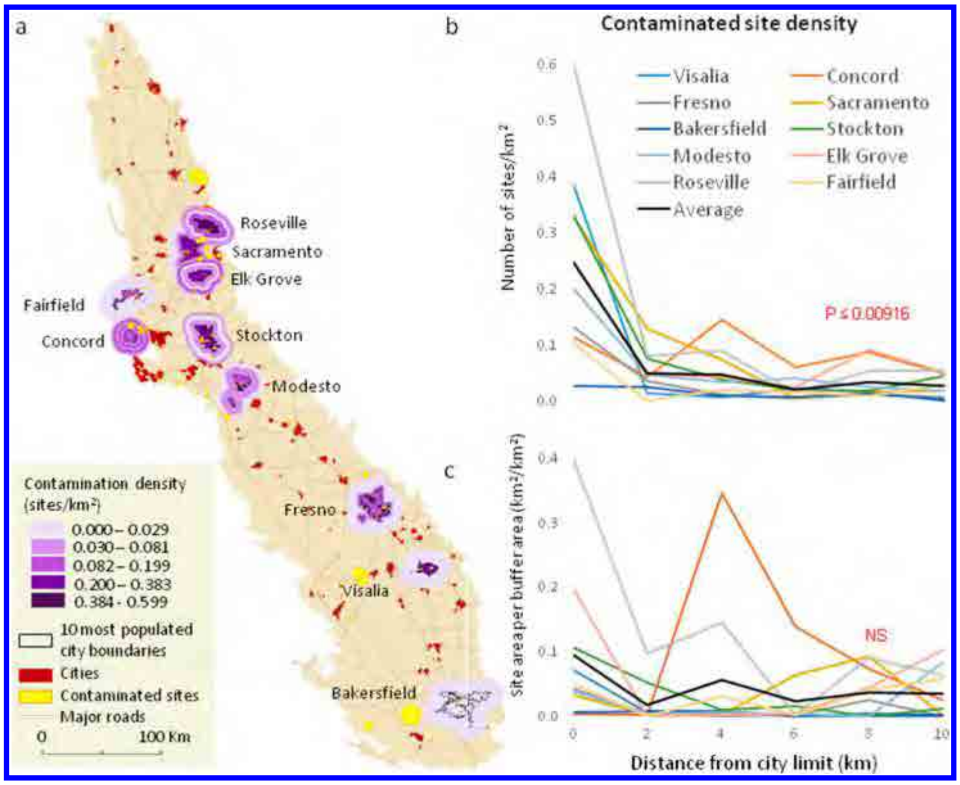

Figure 3. (a) Density of contaminated sites (circular points representing their total area but not shape; number of sites per square kilometer) within the Central Valley's (beige polygon) 10 most-populated cities: (1) within city limits (black line) and (2) across 0–2, 2–4, 4–6, 6–8, and 8–10 km buffers beyond city borders (purple buffers). Graphs show (b) the density of contaminated sites (sites per square kilometer) and (c) the total area of sites as a function of distance from city limits of the 10 most-populated cities in California's Central Valley. Land within each city boundary has a significantly greater number of contaminated sites based on total count (posthoc Tukey test, $P \leq 0.00916$) than buffer classes beyond the city perimeter (number of sites per square kilometer). No significant relationship exists between contamination site area and distance from urban cores. The map was made using ESRI ArcGIS Desktop (version 10.4) software.

not account for this overlap in the final values. We also enumerated spatial relationships between synergistic sites and other land-cover types throughout our analysis to determine the proximity of these opportunities to essential landscapes that may have otherwise been selected for energy siting and development.

Spatial Density and Proximity of Contaminated Lands to Human Populations. To elucidate relationships between attributes (number and size) of nearby contaminated sites potentially favorable for solar energy generation and urban development centers, we first identified the 10 most-populated cities within the Central Valley. We added 5 buffer distances around the perimeter of each city at 2 km increments up to 10 km (i.e., 2, 4, 6, 8, and 10 km). Within cities and each of these buffered rings (e.g., area between 4 and 6 km beyond city limits), we calculated the area and divided the number and area of contaminated sites that fall within each buffer by its associated area (site km^{-2} and site area $[km^2]$ km^{-2}). We included any sites located outside of the CV within 10 km of the city analyzed. Contaminated sites that were in a 10 km radius of more than one of the 10 highly populated city were included in each density analysis. We used generalized linear models (GLMs) to test the effects of distance class on contaminated site metrics (i.e, count and area) and to observe if sites are generally located near, further away, or have no association with urban development centers, which serve as a proxy for electricity demand. Contaminated sites that were within a 10 km radius of multiple cities were observed

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Table 2. Number of Times over PV and CSP Solar Energy Technologies Can Meet California'S Projected Electricity Consumption Needs for 2025 (321 TWh) Based on Land-Sparing Opportunities within the Central Valley, CA: (1) Developed, (2) Salt-Affect Soil, (3) Reservoirs, and (4) Contaminated Sites[a]

		PV				CSP	
		distributed and USSE		USSE only		USSE	
land-cover type[b]		capacity-based (times over)	generation-based (times over)	capacity-based (times over)	generation-based (times over)	capacity-based (times over)	generation-based (times over)
Central Valley		378.6	68.1−83.4	378.6	68.1	398.2	129.7
DNI ≥ 6 kWh m^{-2} day^{-1}		–	–	–	–	135.4	46.9
developed	high intensity	2.8	0.5−0.60	1.5	0.3	–	–
	medium intensity	10.8	1.9−2.35	7.5	1.3−1.6	–	–
	low intensity	9.3	1.7−2.02	1.6	0.3−0.4	0.2	0.1
	open space	19.2	3.5−4.2	6.2	1.1−1.4	1.9	0.7
salt-affected soil	EC ≥ 4 and ≤8	0.6	0.1	0.6	0.1	0.2	0.1
	EC > 8 and ≤16	0.8	0.1−0.2	0.8	0.1−0.2	0.3	0.1
	EC > 16	0.1	0.0	0.1	0.0	0.0	0.0
	SAR ≥ 13	0.2	0.0	0.2	0.0	0.0	0.0
	overlap (EC ≥ 4 and SAR ≥ 13)	3.9	0.7−0.9	3.9	0.7−0.9	1.4	0.4
reservoirs		0.7	0.1−0.2	0.6	0.1	–	–
contaminated		7.1	1.3−1.6	7.0	1.3−1.6	3.0	1.0
total		55.4	9.9−12.1	30.1	5.4−6.6	7.0	2.4
overlapping areas		1.3	0.2−0.3	0.6	0.1	0.1	0.0
total (accounting for overlapping areas)		54.1	9.7−11.8	29.5	5.3−6.5	6.9	2.4

[a]Capacity-based potential is representative of the full energy potential offered from the sun, whereas the generation-based potential estimates the energy potential given current technology capabilities including three PV system types (tilt, one-axis tracking, and two-axis tracking panels) and a CSP trough technology. [b]Total energy potentials account for overlaps in land-cover types to avoid double-counting.

separately and therefore accounted for more than once. See the Supplementary Methods for further details.

RESULTS AND DISCUSSION

We found that 8415 km^2 (equivalent to over 1.5 million American football fields) and 979 km^2 (approximately 183 000 American football fields) of non-conventional surfaces may serve as land-sparing recipient environments for PV and CSP solar energy development, respectively, within the great CV and in places that do not conflict with important farmlands and protected areas for conservation (Figure 1 and Tables 1 and Supplementary Table 1). This could supply a generation-based solar energy potential of up to 4287 TWh $year^{-1}$ for PV and 762 TWh $year^{-1}$ for CSP, which represents 2.8 (CSP) – 14.4% (PV) of the CV area. We accounted for 203 km^2 of overlap across the built-environment, reservoirs, and salt-affected areas, the latter after eliminating land classified as protected areas (federal and state), critical and threatened habitats, and important farmlands from salt-affected soils.

In total, the CV encompasses 58 649 km^2 of CA, about 15% of the total land area in the state, and has a theoretical potential of 121 543 and 127 825 TWh annually for PV and CSP, respectively (Table S1). Considering areas with solar radiation high enough to economically sustain a CSP solar energy facility (locations with a DNI of 6 kWh m^{-2} $year^{-1}$), less than one-third (~19 000 km^2) of the CV is suitable for CSP deployment, and a capacity-based potential of about 44 000 TWh $year^{-1}$.

Among the potential solar energy TESs we studied, the built environment offers the largest land sparing potential in area with the highest solar energy potential for PV systems (Figure 1a), representing between 57% (USSE only) and 76% (small-scale to USSE) of the total energy potential for PV. If only USSE PV systems are considered for development, roughly half of the total built environment is suitable, a constraint owing to areas not meeting minimum parcel requirements for a one MW installation (28 490 m^2 or greater). Specifically, installing PV systems across the built environment could provide a generation-based potential of 2413 TWh $year^{-1}$ utilizing fixed-tilt modules and up to 3336 TWh $year^{-1}$ for dual-axis modules (Table S2). Using CSP technology, both the low-intensity developed and the open spaces within the built environment could yield 242 TWh $year^{-1}$ of generation-based solar energy potential (Table S1). For CSP, the built environment represents 30% of all energy opportunity for the land-sparing solar energy TESs we studied.

Land with salt-affected soils, another potential land sparing solar energy TES, comprises 850 km^2 of the CV, excluding areas identified as important for agriculture and conservation (Figure 2). This remaining salt-affected land makes up 1.5% of the CV region. Generally, regions with high concentrations of salt also have unsuitable levels of sodium. Indeed, we found that 70% of sodic and saline soils overlap; occurring in the same place (Table S2). Geographically, most salt-affected land sparing opportunities suitable for solar energy development are within the interior region of the CV, away from the built environment (Figure 1c).

We found that 2% (1098 km^2) of the CV is composed of contaminated lands with a generation-based potential of 407 and 335 TWh $year^{-1}$ for PV and CSP, respectively. A total of 60% of these sites are clustered within and near (<10 km) the 10 most-populated cities, a buffer area composed of 21% of the CV (inclusive of buffer areas of cities extending beyond the CV border; Figure 3a and Table 1). We found that across the top 10 most-populated cities, population was significantly positively related to the number of contamination sites (GLM, t value of 2.293, P = 0.025916). We also found that land within each city

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boundary has a significantly greater number of contaminated sites based on total count (post-hoc Tukey test, $P \leq 0.00916$; Figures 3b and S2) than buffer classes beyond the city perimeter (number of sites per square kilometer; Figure 3b). We found no statistical relationship between contamination site area and distance from urban cores (Figure 3c). Note that in addition to the 953 contaminated sites quantified for solar energy potential, 51 more sites are included in the density analysis that reside outside of the CV boundary but are within 10 km of cities and 46 of the contaminated sites (Table 1) are accounted for multiple times because they are within the 10 km radius of multiple cities. Lastly, contaminated lands are particularly attractive for USSE projects, and indeed, 412 and 411 of the 953 contaminated sites from the EPA data set pass the minimum area requirement for supporting utility-scale PV and CSP technologies, respectively (Figure 3). Although our emphasis here was relationships between contaminated sites and urban development cores, more-robust analyses exploring spatial relationships between contaminated sites and population at the regional scale may be useful.

Reservoirs comprise 100 km^2 of available surface area for solar energy, just 0.2% of the total land area in the CV. The integration of fixed-tilt PV panels across all reservoir surface area would provide a generation-based energy potential of 39 TWh $year^{-1}$ (Table S1). There are roughly 4300 reservoirs within the CV, 2427 (56%) and 986 (23%) of which are classified as water storage and reservoirs, respectively (Figure S3). These water body types are the greatest targets for floatovoltaic development, and together, they make up roughly 66% of the total surface area of all reservoirs in the CV. While 66% of reservoirs identified in the CV are highest priority, the remaining 38% are treatment, disposal, and evaporator facilities, aquaculture, and unspecified reservoirs (Figure S3). In CA, farmers and water pump stations consume 19 TWh of electricity annually;[72] based on estimated energy potential for floatovoltaics, reservoirs provide enough surface area to supply 2 times the electricity needs of farmers or water pump stations for CA (19 TWh).[72]

California's projected annual electricity consumption needs for 2025, based on moderate assumptions, is 321 TWh.[73] The land-sparing solar energy TESs we explore in this study could meet CA's projected 2025 needs for electricity consumption between 10−13 times over with PV technologies and over two times over with CSP technologies (Table 2). In fact, each land-sparing TES individually can be used to meet the state's energy needs with the exception of reservoirs, which would provide enough surface area to produce electricity to meet 10−20% of CA's 2025 demands. However, reservoirs do offer enough surface area and potential to meet electricity needs within California's agriculture sector (i.e., 19 TWh annually).[72] CSP systems are confined to limited areas within the CV and therefore offer relatively less energy potential than PV; yet still, contaminated lands alone offer adequate space for CSP technologies to meet projected electricity needs for 2025.

Our study found contaminated sites are clustered within or near highly populated cities, many with populations that are projected to rapidly expand owing to urban growth. Thus, contaminated sites may serve as increasingly desirable recipient environments for solar energy infrastructure within the CV of California and agricultural landscapes elsewhere. The mission of the Environmental Protection Agency's (EPA) RE-Powering initiative is to increase awareness of these contaminated sites by offering tools, guidance, and technical assistance to a diverse community of stakeholders. Already, this program has facilitated development from 8 renewable energy projects in 2006 to nearly 200 today.[44] Across the United States alone, there are over 80 000 contaminated sites across 175 000 km^2 of land identified as having renewable energy potential, emphasizing the opportunity to repurpose under-utilized space. Given the globally widespread policy-based adoption of managing hazards in place, allowing for the less than complete remediation of environmental hazards on contaminated sites; the benefits of this TES must be weighed against risks assessed from indefinite oversight and monitoring.[41]

There are few studies or cost−benefit analyses on solar energy over functional water bodies that empirically and quantitatively assess the potential for synergistic outcomes related to water (e.g., water quality), energy, and land. Farmers frequently build water reservoirs to cope with limits on water allotment during drought periods,[74] offering opportunities for dual-use space for solar panels. Although floatovolaics are increasing in popularity, particularly in Asia, where the largest floating solar installation exists,[75] more-comprehensive environmental impact assessments are needed to quantify beneficial outcomes (e.g., reductions in evaporative loss) and address risks. One concern is that avian species may perceive PV modules as water, known as the "lake effect," leading to unintended collisions and possibly injury or mortality.

In 2015, installed capacity of solar energy technologies globally reached 220 GW driven by relatively high average annual growth rates for PV (45.5%, 1990−2015) and CSP (11.4%) compared with other renewable energy systems.[76,77] At these rates, trade-offs between land for energy generation and food production in an era of looming land scarcity may be high[9] when developed without consideration of impacts to land, including food and natural systems. For example, in the United States alone, an area greater than the state of Texas is projected to be impacted by energy development and sprawl, making energy the greatest driver of LULCC at a pace double the historic rate of residential and agricultural development by 2040.[28] California aims to derive half of its electricity generation (160 TWh) from renewable energy sources by 2030, and we show that the CV region can supply 100% of electricity needs from solar energy without compromising critical farmlands and protected habitats.

The extent to which agricultural landscapes can sustain increasing demand for agricultural products and transition to becoming a major solution to global change type threats instead of contributing to them depends on several factors; however, the manner in which land, energy, and water resources are managed within such landscapes is arguably the decisive factor.[4,78] Our study reveals that the great CV of California could accommodate solar energy development on nonconventional surfaces in ways that may preclude loss of farmland and nearby natural habitats that also support agricultural activities by enhancing pollinator services (e.g., wild bees) and crop yields.[79,80] Given the diffuse nature of solar energy, advances in battery storage would likely only enhance the economic and environmental appeal of the four solar energy TES we evaluated.[81,82] The realization of this potential may also confer other techno-ecological synergistic outcomes (as characterized in Figure 1), and additional research could be conducted to improve the certainty and accuracy of these potential benefits. For example, the degree to which realization of solar energy potential in agricultural landscapes on nonconventional surfaces contributes to food system resilience[83] by alleviating competi-

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tion of valuable land among farmers, raising property values, generating clean energy for local communities, enhancing air quality, and providing new job opportunities[14,62] remains largely unexplored.

Other factors impacting the sustainability of agricultural landscapes include the level of funding to support research and development, collaboration across public and private sectors to advance technology and innovation, and policies that bolster decisions and action leading to appropriate renewable energy siting. Research efforts have increasingly focused on identifying where and how renewable energy systems can be sustainably integrated into complex landscapes with environmentally vulnerable ecosystems,[21,22,84−86] but less emphasis has been on decisions with agricultural landscapes[19,78,84,85] despite its importance to food security and nutrition. In the US, the National Science Foundation is prioritizing the understanding of food, energy, and water interactions, identifying it as the most pressing problem of the millennium, but land has remained underemphasized in these programs.[87] Policies that result in cash payments to growers and solar energy developers for land sparing energy development could facilitate, indirectly, the conservation of important farmlands and natural areas. Federal policy could provide the financial support to state and local governments to protect natural and agriculturally critical areas, and decisions can be tailored at these administrative levels to accommodate the land use and water rights unique to the region.

California's Great Central Valley is a vulnerable yet indispensable region for food production globally. Our analysis reveals model options for sustainable solar energy development via use of nonconventional surfaces, i.e., the built environment, salt-affected land, contaminated land, and water reservoirs, as floatovoltaics. These land sparing solar energy development pathways may be relevant to other agricultural landscapes threatened by trade-offs associated with renewable energy development and sprawl.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b05110.

Detailed information about methods and data used for analysis in this study. Figures showing the effect of distance from the 10 most-populated cities, water reservoirs in the Central Valley, theoretical solar radiation potential, and maps of land-sparing solar energy. Tables showing utility-scale solar energy potential and photovoltaic energy potential.(PDF)

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Notes

The authors declare no competing financial interest.

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March 18, 2019

VIA EMAIL
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San Diego County Planning & Development Services
5510 Overland Avenue, Suite 110
San Diego, CA 92123

Re: Supplemental Scoping Comments of Backcountry Against Dumps and Donna Tisdale on the Proposed Boulder Brush Gen-Tie Line and Switchyard Facilities for the Campo Wind Project (PDS2019-MUP-19-002, PDS2019-ER-19-26-001)

Dear Ms. Brown:

On behalf of Backcountry Against Dumps and Donna Tisdale (collectively, "Backcountry"), we respectfully submit the following supplemental scoping comments on Boulder Brush, LLC's (the "Applicant's") proposed Boulder Brush Gen-Tie Line and Switchyard Facilities for the Campo Wind Project ("Boulder Brush" or the "Project;" PDS2019-MUP-19-002, PDS2019-ER-19-16-001), pursuant to the California Environmental Quality Act ("CEQA"), Public Resources Code ("PRC") section 21000 *et seq*., and San Diego County Planning & Development Services' (the "County's") February 14, 2019 Notice of Preparation of an Environmental Impact Report ("NOP"). Please include these supplemental comments in the public record for this Project.

These supplemental comments build on Backcountry's February 21, 2019 scoping comments on the Boulder Brush Project ("Scoping Comments"). These comments attach and summarize the results of a recent study of wind turbine-generated noise in the Project area. In addition, they summarize additional research documenting adverse wind turbine impacts to birds and to human health, both of which impacts must be studied in the environmental impact report ("EIR") for the Project. They also identify two additional categories of environmental impacts that must be analyzed in the EIR.

I. Additional Evidence of Wind Turbine Noise Impacts

Wilson Ihrig, a noise, vibration and acoustical professional consulting firm, obtained noise recordings between November 13 and 17, 2018 in the Boulevard and Jacumba Hot Springs areas. The findings are documented in a 2019 report.[1] Among other things, the report and a predecessor 2014 report on earlier noise measurements "conclusively document the presence of [wind turbine] generated infrasound (IS) as measured at residential and other locations up to 8 miles from the wind turbines at the Kumeyaay and Tule [wind project] facilities," and up to 11 miles from the Ocotillo Wind Energy project. Exhibit 1 at 1. The report also concludes that the 2018 noise recordings "indicate[] excessive amplitude modulated noise generated by the existing WTs." *Id*.

Given those findings, it is no surprise that area residents report numerous side effects from the existing turbines. Backcountry's Scoping Comments documented the association between wind turbine noise and annoyance and sleep disturbance, as do more recent studies.

For example, Deshmukh et al. (2019)[2] reviewed the literature on the impact of wind turbine noise on human health, as well as potential design options for reducing turbine-generated noise. They concluded that the studies they reviewed "reveal that wind turbine noise causes annoyance and even sleep disturbance in some cases." Exhibit 2 at 634.

More evidence has also begun to be published regarding amplitude-modulated wind turbine noise, which the 2019 Wilson Ihrig report documented to already be present in the Project area due to existing turbines. For example, Pohl et al. (2018)[3] conducted a longitudinal study of wind turbine noise annoyance in Germany and found that a "cause for the WT noise annoyance might be the amplitude modulation (AM)." Exhibit 3 at 126. Schäffer et al. (2019)[4] conducted a laboratory experiment with audio-visual simulations and likewise found that, even after accounting for visual impacts, AM increased annoyance.

The wind turbine-generated noise and impacts on area residents are likely to get much worse with the 90 new turbines proposed to be added by the Campo Wind and Torrey Wind projects, whose operation the Boulder Brush Project would make feasible.

II. Additional Evidence of Wind Turbine Bird Impacts

Backcountry established in its Scoping Comments that wind turbines and power lines kill birds, and that Boulder Brush's gen-tie lines and the 90 wind turbines proposed for the connected Campo Wind and Torrey Wind projects will be no different. Two additional recently published studies confirm wind turbines' multi-faceted bird impacts.

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[1] The report is attached hereto as Exhibit 1.
[2] Deshmukh, S., *et al.*, 2019, "Wind Turbine Noise and Its Mitigation Techniques," *Energy Procedia* 160:633-640, attached hereto as Exhibit 2.
[3] Pohl, J., *et al.*, 2018, "Understanding Stress Effects of Wind Turbine Noise – The Integrated Approach," *Energy Policy* 112:119-128, attached hereto as Exhibit 3.
[4] Schäffer, B., *et al.*, 2019, "Influence of Visibility of Wind Farms on Noise Annoyance – A Laboratory Experiment with Audio-Visual Simulations," *Landscape and Urban Planning* 186:67-78, attached hereto as Exhibit 4.

Becciu et al. (2019)[5] reviewed and summarized recent studies that have used radar to track anthropogenic impacts on birds. Among other findings, they noted a recent finding that mortality of nocturnally migrating birds "due to collision with wind turbines occurs regardless of the intensity of the migratory flow." Exhibit 5 at 46. They also noted multiple studies finding that diurnally migrating birds seem to alter their migratory pathways in the presence of wind turbines.

Marques et al. (2019)[6] used global positioning system tracking to model the displacement effects of wind turbines on black kites at the migratory bottleneck of the Strait of Gibraltar. They found that areas up to approximately 674 meters away from the turbines were less used than would be expected. They concluded that "the impacts of wind energy industry on soaring birds are greater than previously acknowledged." Exhibit 6 at 3. Soaring birds include most raptors, including eagles, which are known to use the Campo Wind and Torrey Wind project areas.[7]

III. The EIR Must Analyze the Project's Recreation Impacts

The County's NOP omits recreation from its list of "subject areas to be analyzed in the EIR." NOP at 2. This is not an impact that can be ignored. Rather, it must be analyzed and mitigated. The proliferation of industrial infrastructure in the Project area is ruining the area as a place where locals and visitors alike could experience the beauty and solitude of the high desert environment.

IV. The EIR Must Analyze the Project's Environmental Justice Impacts

The EIR must analyze how the Project might disproportionately impact communities that are underserved, disadvantaged, already overburdened with environmental impacts, or otherwise marginalized, including nearby tribal residents. The County must adopt feasible mitigation measures to offset any environmental justice impacts. The Office of the Attorney General's guidance on this is instructive.[8]

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[5] Becciu, P., *et al.*, 2019, "Environmental Effects on Flying Migrants Revealed by Radar," *Ecography*, attached hereto as Exhibit 5.

[6] Marques, A.T., *et al.*, 2019, "Wind Turbines Cause Functional Habitat Loss for Migratory Soaring Birds," *Journal of Animal Ecology*, attached hereto as Exhibit 6.

[7] *See* BLM and CPUC, Draft Environmental Impact Report/Environmental Impact Statement for East County Substation, Tule Wind, and Energia Sierra Juarez Gen-Tie Projects, December 2010, p. D.2-46, available at: http://www.cpuc.ca.gov/environment/info/dudek/ECOSUB/Draft_EIR/D-2_BioResources.pdf

[8] California Office of the Attorney General, "Environmental Justice at the Local and Regional Level Legal Background," July 2012, report available at: https://oag.ca.gov/sites/all/files/agweb/pdfs/environment/ej_fact_sheet.pdf

Please include this letter and its attached Exhibits in the public record. Thank you for your consideration.

Respectfully submitted,

Stephan C. Volker
Attorney for Backcountry Against Dumps
and Donna Tisdale

SCV:taf

Attachments:

Exhibit 1 – Carman, R.A. and M.A. Amato (Wilson Ihrig), March 18, 2019, "Results of Ambient Noise Measurements of the Existing Kumeyaay Wind and Tule Wind Facilities in the Area of Boulevard and Jacumba Hot Springs Pertaining to the Proposed Torrey and Campo Wind Turbine Facilities."

Exhibit 2 – Deshmukh, S., *et al.*, 2019, "Wind Turbine Noise and Its Mitigation Techniques," *Energy Procedia* 160:633-640.

Exhibit 3 – Pohl, J., *et al.*, 2018, "Understanding Stress Effects of Wind Turbine Noise – The Integrated Approach," *Energy Policy* 112:119-128.

Exhibit 4 – Schäffer, B., *et al.*, 2019, "Influence of Visibility of Wind Farms on Noise Annoyance – A Laboratory Experiment with Audio-Visual Simulations," *Landscape and Urban Planning* 186:67-78.

Exhibit 5 – Becciu, P., *et al.*, 2019, "Environmental Effects on Flying Migrants Revealed by Radar," *Ecography*.

Exhibit 6 – Marques, A.T., *et al.*, 2019, "Wind Turbines Cause Functional Habitat Loss for Migratory Soaring Birds," *Journal of Animal Ecology*.