

Wind Turbines and Health

A Critical Review of the Scientific Literature

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Objective: This review examines the literature related to health effects of wind turbines. **Methods:** We reviewed literature related to sound measurements near turbines, epidemiological and experimental studies, and factors associated with annoyance. **Results:** (1) Infrasound sound near wind turbines does not exceed audibility thresholds. (2) Epidemiological studies have shown associations between living near wind turbines and annoyance. (3) Infrasound and low-frequency sound do not present unique health risks. (4) Annoyance seems more strongly related to individual characteristics than noise from turbines. **Discussion:** Further areas of inquiry include enhanced noise characterization, analysis of predicted noise values contrasted with measured levels postinstallation, longitudinal assessments of health pre- and postinstallation, experimental studies in which subjects are “blinded” to the presence or absence of infrasound, and enhanced measurement techniques to evaluate annoyance.

The development of renewable energy, including wind, solar, and biomass, has been accompanied by attention to potential environmental health risks. Some people who live in proximity of wind turbines have raised health-related concerns about noise from their operations. The issue of wind turbines and human health has also now been explored and considered in a number of policy, regulatory, and legal proceedings.

This review is intended to assess the peer-reviewed literature regarding evaluations of potential health effects among people living in the vicinity of wind turbines. It will include analysis and commentary of the scientific evidence regarding potential links to health effects, such as stress, annoyance, and sleep disturbance, among others, that have been raised in association with living in proximity to wind turbines. Efforts will also be directed to specific components

of noise associated with wind turbines such as infrasound and low-frequency sound and their potential health effects.

We will attempt to address the following questions regarding wind turbines and health:

1. Is there sufficient scientific evidence to conclude that wind turbines adversely affect human health? If so, what are the circumstances associated with such effects and how might they be prevented?
2. Is there sufficient scientific evidence to conclude that psychological stress, annoyance, and sleep disturbance can occur as a result of living in proximity to wind turbines? Do these effects lead to adverse health effects? If so, what are the circumstances associated with such effects and how might they be prevented?
3. Is there evidence to suggest that specific aspects of wind turbine sound such as infrasound and low-frequency sound have unique potential health effects not associated with other sources of environmental noise?

The coauthors represent professional experience and training in occupational and environmental medicine, acoustics, epidemiology, otolaryngology, psychology, and public health.

Earlier reviews of wind turbines and potential health implications have been published in the peer-reviewed literature¹⁻⁶ by state and provincial governments (Massachusetts, 2012, and Australia, 2014, among others) and trade associations.⁷

This review is divided into the following five sections:

1. Noise: The type associated with wind turbine operations, how it is measured, and noise measurements associated with wind turbines.
2. Epidemiological studies of populations living in the vicinity of wind turbines.
3. Potential otolaryngology implications of exposure to wind turbine sound.
4. Potential psychological issues associated with responses to wind turbine operations and a discussion of the health implications of continuous annoyance.
5. Governmental and nongovernmental reports that have addressed wind turbine operations.

METHODS

To identify published research related to wind turbines and health, the following activities were undertaken:

1. We attempted to identify and assess peer-reviewed literature related to wind turbines and health by conducting a review of PubMed, the National Library of Medicine's database that indexes more than 5500 peer-reviewed health and scientific journals with more than 21 million citations. Search terms were wind turbines, wind turbines and health effects, infrasound, infrasound and health effects, low-frequency sound, wind turbine syndrome, wind turbines and annoyance, and wind turbines and sleep disturbances.
2. We conducted a Google search for nongovernmental organization and government agency reports related to wind turbines and environmental noise exposure (see Supplemental Digital Content Appendix 1, available at: <http://links.lww.com/JOM/A179>).

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3. After identifying articles obtained via these searches, they were categorized into five main areas that are noted below (section D) and referred to the respective authors of each section for their review and analysis. Each author then conducted their own additional review, including a survey of pertinent references cited in the identified articles. Articles were selected for review and commentary if they addressed exposure and a health effect—whether epidemiological or experimental—or were primary exposure assessments.
4. Identified studies were categorized into the following areas:
 - I. Sound, its components, and field measurements conducted in the vicinity of wind turbines;
 - II. Epidemiology;
 - III. Effects of sound components such as infrasound and low-frequency sound on health;
 - IV. Psychological factors associated with responses to wind turbines;
 - V. Governmental and nongovernmental reports.
5. The authors are aware of reports and commentaries that are not in the scientific or medical peer-reviewed literature that have raised concern about potential health implications for people who live near wind turbines. These reports describe relatively common symptoms with numerous causes, including headache, tinnitus, and sleep disturbance. Because of the difficulties in comprehensively identifying non-peer-reviewed reports such as these, and the inherent uncertainty in the quality of non-peer-reviewed reports, they were not included in our analysis, aside from some books and government reports that are readily identified. A similar approach of excluding non-peer-reviewed literature in scientific reviews is used by the World Health Organization (WHO)'s International Agency for Research on Cancer (IARC) in its deliberations regarding identification of human carcinogens.⁸ International Agency for Research on Cancer, however, critically evaluates exposure assessments not published in the peer-reviewed literature, if conducted with appropriate quality and in accordance with international standards and guidelines. International Agency for Research on Cancer uses this policy for exposure assessments because many of these efforts, although containing valuable data in evaluating health risks associated with an exposure to a hazard, are not routinely published. The USA National Toxicology Program also limits its critical analysis of potential carcinogens to the peer-reviewed literature. In our view, because of the critical effect of scientific studies on public policy, it is imperative that peer-reviewed literature be used as the basis. Thus, in this review, only peer review studies are considered, aside from exposure-related assessments.

RESULTS

Characteristics of Wind Turbine Sound

In this portion of the review, we evaluate studies in which sound near wind turbines has been measured, discuss the use of modeled sound levels in dose-response studies, and review literature on measurements of low-frequency sound and infrasound from operating wind turbines. We evaluate sound levels measured in areas, where symptoms have been reported in the context of proximity to wind turbines. We address methodologies used to measure wind turbine noise and low-frequency sound. We also address characteristics of wind turbine sound, sound levels measured near existing wind turbines, and the response of humans to different levels and characteristics of wind turbine sound. Special attention is given to challenges and methods of measuring wind turbine noise, as well as low-frequency sound (20 to 200 Hz) and Infrasound (less than 20 Hz).

Wind turbines sound is made up from both moving components and interactions with nonmoving components of the wind turbine (Fig. 1). For example, mechanical components in the nacelle can generate noise and vibration, which can be radiated from the structure, including the tower. The blade has several components that create aerodynamic noise, such as the blade leading edge, which contacts the wind first in its rotation, the trailing edge, and the blade tip. Blade/tower interactions, especially where the blades are downwind of the tower, can create infrasound and low-frequency sound. This tower orientation is no longer used in large wind turbines.⁹

Sound Level and Frequency

Sound is primarily characterized by its pitch or frequency as measured in Hertz (Hz) and its level as measured in decibels (dB). The frequency of a sound is the number of times in a second that the medium through which the sound energy is traveling (ie, air, in the case of wind turbine sound) goes through a compression cycle. Normal human hearing is generally in the range of 20 to 20,000 Hz. As an example, an 88-key piano ranges from about 27.5 to 4186 Hz with middle C at 261.6 Hz. As in music, ranges of frequencies can be described in "octaves," where the center of each octave band has a frequency of twice that of the previous octave band (this is also written as a "1/1 octave band"). Smaller subdivisions can be used such as 1/3 and 1/12 octaves. The level of sound pressure for each frequency band is reported in decibel units.

To represent the overall sound level in a single value, the levels from each frequency band are logarithmically added. Because human hearing is relatively insensitive to very low- and high-frequency sounds, frequency-specific adjustments or weightings are added to the unweighted sound levels before summing to the overall level. The most common of these is the A-weighting, which simulates the human response to various frequencies at relatively low levels (40 phon or about 50 dB). Examples of A-weighted sound levels are shown in Fig. 2.

Other weightings are cited in the literature, such as the C-weighting, which is relatively flat at the audible spectrum; G-weighting, which simulates human perception and annoyance of sound that lie wholly or partly in the range from 1 to 20 Hz; and Z-weighting, which does not apply any weighting. The weighting of the sound is indicated after the dB label. For example, an A-weighted sound level of 45 dB would be written as 45 dBA or 45 dB(A). If no label is shown, the weighting is either implied or unweighted.

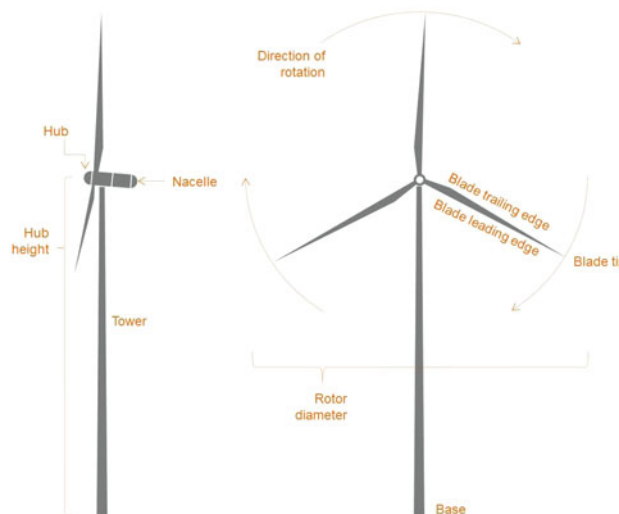


FIGURE 1 . Schematic of a modern day wind turbine.

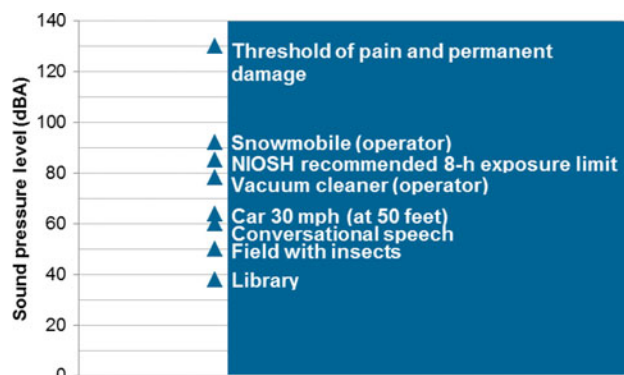


FIGURE 2. Sample A-weighted sound pressure levels.

Beyond the overall level, wind turbine noise may be amplitude modulated or have tonal components. Amplitude modulation is a regular cycling in the level of pure tone or broadband sound. A typical three-bladed wind turbine operating at 15 RPM would have a modulation period or cycle length of about 1.3 seconds. Tones are frequencies or narrow frequency bands that are much louder than the adjacent frequencies in sound spectra. Prominent tones can be identified through several standards, including ANSI S12.9 Part 4 and IEC 61400-11. Relative high-, mid-, and low-frequency content can also define how the sound is perceived, as well as many qualitative factors unique to the listener. Consequently, more than just the overall levels can be quantified, and studies have measured the existence of amplitude modulation, prominent tones, and spectral content in addition to the overall levels.

Wind Turbine Sound Power and Pressure Levels

The sound *power* level is the intrinsic sound energy radiated by a source. It is not dependent on the particular environment of the sound source and the location of the receiver relative to the source. The sound *pressure* level (SPL), which is measured by a sound-level meter at a location, is a function of the sound *power* emitted by neighboring sources and is highly dependent on the environment and the location of the receiver relative to the sound source(s).

Wind turbine sound is typically broadband in character with most of the sound energy at lower frequencies (less than 1000 Hz). Although wind turbines produce sound at frequencies less than the 25 Hz 1/3 octave band, sound power data are rarely published below that frequency. Most larger, utility-scale wind turbines have sound power levels between 104 and 107 dBA. Measured sound levels because of wind turbines depend on several factors, including weather conditions, the number of turbines, turbine layout, local topography, the particular turbine used, distance between the turbines and the receiver, and local flora. Meteorological conditions alone can cause 7 to 14 dB variations in sound levels.¹⁰ Examples of the SPLs because of a single wind turbine with three different sound powers, and at various distances, are shown in Fig. 3 as calculated with ISO 9613-2.¹¹ Measurement results of A-weighted, C-weighted, and G-weighted sound levels have confirmed that wind turbine sound attenuates logarithmically with respect to distance.¹²

With respect to noise standards, Hessler and Hessler¹³ found an arithmetic average of 45 dBA daytime and 40 dBA nighttime for governments outside the United States, and a nighttime average of 47.7 dBA for US state noise regulation and siting standards. The metrics for those levels can vary. Common metrics are the day-evening-night level (Lden), day-night level (Ldn), equivalent average level (Leq), level exceeded 90% of the time (L90), and median (L50). The application of how these are measured and the time period over which they are measured varies, meaning that, from a practical

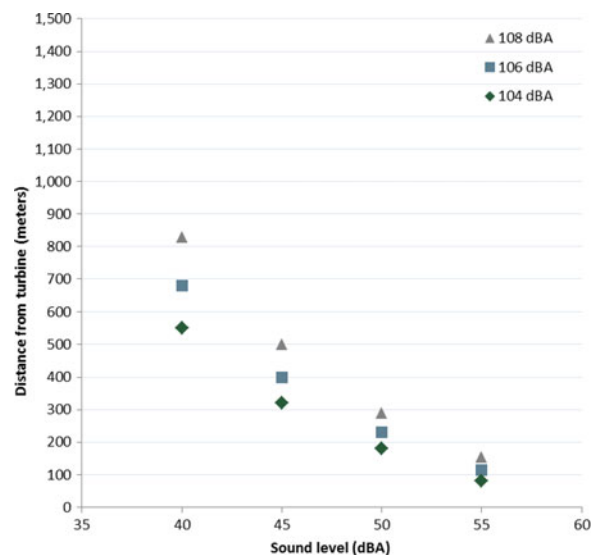


FIGURE 3. Sound levels at varying setbacks and turbine sound power levels—RSG Modeling, Using ISO 9613-2.

standpoint, sound-level limits are even more varied than the explicit numerical level. The Leq is one of the more commonly used metric. It is the logarithmic average of the squared relative pressure over a period of time. This results in a higher weighting of louder sounds.

Owing to large number of variables that contribute to SPLs because of wind turbines at receivers, measured levels can vary dramatically. At a wind farm in Texas, O'Neal et al¹⁴ measured sound levels with the nearest turbine at 305 m (1000 feet) and with four turbines within 610 m (2000 feet) at 50 to 51 dBA and 63 dBC (10-minute Leq), with the turbines producing sufficient power to emit the maximum sound power. During the same test, sound levels were 27 dBA and 47 dBC (10-minute Leq) inside a home that was located 290 m (950 feet) from the nearest turbine and within 610 m (2000 feet) of four turbines¹⁵ (see Fig. 4).

Bullmore et al¹⁶ measured wind turbine sound at distances from 100 to 754 m (330 to 2470 feet), where they found sound levels ranging from 40 to 55 dBA over various wind conditions. At typical receiver distances (greater than 300 m or 1000 feet), sound was attenuated to below the threshold of hearing at frequencies above the 1.25 kHz 1/3 octave band. In studies mentioned here, measurements were made with the microphone between 1 and 1.6 m (3 and 5 feet) above ground.

Wind Turbine Emission Characteristics

Low-Frequency Sound and Infrasond

Low-frequency sound is typically defined as sound from 20 to 200 Hz, and infrasound is sound less than 20 Hz. Low-frequency sound and infrasound measurement results at distances close to wind turbines (< 500 meters) typically show infrasound because of wind farms, but not above audibility thresholds (such as ISO 226 or as published by the authors^{12,15,17–21,149}). One study found sound levels 360 m and 200 m from a wind farm to be 61 dBG and 63 dBG, respectively. The threshold of audibility for G-weighted sound levels is 85 dBG. The same paper found infrasound levels of 69 dBG 250 m from a coastal cliff face and 76 dBG in downtown Adelaide, Australia.¹⁸ One study found that, even at distances less than 450 feet (136 m), infrasound levels were 80 dBG or less. At more typical receiver distances (greater than 300 m or 1000 feet), infrasound levels were 72 dBG or less. This corresponded to A-weighted sound

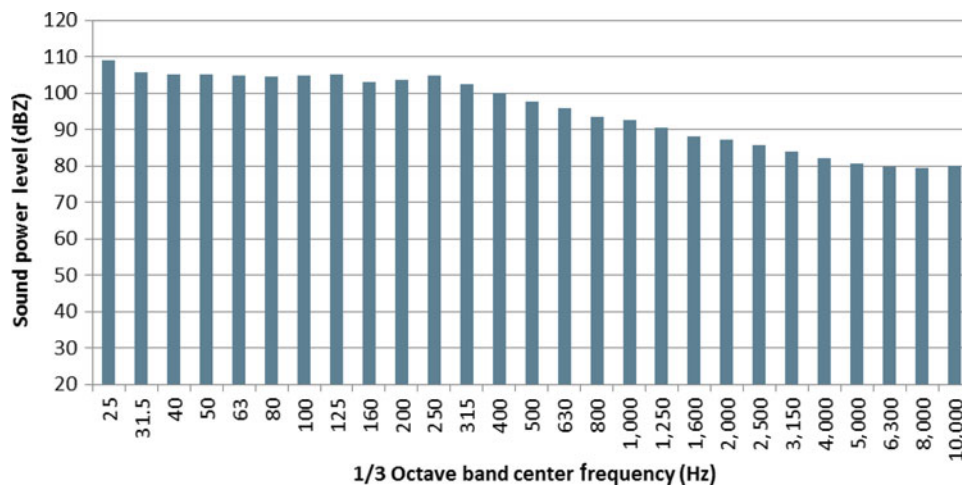


FIGURE 4. Sound power of the Siemens SWT 2.3-93 (TX) wind turbine.¹⁵

levels of 56 and 49 dBA, respectively, higher than most existing regulatory noise limits.¹²

Farther away from wind farms (1.5 km) infrasound is no higher than what would be caused by localized wind conditions, reinforcing the necessity for adequate wind-caused pseudosound reduction measures for wind turbine sound-level measurements.²²

Low-frequency sound near wind farms is typically audible, with levels crossing the threshold of audibility between 25 and 125 Hz depending on the distance between the turbines and measurement location.^{12,15,19,20,23} Figure 5 shows the frequency spectrum of a wind farm measured at about 3500 feet compared with a truck at 50 feet, a field of insects and birds, wind moving through vegetation, and the threshold of audibility according to ISO 387-7.

Amplitude Modulation

Wind turbine sound emissions vary with blade velocity and are characterized in part by amplitude modulation, a broadband oscillation in sound level, with a cycle time generally corresponding to the blade passage frequency. The modulation is typically located in the 1/1 octave bands from 125 Hz to 2 kHz. Fluctuation magnitudes are typically not uniform throughout the frequency range. These fluctuations are typically small (2 to 4 dB) but under more unusual circumstances can be as great as 10 dB for A-weighted levels and as much as 15 dB in individual 1/3 octave bands.^{19,24} Stigwood et al²⁴ found that, in groups of several turbines, the individual modulations can often synchronize causing periodic increases in the modulation magnitude for periods of 6 to 20 seconds with occasional periods where the individual turbine modulations average each other out, minimizing the modulation magnitude. This was not always the case though, with periods of turbine synchronization occasionally lasting for hours under consistent high wind shear, wind strength, and wind direction.

Amplitude modulation is caused by many factors, including blade passage in front of the tower (shadowing), sound emission directivity of the moving blade tips, yaw error of the turbine blades (where the turbine blades are not perpendicular to the wind), inflow turbulence, and high levels of wind shear.^{19,24,25} Amplitude modulation level is not correlated with wind speed. Most occurrences of “enhanced” amplitude modulation (a higher magnitude of modulation) are caused by anomalous meteorological conditions.¹⁹ Amplitude modulation varies by site. Some sites rarely exhibit amplitude modulation, whereas at others amplitude modulation has been measured up to 30% of the time.¹⁰ It has been suggested by some that

amplitude modulation may be the cause of “infrasound” complaints because of confusing of amplitude modulation, the modulation of a broadband sound, with actual infrasound.¹⁹

Tonality

Tones are specific frequencies or narrow bands of frequencies that are significantly louder than adjacent frequencies. Tonal sound is not typically generated by wind turbines but can be found in some cases.^{20,26} In most cases, the tonal sound occurs at lower frequencies (less than 200 Hz) and is due to mechanical noise originating from the nacelle, but has also been found to be due to structural vibrations originating from the tower, and anomalous aerodynamic characteristics of the blades²⁷ (see Fig. 5).

Sound Levels at Residences where Symptoms Have Been Reported

One recent research focus has been the sound levels at (and in) the residences of people who have complained about sound levels emitted by turbines as some have suggested that wind turbine noise may be a different type of environmental noise.²⁸ Few studies have actually measured sound levels inside or outside the homes of people. Several hypotheses have been proposed about the characteristics of wind turbine noise complaints, including infrasound,²⁸ low-frequency tones,²⁰ amplitude modulation,^{19,29} and overall noise levels.

Overall Noise Levels

Because of the large variability of noise sensitivity among people, sound levels associated with self-reported annoyance can vary considerably. (Noise sensitivity and annoyance are discussed in more detail later in this review.) People exposed to measured external sound levels from 38 to 53 dBA (10-minute or 1-hour Leq). Department of Trade and Industry,¹⁹ Walker et al,²⁸ Gabriel et al,²⁹ and van den Berg et al^{30,149} have reported annoyance. Sound levels have also been measured inside complainant residences at between 22 and 37 dBA (10-minute Leq).¹⁹

Low Frequency and Infrasonic Levels

Concerns have been raised in some settings that low-frequency sound and infrasound may be special features of wind turbine noise that lead to adverse health effects.³¹ As a result, noise measurements in areas of operating wind turbines have focused specifically

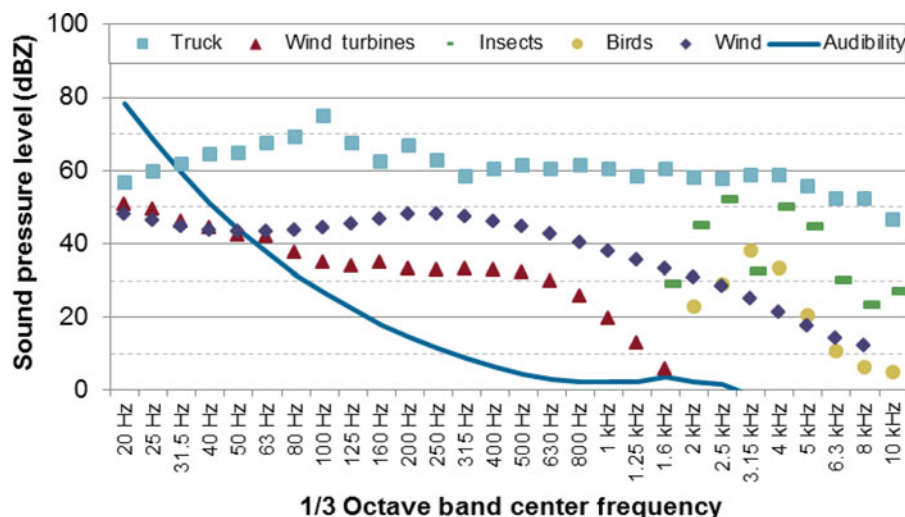


FIGURE 5. Comparison of frequency spectrum of a truck passby at 50 feet, wind turbines at 3500 feet, insects, birds, wind, and the threshold of audibility according to ISO 387-7.

on sound levels in the low-frequency range and occasionally the infrasonic range.

Infrasonic sound levels at residences are typically well below published audibility thresholds, even thresholds for those particularly sensitive to infrasound. Nevertheless, low-frequency sound typically exceeds audibility thresholds in a range starting between 25 and 125 Hz.^{19,20,23} In some cases, harmonics of the blade passage frequency (about 1 Hz, ie infrasound) have been measured at homes of people who have raised concerns about health implications of living near wind turbine with sound levels reaching 76 dB; however, these are well below published audibility thresholds.²⁸

Amplitude Modulation

Amplitude modulation has been suggested as a major cause of complaints surrounding wind turbines, although little data have been collected to confirm this hypothesis. A recent study of residents surrounding a wind farm that had received several complaints showed predicted sound levels at receiver distances to be 33 dBA or less. Residents were instructed to describe the turbine sound, when they found it annoying. Amplitude modulation was present in 68 of 95 complaints. Sound recorders distributed to the residents exhibited a high incidence of amplitude modulation.²⁹

Limited studies have addressed the percentage of complaints surrounding utility-scale wind farms, with only one comparing the occurrence of complaints with sound levels at the homes. The complaint rate among residents within 2000 feet (610 m) of the perimeter of five mid-western United States wind farms was approximately 4%. All except one of the complaints were made at residences, where wind farm sound levels exceeded 40 dBA.¹³ The authors used the LA90 metric to assess wind farm sound emissions. LA90 is the A-weighted sound level that is exceeded 90% of the time. This metric is used to eliminate wind-caused spikes and other short-term sound events that are not caused by the wind farm.

In Northern New England, 5% of households within 1000 m of turbines complained to regulatory agencies about wind turbine noise.³² All complaints were included, even those that were related to temporary issues that were resolved. Up to 48% of the complainants were at wind farms, where at least one noise violation was found or a variance from the noise standard. A third of the all complaints were due to a single wind farm.

Sound Measurement Methodology

Collection of accurate, comparable, and useful noise data depends on careful and consistent methodology. The general method-

ology for environmental sound level monitoring is found in ANSI 12.9 Part 2. This standard covers basic requirements that include the type of measurement equipment necessary, calibration procedures, windscreen specifications, microphone placement guidance, and suitable meteorological conditions. Nevertheless, there are no recommendations for mitigating the effects of *high* winds (greater than 5 m/s) or measuring in the infrasonic frequency range (less than 20 Hz).³³ Another applicable standard is IEC 61400-11, which provides a method for determining the sound power of individual wind turbines. The standard gives specifications for measurement positions, the type of data needed, data analysis methods, report content requirements, determination of tonality, determination of directivity, and the definitions and descriptors of different acoustical parameters.³⁴ The standard specifies a microphone mounting method to minimize wind-caused pseudosound, but some have found the setup to be insufficient under gusty wind conditions, and no recommendations are given for infrasound measurement.³⁵ Because the microphone is ground mounted, it is not suitable for long-term measurements.

Low-Frequency Sound and Infrasound Measurement

There are no standards currently in place for the measurement of wind turbine noise that includes the infrasonic range (ie, frequencies less than 20 Hz), although one is under development (ANSI/ASA S12.9 Part 7). Consequently, all current attempts to measure low-frequency sound and infrasound have either used an existing methodology, an adapted existing methodology, or proposed a new methodology.

The main problem with measuring low-frequency sound and infrasound in environmental conditions is wind-caused pseudosound due to air pressure fluctuation, because air flows over the microphone. With conventional sound-level monitoring, this effect is minimized with a wind screen and/or elimination of data measured during windy periods (less than 5 m/s [11 mph] at a 2-m [6.5 feet] height).³⁶ In the case of wind turbines, where maximum sound levels may be coincident with ground wind speeds greater than 5 m/s (11 mph), this is not the best solution. With infrasound in particular, wind-caused pseudosound can influence measurements, even at wind speeds down to 1 m/s.¹² In fact, many sound-level meters do not measure infrasonic frequencies.

A common method of dealing with infrasound is using an additional wind screen to further insulate the microphone from air flow.^{18,35} In some cases, this is simply a larger windscreen that further insulates the microphone from air flow.³⁵ One author used a

windscreen with a subterranean pit to shelter the microphone, and another used wind resistant cloth.³⁵ A compromise to an underground microphone mounting is mounting the microphone close (20-cm height) to the ground, minimizing wind influence, or using a standard ground mounted microphone with mounting plate, as found in IEC 61400-11.³⁵ Low-frequency sound and infrasound differences between measurements made with dedicated specialized windscreens and/or measurement setup and standard wind screens/measurements setups can be quite large.^{12,37} Nevertheless, increased measurement accuracy can come at the cost of reduced accuracy at higher frequencies using some methods.³⁸

To further filter out wind-caused pseudosound, some authors have advocated a combination of microphone arrays and signal processing techniques. The purpose of the signal processing techniques is to detect elements of similarity in the sound field measured at the different microphones in the array.

Levels of infrasound from other environmental sources can be as high as infrasound from wind turbines. A study of infrasound measured at wind turbines and at other locations away from wind turbines in South Australia found that the infrasound level at houses near the wind turbines is no greater than that found in other urban and rural environments. The contribution of wind turbines to the infrasound levels is insignificant in comparison with the background level of infrasound in the environment.²²

Conclusions

Wind turbine noise measurement can be challenging because of the necessity of measuring sound levels during high winds, and down to low frequencies. No widely accepted measurement methodologies address all of these issues, meaning that methods used in published measurements can differ substantially, affecting the comparability of results.

Measurements of low-frequency sound, infrasound, tonal sound emission, and amplitude-modulated sound show that infrasound is emitted by wind turbines, but the levels at customary distances to homes are typically well below audibility thresholds, even at residences where complaints have been raised. Low-frequency sound, often audible in wind turbine sound, typically crosses the audibility threshold between 25 and 125 Hz depending on the location and meteorological conditions.^{12,15,19,20,23} Amplitude modulation, or the rapid (once per second) and repetitive increase and decrease of broadband sound level, has been measured at wind farms. Amplitude modulation is typically 2 to 4 dB but can vary more than 6 dB in some cases (A-weighted sound levels).^{19,24}

A Canadian report investigated the total number of noise-related complaints because of operating wind farms in Alberta, Canada, over its entire history of wind power. Wind power capacity exceeds 1100 MW; some of the turbines have been in operation for 20 years. Five noise-oriented complaints at utility-scale wind farms were reported over this period, none of which were repeated after the complaints were addressed. Complaints were more common during construction of the wind farms; other power generation methods (gas, oil, etc) received more complaints than wind power. Farmers and ranchers did not raise complaints because of effects on crops and cattle.⁴¹ An Australian study found a complaint rate of less than 1% for residents living within 5 km of turbines greater than 1 MW. Complaints were concentrated among a few wind farms; many wind farms never received complaints.¹⁵

Reviewing complaints in the vicinity of wind farms can be effective in determining the level and extent of annoyance because of wind turbine noise, but there are limitations to this approach. A complaint may be because of higher levels of annoyance (rather annoyed or very annoyed), and the amount of annoyance required for an individual to complain may be dependent on the personality of the person and the corresponding attitude toward the visual effect of the turbines, their respective attitudes toward wind energy, and whether

they derive economic benefit from the turbines. (All of these factors are discussed in more detail later in this report.)

Few studies have addressed sound levels at the residents of people who have described symptoms they consider because of wind turbines. Limited available data show a wide range of levels (38 to 53 dBA [10-minute or 1-hour Leq] outside the residence and from 23 to 37 dBA [10-minute Leq] inside the residence).^{19,26,28,28} The rate of complaints surrounding wind farms is relatively low; 3% for residents within 1 mile of wind farms and 4% to 5% within 1 km.^{13,32,41}

Epidemiological Studies of Wind Turbines

Key to understanding potential effects of wind turbine noise on human health is to consider relevant evidence from well-conducted epidemiological studies, which has the advantage of reflecting risks of real-world exposures. Nevertheless, environmental epidemiology is an observational (vs experimental) science that depends on design and implementation characteristics that are subject to numerous inherent and methodological limitations. Nevertheless, evidence from epidemiological studies of reasonable quality may provide the best available indication of whether certain exposures—such as industrial wind turbine noise—may be harming human health. Critical review and synthesis of the epidemiological evidence, combined with consideration of evidence from other lines of inquiry (ie, animal studies and exposure assessments), provide a scientific basis for identifying causal relationships, managing risks, and protecting public health.

Methods

Studies of greatest value for validly identifying risk factors for disease include well-designed and conducted cohort studies and case-control studies—provided that specific diseases could be identified—followed by cross-sectional studies (or surveys). Case reports and case series do not constitute epidemiological studies and were not considered because they lack an appropriate comparison group, which can obscure a relationship or even suggest one where none exists.^{39,40,42} Such studies may be useful in generating hypotheses that might be tested using epidemiological methods but are not considered capable of demonstrating causality, a position also taken by international agencies such as the WHO.⁸

Epidemiological studies selected for this review were identified through searches of PubMed and Google Scholar using the following key words individually and in various combinations: “wind,” “wind turbine,” “wind farm,” “windmill,” “noise,” “sleep,” “cardiovascular,” “health,” “symptom,” “condition,” “disease,” “cohort,” “case-control,” “cross-sectional,” and “epidemiology.” In addition, general Web searches were performed, and references cited in all identified publications were reviewed. Approximately 65 documents were identified and obtained, and screened to determine whether (1) the paper described a primary epidemiological study (including experimental or laboratory-based study) published in a peer-reviewed health, medical or relevant scientific journal; (2) the study focused on or at least included wind turbine noise as a risk factor; (3) the study measured at least one outcome of potential relevance to health; and (4) the study attempted to relate the wind turbine noise with the outcome.

Results

Of the approximately 80 articles initially identified in the search, only 20 met the screening criteria (14 observational and six controlled human exposure studies), and these were reviewed in detail to determine the relative quality and validity of reported findings. Other documents included several reviews and commentaries^{4,5,7,43–51}; case reports, case studies, and surveys^{23,52–54}; and documents published in media other than peer-reviewed journals. One study published as part of a conference

proceedings did not meet the peer-reviewed journal eligibility criterion but was included because it seemed to be the first epidemiological study on this topic and an impetus for subsequent studies.⁵⁵

The 14 observational epidemiological studies were critically reviewed to assess their relative strengths and weaknesses on the basis of the study design and the general ability to avoid selection bias (eg, the selective volunteering of individuals with health complaints), information bias (eg, under- or overreporting of health complaints, possibly because of reliance on self-reporting), and confounding bias (the mixing of possible effects of other strong risk factors for the same disease because of correlation with the exposure).

Figure 6 depicts the 14 observational epidemiological studies published in peer-reviewed health or medical journals, all of which were determined to be cross-sectional studies or surveys. As can be seen from the figure, the 14 publications were based on analyses of data from only eight different study populations, that is, six publications were based on analyses of a previously published study (eg, Pedersen et al⁵⁶ and Bakker et al⁵⁷ were based on the data from Pedersen et al⁵⁸) or on combined data from previously published studies (eg, Pedersen and Larsman⁵⁹ and Pedersen and Wayne⁶⁰ were based on the combined data from Pedersen and Wayne^{61,62}; and Pedersen⁶³ and Janssen et al⁶⁴ were based on the combined data from Pedersen et al,⁵⁸ Pedersen and Wayne,⁶¹ and Pedersen and Wayne⁶²). Therefore, in the short summaries of individual studies below, publications based on the same study population(s) are grouped.

Summary of Observational Epidemiological Studies

Possibly the first epidemiological study evaluating wind turbine sound and noise annoyance was published in the proceedings of the 1993 European Community Wind Energy Conference.⁵⁵ Investigators surveyed 574 individuals (159 from the Netherlands, 216 from Germany, and 199 from Denmark). Up to 70% of the people

resided near wind turbines for at least 5 years. No response rates were reported, so the potential for selection or participation bias cannot be evaluated. Wind turbine sound levels were calculated in 5 dBA intervals for each respondent, on the basis of site measurements and residential distance from turbines. The authors claimed that noise-related annoyance was weakly correlated with objective sound levels but more strongly correlated with indicators of respondents' attitudes and personality.⁵⁵

In a cross-sectional study of 351 participants residing in proximity to wind turbines (power range 150 to 650 kW), Pedersen (a coauthor of the Wolsink⁵⁵ study) and Persson and Wayne⁶¹ described a statistically significant association between modeled wind turbine audible noise estimates and self-reported annoyance. In this section, "statistically significant" means that the likelihood that the results were because of chance is less than 5%. No respondents among the 12 exposed to wind turbine noise less than 30 dBA reported annoyance with the sound; however, the percentage reporting annoyance increased with noise exceeding 30 dBA. No differences in health or well-being outcomes (eg, tinnitus, cardiovascular disease, headaches, and irritability) were observed. With noise exposures greater than 35 dBA, 16% of respondents reported sleep disturbance, whereas no sleep disturbance was reported among those exposed to less than 35 dBA. Although the authors observed that the risk of annoyance from wind turbine noise exposure increased statistically significantly with each increase of 2.5 dBA, they also reported a statistically significant risk of reporting noise annoyance among those self-reporting a negative attitude toward the visual effect of the wind turbines on the landscape scenery (measured on a five-point scale ranging from "very positive" to "very negative" opinion). These results suggest that attitude toward visual effect is an important contributor to annoyance associated with wind turbine noise. In addition to its reliance on self-reported outcomes, this study is limited by selection or participation bias, suggested by the difference in response rate between the highest-exposed individuals (78%) versus lowest-exposed individuals (60%).

Pedersen⁶² examined the association between modeled wind turbine sound pressures and self-reported annoyance, health, and well-being among 754 respondents in seven areas in Sweden with wind turbines and varying landscapes. A total of 1309 surveys were distributed, resulting in a response rate of 57.6%. Annoyance was significantly associated with SPLs from wind turbines as well as having a negative attitude toward wind turbines, living in a rural area, wind turbine visibility, and living in an area with rocky or hilly terrain. Those annoyed by wind turbine noise reported a higher prevalence of lowered sleep quality and negative emotions than those not annoyed by noise. Because of the cross-sectional design, it cannot be determined whether wind turbine noise caused these complaints or if those who experienced disrupted sleep and negative emotions were more likely to notice and report annoyance from noise. Measured SPLs were not associated with any health effects studied. In the same year, Petersen et al reported on what they called a "grounded theory study" in which 15 informants were interviewed in depth regarding the reasons they were annoyed with wind turbines and associated noise. Responses indicated that these individuals perceived the turbines to be an intrusion and associated with feelings of lack of control and influence.⁶⁵ Although not an epidemiological study, this exercise was intended to elucidate the reasons underlying the reported annoyance with wind turbines.

Further analyses of the combined data from Pedersen and Wayne^{61,62} (described above) were published in two additional papers.^{59,60} The pooled data included 1095 participants exposed to wind turbine noise of at least 30 dBA. As seen in the two original studies, a significant association between noise annoyance and SPL was observed. A total of 84 participants (7.7%) reported being fairly or very annoyed by wind turbine noise. Respondents reporting wind turbines as having a negative effect on the scenery were also

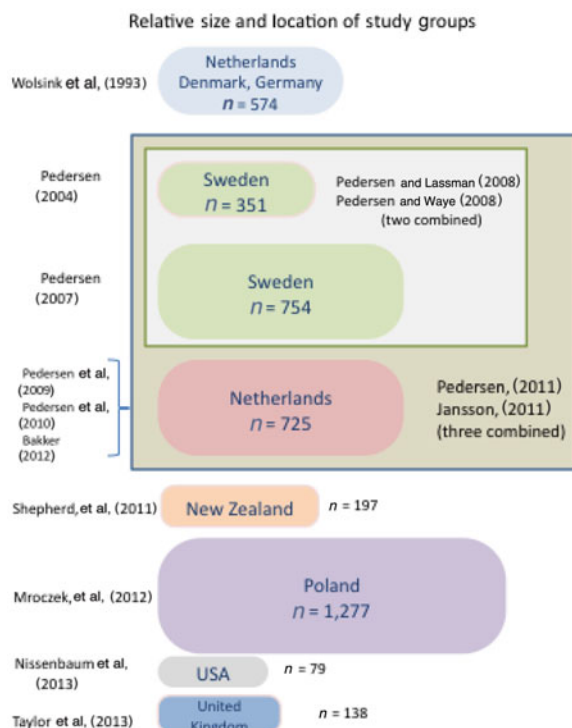


FIGURE 6. The 14 observational epidemiological studies published in peer-reviewed health or medical journals, all of which were determined to be cross-sectional studies or surveys.

statistically significantly more likely to report annoyance to wind turbine noise, regardless of SPLs.⁵⁹ Self-reported stress was higher among those who were fairly or very annoyed compared with those not annoyed; however, these associations could not be attributed specifically to wind turbine noise. No differences in self-reported health effects such as hearing impairment, diabetes, or cardiovascular diseases were reported between the 84 (7.7%) respondents who were fairly or very annoyed by wind turbine noise compared with all other respondents.⁶⁰ The authors did not report the power of the study.

Pederson et al^{56–58} evaluated the data from 725 residents in the Netherlands living within 2.5 km of a site containing at least two wind turbines of 500 kW or greater. Using geographic information systems methods, 3727 addresses were identified in the study target area, for which names and telephone numbers were found for 2056; after excluding businesses, 1948 were determined to be residences and contacted. Completed surveys were received from 725 for a response rate of 37%. Although the response rate was lower than in previous cross-sectional studies, nonresponse analyses indicated that similar proportions responded across all landscape types and sound pressure categories.⁵⁷ Calculated sound levels, other sources of community noise, noise sensitivity, general attitude, and visual attitude toward wind turbines were evaluated. The authors reported an exposure–response relationship between calculated A-weighted SPLs and self-reported annoyance. Wind turbine noise was reported to be more annoying than transportation noise or industrial noise at comparable levels. Annoyance, however, was also correlated with a negative attitude toward the visual effect of wind turbines on the landscape. In addition, a statistically significantly decreased level of annoyance from wind turbine noise was observed among those who benefited economically from wind turbines, despite equal perception of noise and exposure to generally higher (greater than 40 dBA) sound levels.⁵⁸ Annoyance was strongly correlated with self-reporting a negative attitude toward the visual effect of wind turbines on the landscape scenery (measured on a five-point scale ranging from “very positive” to “very negative” opinion). The low response rate and reliance on self-reporting of noise annoyance limit the interpretation of these findings.

Results of further analyses of noise annoyance were reported in a separate report,⁵⁶ which indicated that road traffic noise had no effect on annoyance to wind turbine noise and vice versa. Visibility of, and attitude toward, wind turbines and road traffic were significantly related to annoyance from their respective noise source; stress was significantly associated with both types of noise.^{56,157}

Additional analyses of the same data were performed using a structural equation approach that indicated that, as with annoyance, sleep disturbance increased with increasing SPL because of wind turbines; however, this increase was statistically significant only at pressures of 45 dBA and higher. Results of analyses of the combined data from the two Swedish^{61,62} and the Dutch⁵⁸ cross-sectional studies have been published in two additional papers. Using the combined data from these three predecessor studies, Pedersen et al^{56,58} identified 1755 (ie, 95.9%) of the 1830 total participants for which complete data were available to explore the relationships between calculated A-weighted SPLs and a range of indicators of health and well-being. Specifically, they considered sleep interruption; headache; undue tiredness; feeling tense, stressed, or irritable; diabetes; high blood pressure; cardiovascular disease; and tinnitus.⁶³ As in the precursor studies, noise annoyance indoors and outdoors was correlated with A-weighted SPLs. Sleep interruption seemed at higher sound levels and was also related to annoyance. No other health or well-being variables were consistently related to SPLs. Stress was not directly associated with SPLs but was associated with noise-related annoyance.

Another report based on these data (in these analyses, 1820 of the 1830 total participants) modeled the relationship between wind turbine noise exposure and annoyance indoors and outdoors.⁶⁴

The authors excluded respondents who benefited economically from wind turbines, then compared their modeled results with other modeled relationships for industrial and transportation noise; they claimed that annoyance from wind turbine noise at or higher than 45 dBA is associated with more annoyance than other noise sources.

Shepherd et al,⁶⁶ who had conducted an earlier evaluation of noise sensitivity and Health Related Quality of Life (HRQL),¹⁵⁸ compared survey results from 39 residents located within 2 km of a wind turbine in the South Makara Valley in New Zealand with 139 geographically and socioeconomically matched individuals who resided at least 8 km from any wind farm. The response rates for both the proximal and more distant study groups were poor, that is, 34% and 32%, respectively, although efforts were made to blind respondents to the study hypotheses. No indicator of exposure to wind turbine noise was considered beyond the selection of individuals based on the proximity of their residences from the nearest wind turbine. Health-related quality-of-life (HRQOL) scales were used to describe and compare the general well-being and well-being in the physical, psychological, and social domains of each group. The authors reported statistically significant differences between the groups in some HRQOL domain scores, with residents living within 2 km of a turbine installation reporting lower mean physical HRQOL domain score (including lower component scores for sleep quality and self-reported energy levels) and lower mean environmental quality-of-life (QOL) scores (including lower component scores for considering one's environment to be less healthy and being less satisfied with the conditions of their living space). No differences were reported for social or psychological HRQOL domain scores. The group residing closer to a wind turbine also reported lower amenity but not related to traffic or neighborhood noise annoyance. Lack of actual wind turbine and other noise source measurements, combined with the poor response rate (both noted by the authors as limitations), limits the inferential value of these results because they may pertain to wind turbine emissions.⁶⁶

Possibly the largest cross-sectional epidemiological study of wind turbine noise on QOL was conducted in an area of northern Poland with the most wind turbines.⁶⁷ Surveys were completed by a total of 1277 adults (703 women and 574 men), aged 18 to 94 years, representing a 10% two-stage random sample of the selected communities. Although the response rate was not reported, participants were sequentially enrolled until a 10% sample was achieved, and the proportion of individuals invited to participate but unable or refusing to participate was estimated at 30% (B. Mroczek, dr hab n. zdr., e-mail communication, January 2, 2014). Proximity of residence was the exposure variable, with 220 (17.2%) respondents within 700 m; 279 (21.9%) between 700 and 1000 m; 221 (17.3%) between 1000 and 1500 m; and 424 (33.2%) residing more than 1500 m from the nearest wind turbine. Indicators of QOL and health were measured using the Short Form–36 Questionnaire (SF-36). The SF-36 consists of 36 questions specifically addressing physical functioning, role-functioning physical, bodily pain, general health, vitality, social functioning, role-functioning emotional, and mental health. An additional question concerning health change was included, as well as the Visual Analogue Scale for health assessment. It is unclear whether age, sex, education, and occupation were controlled for in the statistical analyses. The authors report that, within all subscales, those living closest to wind farms reported the best QOL, and those living farther than 1500 m scored the worst. They concluded that living in close proximity of wind farms does not result in the worsening of, and might improve, the QOL in this region.⁶⁷

A small survey of residents of two communities in Maine with multiple industrial wind turbines compared sleep and general health outcomes among 38 participants residing 375 to 1400 m from the nearest turbine with another group of 41 individuals residing 3.3 to 6.6 km from the nearest wind turbine.⁶⁸ Participants completed questionnaires and in-person interviews on a range of

health and attitudinal topics. Prevalence of self-reported health and other complaints was compared by distance from the wind turbines, statistically controlling for age, sex, site, and household cluster in some analyses. Participants living within 1.4 km of a wind turbine reported worse sleep, were sleepier during the day, and had worse SF-36 Mental Component Scores compared with those living farther than 3.3 km away. Statistically significant correlations were reported between Pittsburgh Sleep Quality Index, Epworth Sleepiness Scale, SF-36 Mental Component Score, and log-distance to the nearest wind turbine. The authors attributed the observed differences to the wind turbines⁶⁸; methodological problems such as selection and reporting biases were overlooked. This study has a number of methodological limitations, most notably that all of the “near” turbine groups were plaintiffs in a lawsuit against the wind turbine operators and had already been interviewed by the lead investigator prior to the study. None of the “far” group had been interviewed; they were “cold called” by an assistant. This differential treatment of the two groups introduces a bias in the integrity of the methods and corresponding results. Details of the far group, as well as participation rates, were not noted.⁶⁸

In another study, the role of negative personality traits (defined by the authors using separate scales for assessing neuroticism, negative affectivity, and frustration intolerance) on possible associations between actual and perceived wind turbine noise and medically unexplained nonspecific symptoms was investigated via a mailed survey.⁶⁹ Of the 1270 identified households within 500 m of eight 0.6 kW micro-turbine farms and within 1 km of four 5 kW small wind turbine farms in two cities in the United Kingdom, only 138 questionnaires were returned, for a response rate of 10%. No association was noted between calculated and actual noise levels and nonspecific symptoms. A correlation between perceived noise and nonspecific symptoms was seen among respondents with negative personality traits. Despite the participant group’s reported representativeness of the target population, the low survey response rate precludes firm conclusions on the basis of these data.⁶⁹

In a study of residents living near a “wind park” in Western New York State, surveys were administered to 62 individuals living in 52 homes.⁷⁰ The wind park included 84 turbines. No association was noted between self-reported annoyance and short duration sound measurements. A correlation was noted between the measure of a person’s concern regarding health risks and reported measures of the prevalence of sleep disturbance and stress. While a cross-sectional study is based on self-reported annoyance and health indicators, and therefore limited in its interpretation, one of its strengths is that it is one of the few studies that performed actual sound measurements (indoors and outdoors).

A small but detailed study on response to the wind turbine noise was carried out in Poland.⁷¹ The study population consisted of 156 people, age 15–82 years, living in the vicinity of 3 wind farms located in the central and northwestern parts of Poland. No exclusion criteria were applied, and each individual agreeing to participate was sent a questionnaire patterned after the one used in the Pederson 2004 and Pederson 2007 studies and including questions on living conditions, self-reported annoyance due to noise from wind turbines, and self-assessment of physical health and well-being (such as headaches, dizziness, fatigue, insomnia, and tinnitus). The response rate was 71%. Distance from the nearest wind turbine and modeled A-weighted SPLs were considered as exposure indicators. One third (33.3%) of the respondents found wind turbine noise annoying outdoors, and one fifth (20.5%) found the noise annoying while indoors. Wind turbine noise was reported as being more annoying than other environmental noises, and self-reported annoyance increased with increasing A-weighted SPLs. Factors such as attitude toward wind turbines and “landscape littering” (visual impact) influenced the perceived annoyance from the wind turbine noise. This study, as with most others, is limited by the cross-sectional design

and reliance on self-reported health and well-being indicators; however, analyses focused on predictors of self-reported annoyance, and found that wind turbine noise, attitude toward wind turbines, and attitude toward “landscape littering” explain most of the reported annoyance.

Other Possibly Relevant Studies

A publication based on the self-reporting of 109 individuals who “perceived adverse health effects occurring with the onset of an industrial wind turbine facility” indicated that 102 reported either “altered health or altered quality of life.” The authors appropriately noted that this was a survey of self-selected participants who chose to respond to a questionnaire specifically designed to attract those who had health complaints they attributed to wind turbines, with no comparison group. Nevertheless, the authors inappropriately draw the conclusion that “Results of this study suggest an underlying relationship between wind turbines and adverse health effects and support the need for additional studies.”^{48(p.336)} Such a report cannot provide valid evidence of any relationship for which there is no comparison and is of little if any inferential value.

Researchers at the School of Public Health, University of Sydney, in Australia conducted a study to explore psychogenic explanations for the increase around 2009 of wind farm noise and/or health complaints and the disproportionate corresponding geographic distribution of those complaints.⁵² They obtained records of complaints about noise or health from residents living near all 51 wind farms (1634 turbines) operating between 1993 and 2012 from wind farm companies and corroborated with documents such as government public enquiries, news media records, and court affidavits. Of the 51 wind farms, 33 (64.7%) had no record of noise or health complaints, including all wind farms in Western Australia and Tasmania. The researchers identified 129 individuals who had filed complaints, 94 (73%) of whom lived near six wind farms targeted by anti-wind advocacy groups. They observed that 90% of complaints were registered after anti-wind farm groups included health concerns as part of their advocacy in 2009. The authors concluded that their findings were consistent with their psychogenic hypotheses.

Discussion

No cohort or case-control studies were located in this updated review of the peer-reviewed literature. The lack of published case-control studies is less surprising and less critical because there has been no discrete disease or constellation of diseases identified that likely or might be explained by wind turbine noise. Anecdotal reports of symptoms associated with wind turbines include a broad array of nonspecific symptoms, such as headache, stress, and sleep disturbance, that afflict large proportions of the general population and have many recognized risk factors. Retrospectively associating such symptoms with wind turbines or even measured wind turbine noise—as would be necessary in case-control studies—does not prevent recall bias from influencing the results.

Although cross-sectional studies and surveys have the advantage of being relatively simple and inexpensive to conduct, they are susceptible to a number of influential biases. Most importantly, however, is the fact that, because of the simultaneous ascertainment of both exposure (eg, wind turbine noise) and health outcomes or complaints, the temporal sequence of exposure-outcome relationship cannot be demonstrated. If the exposure cannot be established to precede the incidence of the outcome—and not the reverse, that is, the health complaint leads to increased perception of or annoyance with the exposure, as with insomnia headaches or feeling tense/stressed/irritable—the association cannot be evaluated for a possible causal nature.

Conclusions

A critical review and synthesis of the evidence available from the eight study populations studied to date (and reported in 14 publications) provides some insights into the hypothesis that wind turbine noise harms human health in those living in proximity to wind turbines. These include the following:

- No clear or consistent association is seen between noise from wind turbines and any reported disease or other indicator of harm to human health.
- In most surveyed populations, some individuals (generally a small proportion) report some degree of annoyance with wind turbines; however, further evaluation has demonstrated:
 - Certain characteristics of wind turbine sound such as its intermittence or rhythmicity may enhance reported perceptibility and annoyance;
 - The context in which wind turbine noise is emitted also influences perceptibility and annoyance, including urban versus rural setting, topography, and landscape features, as well as visibility of the wind turbines;
 - Factors such as attitude toward visual effect of wind turbines on the scenery, attitude toward wind turbines in general, personality characteristics, whether individuals benefit financially from the presence of wind turbines, and duration of time wind turbines have been in operation all have been correlated with self-reported annoyance; and
 - Annoyance does not correlate well or at all with objective sound measurements or calculated sound pressures.
- Complaints such as sleep disturbance have been associated with A-weighted wind turbine sound pressures of higher than 40 to 45 dB but not any other measure of health or well-being. Stress was associated with annoyance but not with calculated sound pressures.⁶³
- Studies of QOL including physical and mental health scales and residential proximity to wind turbines report conflicting findings—one study (with only 38 participants living within 2.0 km of the nearest wind turbine) reported lower HRQOL among those living closer to wind turbines than respondents living farther away,⁶⁶ whereas the largest of all studies (with 853 living within 1500 m of the nearest wind turbine)⁶⁷ found that those living closer to wind turbines reported higher QOL and health than those living farther away.⁶⁷

Because these statistical correlations arise from cross-sectional studies and surveys in which the temporal sequence of the exposure and outcome cannot be evaluated, and where the effect of various forms of bias (especially selection/volunteer bias and recall bias) may be considerable, the extent to which they reflect causal relationships cannot be determined. For example, the claims such as “We conclude that the noise emissions of wind turbines disturbed the sleep and caused daytime sleepiness and impaired mental health in residents living within 1.4 km of the two wind turbines installations studied” cannot be substantiated on the basis of the actual study design used and some of the likely biases present.⁷⁰

Notwithstanding the limitations inherent to cross-sectional studies and surveys—which alone may provide adequate explanation for some of the reported correlations—several possible explanations have been suggested for the wind turbines–associated annoyance reported in many of these studies, including attitudinal and even personality characteristics of the survey participants.⁶⁹ Pedersen and colleague,⁵⁹ who have been involved in the majority of publications on this topic, noted “The enhanced negative response [toward wind turbines] could be linked to aesthetical response, rather than to multi-modal effects of simultaneous auditory and visual stimulation, and a risk of hindrance to psycho-physiological restoration could not be excluded.”^(p.389) They also found that wind turbines might

be more likely to elicit annoyance because some perceive them to be “intrusive” visually and with respect to their noise.⁶⁵ Alternative explanations on the basis of evaluation of all health complaints filed between 1993 and 2012 with wind turbine operators across Australia include the influence of anti-wind power activism and the surrounding publicity on the likelihood of health complaints, calling the complaints “communicated diseases.”⁵²

As noted earlier, the 14 papers meeting the selection criteria for critical review and synthesis were based on only eight independent study groups—three publications were based on the same study group from the Netherlands⁵⁸ and four additional publications were based on the combined data from the two Swedish surveys^{61,62} or from the combined data from all three. The findings across studies based on analyses of the same data are not independent observations, and therefore the body of available evidence may seem to be larger and more consistent than it should. This observation does not necessarily mean that the relationships observed (or the lack of associations between calculated wind turbines sound pressures and disease or other indicators of health) are invalid, but that consistency across reports based on the same data should not be overinterpreted as independent confirmation of findings. Perhaps more important is that all eight were cross-sectional studies or surveys, and therefore inherently limited in their ability to demonstrate the presence or absence of true health effects.

Recent controlled exposure laboratory evaluations lend support to the notion that reports of annoyance and other complaints may reflect, at least in part, preconceptions about the ability of wind turbine noise to harm health^{52,71,72} or even the color of the turbine⁷³ more than the actual noise emission.

Sixty years ago, Sir Austin Bradford Hill delivered a lecture entitled “Observations and Experiment” to the Royal College of Occupational Medicine. In his lecture, Hill stated that “The observer may well have to be more patient than the experimenter—awaiting the occurrence of the natural succession of events he desires to study; he may well have to be more imaginative—sensing the correlations that lie below the surface of his observations; and he may well have to be more logical and less dogmatic—avoiding as the evil eye the fallacy of ‘*post hoc ergo propter hoc*,’ the mistaking of correlation for causation.”^{74(p.1000)}

Although it is typical and appropriate to point out the obvious need for additional research, it may be worth emphasizing that more research of a similar nature—that is, using cross-sectional or survey approaches—is unlikely to be informative, most notably for public policy decisions. Large, well-conducted prospective cohort studies that document baseline health status and can objectively measure the incidence of new disease or health conditions over time with the introduction would be the most informative. On the contrary, the phenomena that constitute wind turbine exposures—primarily noise and visual effect—are not dissimilar to many other environmental (eg, noise of waves along shorelines) and anthropogenic (eg, noise from indoor Heating Ventilation and Air Conditioning or road traffic) stimuli, for which research and practical experience indicate no direct harm to human health.

Sound Components and Health: Infrasound, Low-Frequency Sound, and Potential Health Effects

Introduction

This section addresses potential health implications of infrasound and low-frequency sound because claims have been made that the frequency of wind turbine sound has special characteristics that may present unique health risks in comparison with other sources of environmental sound.

Wind turbines produce two kinds of sound. Gears and generators can make mechanical noise, but this is less prominent than the

TABLE 1. Human Thresholds for Different Frequencies

Frequency (Hz)	Threshold (dB SPL)
100	27
25	69
10	97

SPL, sound pressure level.

aerodynamic noise of the blades, whose tips may have velocities in excess of 200 mph. Three-bladed turbines often rotate about once every 3 seconds; their “blade-pass” frequency is thus about 1 Hz (Hz: cycle per second). For this reason, the aerodynamic noise often rises and falls about once per second, and some have described the sounds as “whooshing” or “pulsing.”

Several studies^{44,75,76} have shown that at distances of 300 m or more, wind turbine sounds are below human detection thresholds for frequencies less than 50 Hz. The most audible frequencies (those whose acoustic energies exceed human thresholds the most) are in 500 to 2000 Hz range. At this distance from a single wind turbine, overall levels are typically 35 to 45 dBA.^{77,78} These levels can be audible in a typical residence with ambient noise of 30 dBA and windows open (a room with an ambient level of 30 dBA would be considered by most people to be quiet or very quiet). In outdoor environments, sound levels drop about 6 dB for every doubling of the distance from the source, so one would predict levels of 23 to 33 dBA, that is, below typical ambient noise levels in homes, at a distance of 1200 m. For a wind farm of 12 large turbines, Møller and Pedersen⁷⁹ predicted a level of 35 dBA at a distance of 453 m.

As noted earlier in this report, sound intensity is usually measured in decibels (dB), with 0 dB SPL corresponding to the softest sounds young humans can hear. Nevertheless, humans hear well only within the frequency range that includes the frequencies most important for speech understanding—about 500 to 5000 Hz. At lower frequencies, hearing thresholds are much higher.⁷⁵ Although frequencies lower than 20 Hz are conventionally referred to as “infrasound,” sounds in this range can in fact be heard, but only when they are extremely intense (a sound of 97 dB SPL has 10 million times as much energy as a sound of 27 dB; see Table 1).

Complex sounds like those produced by wind turbines contain energy at multiple frequencies. The most complete descriptions of such sounds include dB levels for each of several frequency bands (eg, 22 to 45 Hz, 45 to 90 Hz, 90 to 180 Hz, . . . , 11,200 to 22,400 Hz). It is simpler, and appropriate in most circumstances, to specify overall sound intensity using meters that give full weight to the frequencies people hear well, and less weight to frequencies less than 500 Hz and higher than 5000 Hz. The resulting metric is “A-weighted” decibels or dBA. Levels in dBA correlate well with audibility; in a very quiet place, healthy young people can usually detect sounds less than 20 dBA.

Low-Frequency Sound and Infrasound

Low-frequency noise (LFN) is generally considered frequencies from 20 to 250 Hz, as described earlier in more detail in subsection “Low Frequency and Infrasonic Levels.” The potential health implications of low-frequency sound from wind turbines have been investigated in a study of four large turbines and 44 smaller turbines in the Netherlands.¹⁷ In close proximity to the turbines, infrasound levels were below audibility. The authors suggested that LFN could be an important aspect of wind turbine noise; however, they did not link measured or modeled noise levels with any health outcome measure, such as annoyance.

A literature review of infrasound and low-frequency sound concluded that low-frequency sound from wind turbines at residences did not exceed levels from other common noise sources, such as traffic.⁴⁴ The authors concluded that a “statistically significant association between noise levels and self-reported sleep disturbance was found in two of the three [epidemiology] studies.”^(p.1) It has been suggested that LFN from wind turbines causes other and more serious health problems, but empirical support for these claims is lacking.⁴⁴

Sounds with frequencies lower than 20 Hz (ie, infrasound) may be audible at very high levels. At even higher levels, subjects may experience symptoms from very low-frequency sounds—ear pressure (at levels as low as 127 dB SPL), ear pain (at levels higher than 145 dB), chest and abdominal movement, a choking sensation, coughing, and nausea (at levels higher than 150 dB).^{80,81} The National Aeronautics and Space Administration considered that infrasound exposures lower than 140 dB SPL would be safe for astronauts; American Conference of Governmental Industrial Hygienists recommends a threshold limit value of 145 dB SPL for third-octave band levels between 1 and 80 Hz.⁸¹ As noted earlier, infrasound from wind turbines has been measured at residential distances and noted to be many orders of magnitude below these levels.

Whenever wind turbine sounds are audible, some people may find the sounds annoying, as discussed elsewhere in this review. Some authors, however, have hypothesized that even inaudible sounds, especially at very low frequencies, could affect people by activating several types of receptors, including the following:

1. Outer hair cells of the cochlea⁸²;
2. Hair cells of the normal vestibular system,⁸³ especially the otolith organs⁸⁴;
3. Hair cells of the vestibular system after its fluid dynamics have been disrupted by infrasound⁸²;
4. Visceral graviceptors acting as vibration sensors.⁸³

To evaluate these hypotheses, it is useful to review selected aspects of the anatomy and physiology of the inner ear (focusing on the differences between the cochlea and the vestibular organs), vibrotactile sensitivity to airborne sound, and the types of evidence that, while absent at present, could in theory support one or more of these hypotheses.

How the Inner Ear Works

The inner ear contains the cochlea (the organ of hearing) and five vestibular organs (three semicircular canals and two otolith organs, transmitting information about head position and movement). The cochlea and the vestibular organs have one important feature in common—they both use hair cells to convert sound or head movement into nerve impulses that can then be transmitted to the brain. Hair cells are mechanoreceptors that can elicit nerve impulses only when their stereocilia (or sensory hairs) are bent.

The anatomy of the cochlea ensures that its hair cells respond well to airborne sound and poorly to head movement, whereas the anatomy of the vestibular organs optimizes hair cell response to head movement and minimizes response to airborne sound. Specifically, the cochlear hair cells are not attached to the bony otic capsule, and the round window permits the cochlear fluids to move more freely when air-conducted sound causes the stapes to move back and forth in the oval window. Conversely, the vestibular hair cells are attached to the bony otic capsule, and the fluids surrounding them are not positioned between the two windows and thus cannot move as freely in response to air-conducted sound. At the most basic level, this makes it unlikely that inaudible sound from wind turbines can affect the vestibular system.

Responding to Airborne Sound

Airborne sound moves the eardrum and ossicles back and forth; the ossicular movement at the oval window then displaces inner ear fluid, causing a movement of membranes in the cochlea, with bending of the hair cell stereocilia. Nevertheless, this displacement of the cochlear hair cells depends on the fact that there are two windows separating the inner ear from the middle ear, with the cochlear hair cells positioned between them—whenever the oval window (the bony footplate of the stapes, constrained by a thin annular ligament) is pushed inward, the round window (a collagenous membrane lined by mucous membrane) moves outward, and vice versa. When the round window is experimentally sealed,⁸⁵ the cochlea's sensitivity to sound is reduced by 35 dB.

The vestibular hair cells are not positioned between the two cochlear windows, and therefore airborne sound-induced inner ear fluid movement does not efficiently reach them. Instead, the vestibular hair cells are attached to the bone of the skull so that they can respond faithfully to head movement (the cochlear hair cells are not directly attached to the skull). As one might expect, vestibular hair cells can respond to head vibration (bone-conducted sound), such as when a tuning fork is held to the mastoid. Very intense airborne sound can also make the head vibrate; people with severe conductive hearing loss can hear airborne sound in this way, but only when the sounds are made 50 to 60 dB more intense than those audible to normal people.

The cochlea contains two types of hair cells. It is often said that we hear with our inner hair cells (IHCs) because all the “type I” afferent neurons that carry sound-evoked impulses to the brain connect to the IHCs. The outer hair cells (OHCs) are important as “preamplifiers” that make it possible to hear very soft sounds; they are exquisitely tuned to specific frequencies, and when they move they create fluid currents that then displace the stereocilia of the IHCs.

Although more numerous than the IHCs, the OHCs receive only very scanty afferent innervation, from “type II” neurons, the function of which is unknown. Salt and Hullar⁸² have pointed out that OHCs generate measurable electrical responses called cochlear microphonics to very low frequencies (eg, 5 Hz) at levels that are presumably inaudible to the animals and have hypothesized that the type II afferent fibers from the OHCs might carry this information to the brain. Nevertheless, it seems that no one has ever recorded action potentials from type II cochlear neurons, nor have physiological responses other than cochlear microphonics been recorded in response to inaudible sounds.^{86,87} In other words, as Salt and Hullar⁸² acknowledge, “The fact that some inner ear components (such as the OHC) may respond to [airborne] 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.”^(p.19)

Responses of the Vestibular Organs

As previously noted, vestibular hair cells are efficiently coupled to the skull. The three semicircular canals in each ear are designed to respond to head rotations (roll, pitch, yaw, or any combination). When the head rotates, as in shaking the head to say “no,” the fluid in the canals lags behind the skull and bends the hair cells. The otolith organs (utricle and saccule) contain calcium carbonate crystals (otoconia) that are denser than the inner ear fluid, and this allows even static head position to be detected; when the head is tilted, gravitational pull on the otoconia bends the hair cells. The otolith organs also respond to linear acceleration of the head, as when a car accelerates.

Many people complaining about wind turbines have reported dizziness, which can be a symptom of vestibular disorders; this has led to suggestions that wind turbine sound, especially inaudible infrasound, can stimulate the vestibular organs.^{83,84} Pierpont⁸³ introduced a term “Wind Turbine Syndrome” based on a case series of 10

families who reported symptoms that they attributed to living near wind turbines. The author invited people to participate if they thought they had symptoms from living in the vicinity of wind turbines; this approach introduces substantial selection bias that can distort the results and their corresponding significance. Telephone interviews were conducted; no medical examination, diagnostic studies or review, and documentation of medical records were conducted as part of the case series. Noise measurements were not provided. Nonetheless, the author described a collection of nonspecific symptoms that were described as “Wind Turbine Syndrome.” The case series, at the time of preparation of this review, has not been published in the peer-reviewed scientific literature. Although not medically recognized, advocates of this “disorder” suggest that wind turbines produce symptoms, such as headaches, memory loss, fatigue, dizziness, tachycardia, irritability, poor concentration, and anxiety.⁸⁸

To support her hypotheses, Pierpont cited a report by Todd et al⁸⁹ that demonstrated human vestibular responses to bone-conducted sound at levels below those that can be heard. But as previously noted, this effect is not surprising because the vestibular system is designed to respond to head movement (including head vibration induced by direct contact with a vibrating source). The relevant issue is how the vestibular system responds to airborne sound, and here the evidence is clear. Vestibular responses to airborne sound require levels well above audible thresholds.^{90,91} Indeed, clinical tests of vestibular function using airborne sound use levels in excess of 120 dB, which raise concerns of acoustic trauma.⁹²

Salt and Hullar⁸² acknowledge that a normal vestibular system is unlikely to respond to inaudible airborne sound—“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.”^(p.12) They go on to hypothesize that infrasound may cause endolymphatic hydrops, a condition in which one of the inner ear fluid compartments is swollen and may disturb normal hair cell function. But here, too, they acknowledge the lack of evidence—“... it has never been tested whether stimuli in the infrasound range cause endolymphatic hydrops.”^(p.19) In previous research, Salt⁹³ was able to create temporary hydrops in animals using airborne sound, but only at levels (115 dB at 200 Hz) that are many orders of magnitude higher than levels that could exist at residential distances from wind turbines.

Human Vibrotactile Sensitivity to Airborne Sound

Very loud sound can cause head and body vibration. As previously noted, a person with absent middle ear function but an intact cochlea may hear sounds at 50 to 60 dB SPL. Completely deaf people can detect airborne sounds using the vibrotactile sense, but only at levels far above hearing threshold, for example, 128 dB SPL at 16 Hz.⁹⁴ Vibrotactile sensation depends on receptors in the skin and joints.

Pierpont⁸³ hypothesized that “visceral graviceptors,”^{95,96} which contain somatosensory receptors, could detect airborne infrasound transmitted from the lungs to the diaphragm and then to the abdominal viscera. These receptors would seem to be well suited to detect body tilt or perhaps whole-body vibration, but there is no evidence that airborne sound could stimulate sensory receptors in the abdomen. Airborne sound is almost entirely reflected away from the body; when Takahashi et al⁹⁷ used airborne sound to produce chest or abdominal vibration that exceeded ambient body levels, levels had to exceed 100 dB at 20 to 50 Hz.

Further Studies of Note

The influence of preconception on mood and physical symptoms after exposure to LFN was examined by showing 54 university

students one of two series of short videos that either promoted or dispelled the notion that sounds from wind turbines had health effects, then exposing subjects to 10 minutes of quiet period followed by infrasound (40 dB at 5 Hz) generated by computer software, and assessing mood and a series of physical symptoms.⁷¹ In a double-blind protocol, participants first exposed to either a “high-expectancy” presentation included first-person accounts of symptoms attributed to wind turbines or a “low-expectancy” presentation showed experts stating scientific positions indicating that infrasound does not cause symptoms. Participants were then exposed to 10 minutes of infrasound and 10 minutes of sham infrasound. Physical symptoms were reported before and during each 10-minute exposure. The study showed that healthy volunteers, when given information designed to invoke either high or low expectations that exposure to infrasound causes symptom complaints, reported symptoms that were consistent with the level of expectation. These data demonstrate that the participants’ expectations of the wind turbine sounds determined their patterns of self-reported symptoms, regardless of whether the exposure was to a true or sham wind turbine sound. The concept known as a “nocebo” response, essentially the opposite of a placebo response, will be discussed in more detail later in this report. A nocebo response refers to how a preconceived negative reaction can occur in anticipation of an event.⁹⁸

A further study assessed whether positive or negative health information about infrasound generated by wind turbines affected participants’ symptoms and health perceptions in response to wind farm sound.⁷² Both physical symptoms and mood were evaluated after exposure to LFN among 60 university students first shown high-expectancy or low-expectancy short videos intended to promote or dispel the notion that wind turbines sounds impacted health. One set of videos presented information indicating that exposure to wind turbine sound, particularly infrasound, poses a health risk, whereas the other set presented information that compared wind turbine sound to subaudible sound created by natural phenomena such as ocean waves and the wind, emphasizing their positive effects on health. Students were continuously exposed during two 7-minute listening sessions to both infrasound (50.4 dB, 9 Hz) and audible wind farm sound (43 dB), which had been recorded 1 km from a wind farm, and assessed for mood and a series of physical symptoms. Both high-expectancy and low-expectancy groups were made aware that they were listening to the sound of a wind farm and were being exposed to sound containing both audible and subaudible components and that the sound was at the same level during both sessions. Participants exposed to wind farm sound experienced a placebo response elicited by positive preexposure expectations, with those participants who were given expectations that infrasound produced health benefits reporting positive health effects. They concluded that reports of symptoms or negative effects could be nullified if expectations could be framed positively.

University students exposed to recorded sounds from locations 100 m from a series of Swedish wind turbines for 10 minutes were assessed for parameters of annoyance.⁹⁹ Sound was played at a level of 40 dBAeq (the “eq” refers to the average level over the 10-minute exposure). After the initial exposure, students were exposed to an additional 3 minutes of noise while filling out questionnaires. Authors reported that ratings of annoyance, relative annoyance, and awareness of noise were different among the different wind turbine recordings played at equivalent noise levels. Various psychoacoustic parameters (sharpness, loudness, roughness, fluctuation strength, and modulation) were assessed and then grouped into profiles. Attributes such as “lapping,” “swishing,” and “whistling” were more easily noticed and potentially annoying, whereas “low frequency” and “grinding” were associated with less intrusive and potentially less annoying sounds.

Adults exposed to sounds recorded from a 1.5 MW Korean wind turbine were assessed for the degree of noise annoyance.¹⁰⁰

Over a 40-minute period, subjects were exposed to a series of 25 random 30-second bursts of wind turbine noise, separated by at least 10 seconds of quiet between bursts. Following a 3-minute quiet period, this pattern was repeated. Participants reported their annoyance on a scale of 1 to 11. Authors found that the amplitude modulation of wind turbine noise had a statistically significant effect on the subjects’ perception of noise annoyance.

The effect of psychological parameters on the perception of noise from wind turbines was also assessed in Italian adults from both urban and rural areas. Recorded sounds from different distances (150 m, 250 m, and 500 m) away from wind turbines were played while pictures of wind turbines were shown and subjects described their reaction to the pictures.⁷³ Pictures differed in color, the number of wind turbines, and distance from wind turbines. Pictures had a weak effect on individual reactions to the number of wind turbines; the color of the wind turbines influenced both visual and auditory individual reactions, although in different ways.

Epilepsy and Wind Turbines

Rapidly changing visual stimuli, such as flashing lights or oscillating pattern changes, can trigger seizures in susceptible persons, including some who never develop spontaneous seizures; stimuli that change at rates of 12 to 30 Hz are most likely to trigger seizures.¹⁰¹ Rotating blades (of a ceiling fan, helicopter, or wind turbine) that interrupt light can produce a flicker, leading to a concern that wind turbines might cause seizures. Nevertheless, large wind turbines (2 MW or more) typically rotate at rates less than 1 Hz; with three blades, the frequency of light interruption would be less than 3 Hz, a rate that would pose negligible risk to developing a photoepileptic seizure.¹⁰²

Smedley et al¹⁰³ applied a complex simulation model of seizure risk to wind turbines, assuming worst-case conditions—a cloudless day, an observer looking directly toward the sun with wind turbine blades directly between the observer and the sun, but with eyes closed (which scatters the light more broadly on the retina); they concluded that there would be a risk of seizures at distances up to nine times the turbine height, but only when blade frequency exceeds 3 Hz, which would be rare for large wind turbines. Smaller turbines, typically providing power for a single structure, often rotate at higher frequencies and might pose more risk of provoking seizures. At the time of preparation of this report, there has been no published report of a photoepileptic seizure being triggered by looking at a rotating wind turbine.

Sleep and Wind Turbines

Sleep disturbance is relatively common in the general population and has numerous causes, including illness, depression, stress, and the use of medications, among others. Noise is well known to be potentially disruptive to sleep. The key issue with respect to wind turbines is whether the noise is sufficiently loud to disrupt sleep. Numerous environmental studies of noise from aviation, rail, and highways have addressed sleep implications, many of which are summarized in the WHO’s position paper on Nighttime Noise Guidelines (Fig. 7).¹⁰⁴ This consensus document is based on an expert analysis of environmental noise from sources other than wind turbines, including transportation, aviation, and railway noise. The WHO published the figure (Fig. 7) to indicate that significant sleep disturbance from environmental noise begins to occur at noise levels greater than 45 dBA. This figure is based on an analysis of pooled data from 24 different environmental noise studies, although no wind turbine–related noise studies were included in the analysis. Nonetheless, the studies provide substantial data on environmental noise exposure that can be contrasted with noise levels associated with wind turbine operations to enable one to draw reasonable inferences.

In contrast to the WHO position, an author in an editorial claimed that routine wind turbine operations that result in noise

levels less than 45 dBA can have substantial effects on sleep, with corresponding adverse health effects.¹⁰⁵ Another author, however, challenged the basis of the assertion by pointing out that Hanning had ignored 17 reviews on the topic with alternative perspectives and different results.¹⁰⁶

Sleep disturbance is a potential extra-auditory effect of noise, and research has shown a link between wind turbine noise and sleep disruption.^{4,57,63,66,107} As with the other variables reviewed, quantifying sleep quality is typically done with coarse measures. In fact, this reviewer identified no studies that used a multi-item validated sleep measure. Research studies typically rely on a single item (sometimes answered yes/no) to measure sleep quality. Such coarse measurement of sleep quality is unfortunate because impaired sleep is a plausible pathway by which wind turbine noise exposure may impact both psychological well-being and physical health.

Disturbed sleep can be associated with adverse health effects.¹⁰⁸ Awakening thresholds, however, depend on both physical and psychological factors. Signification is a psychological factor that refers to the meaning or attitude attached to a sound. Sound with high signification will awaken a sleeper at lower intensity than sound lacking signification.¹⁰⁸ As reviewed above, individuals often attach attitudes to wind turbine sound; as such, wind turbine sleep disruption may be impacted by psychological factors related to the sound source.

Shepherd et al⁶⁶ found a significant difference in perceived sleep quality between their wind farm and comparison groups, with the wind farm group reporting worse sleep quality. In the wind farm group, noise sensitivity was strongly correlated with sleep quality. In both the wind farm and comparison groups, sleep quality showed similar strong positive relationships with physical HRQL and psychological HRQL. Pedersen⁶³ found that sound-level exposure was associated with sleep interruption in two of three studies reviewed; however, the effect sizes associated with sound exposure were minimal.

Bakker et al⁵⁷ found that noise exposure was related to sleep disturbance in quiet areas ($d = 0.40$) but not for individuals in noisy areas ($d = 0.02$). Nevertheless, when extreme sound exposure groups were composed,⁵⁷ data showed that individuals living in high sound areas (greater than 45 dBA) had significantly greater sleep disruption than subjects in low sound areas (less than 30 dBA). Annoyance rat-

ings were more strongly associated with sleep disruption.⁵⁷ Furthermore, when⁵⁷ structural equation models (SEMs) were applied, the direct association between sound level and sleep disruption was lost and annoyance seemed to mediate the effect of wind turbine sound on sleep disturbance. Across the reviewed studies it seems that sleep disruption was associated with sound-level exposure; however, the associations were weak and annoyance ratings were more strongly and consistently associated with self-reported sleep disruption.

Conclusions

Infrasound and low-frequency sound can be generated by the operation of wind turbines; however, neither low-frequency sound nor infrasound in the context of wind turbines or in experimental studies has been associated with adverse health effects.

Annoyance, Wind Turbines, and Potential Health Implications

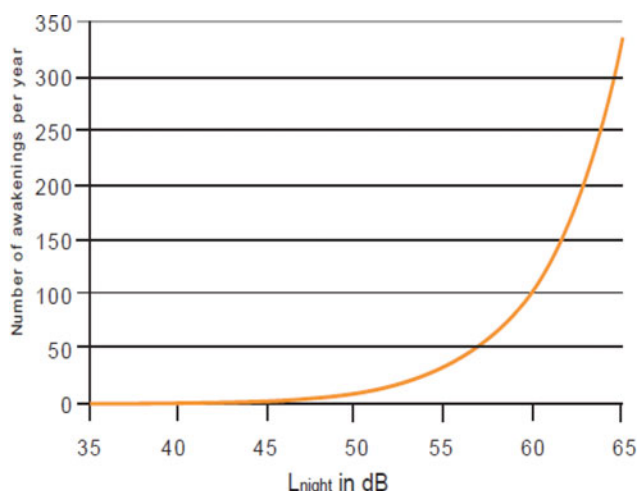
The potential effect of noise on health may occur through both physiological (sleep disturbance) and psychological pathways. Psychological factors related to noise annoyance reported in association with wind turbine noise will be reviewed and analyzed. A critique of the methodological adequacy of the existing wind turbine research as it relates to psychological outcomes will be addressed.

As noted earlier, “annoyance” has been used as an outcome measure in environmental noise studies for many decades. Annoyance is assessed via a questionnaire. Because annoyance has been associated under certain circumstances with living in the vicinity of wind turbines, this section examines the significance of annoyance, risk factors for reporting annoyance in the context of wind turbines, and potential health implications.

For many years, it has been recognized that exposure to high noise levels can adversely affect health^{109,110} and that environmental noise can adversely affect psychological and physical health.¹¹¹ Key to evaluating the health effects of noise exposure—like any hazard—is a thorough consideration of noise intensity and duration. When outcomes are broadened to include more subjective qualities like annoyance and QOL, additional psychological factors must be studied.

Noise-related annoyance is a subjective psychological condition that may result in anger, disappointment, dissatisfaction, withdrawal, helplessness, depression, anxiety, distraction, agitation, or exhaustion.¹¹² Annoyance is primarily identified using standardized self-report questionnaires. Well-established psychiatric conditions like major depressive disorder are also subjective states that are most often identified by self-report questionnaires. Despite its subjective nature, noise annoyance was included as a negative health outcome by the WHO in their recent review of disease burden related to noise exposure.¹¹² The inclusion of annoyance with conditions like cardiovascular disease reinforces its status as a legitimate primary health outcome for environmental noise research.

This section reviews the literature on the effect of wind turbines, including noise-related annoyance and its corresponding effect on health, QOL, and psychological well-being. “Quality of life” is a multidimensional concept that captures subjective aspects of an individual’s experience of functioning, well-being, and satisfaction across the physical, mental, and social domains of life. The WHO defines QOL as “an individual’s perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns. It is a broad ranging concept affected in complex ways by the person’s physical health, psychological status, personal beliefs, social relationships and their relationship to salient features of their environment”.^{113(p1404)} Numerous well-validated QOL measures are available, with the SF-12 and SF-36¹¹⁴ and the WHO Quality of Life—Short Form (WHOQOL-BREF¹¹⁵) being among the most commonly used. Quality of life measures have been widely



Source: Miedema, Passchier-Vermeer and Vos, 2003

FIGURE 7. Worst-case prediction of noise-induced behavioral awakenings. Adapted from WHO¹⁰⁴ (Chapter 3); Miedema et al.¹⁶³

adopted as primary outcomes for clinical trials and cost-effectiveness research.

Meta-analysis is a quantitative method for summarizing the relative strength of an effect or relationship as observed across multiple independent studies.¹¹⁶ The increased application of meta-analysis has had a considerable effect on how literature reviews are approached. Currently, more than 20 behavioral science journals require that authors report measures of effect size along with tests of significance.¹¹⁷ The use of effect size indicators enhances the comparability of findings across studies by changing the reported outcome statistics to a common metric. In behavioral health, the most frequently used effect size indicators are the Cohen d ¹¹⁸ and r the zero-order (univariate) correlation coefficient.¹¹⁷ An additional advantage of reporting outcomes as effect size units is that benchmarks exist for judging the magnitude of these (significant) differences. Studies reviewed below report an array of statistical analyses (the t test, analysis of variances, odds ratios, and point-biserial and biserial correlations), some of which are not suitable for conversion into the Cohen d ; thus, following the recommendations of McGrath and Meyer,¹¹⁷ r will be used as the common effect size measure for evaluating studies. As reference points, r between 0.10 and 0.23 represents small effects, r between 0.24 and 0.36 represents medium effects, and r of 0.37 and greater represent large effects.¹¹⁷ Although these values offer useful guidelines for comparing findings, it is important to realize that, in health-related research, very small effects with $r < 0.10$ can be of great importance.¹¹⁹

Noise Sensitivity

Noise sensitivity is a stable and normally distributed psychological trait,¹²⁰ but predicting who will be annoyed by sound is not a straightforward process.¹²¹ Noise sensitivity has been raised as a major risk factor for reporting annoyance in the context of environmental noise.¹⁵⁶ Noise sensitivity is a psychological trait that affects how a person reacts to sound. Despite lacking a standard definition, people can usually reliably rate themselves as low (noise tolerant), average, or high on noise sensitivity questionnaires; those who rate themselves as high are by definition noise sensitive.

Noise-sensitive individuals react to environmental sound more easily, evaluate it more negatively, and experience stronger emotional reactions than noise tolerant people.^{122–124,146,153–156,159–161} Noise sensitivity is not related to objectively measured auditory thresholds,¹²⁵ intensity discrimination, auditory reaction time, or power-function exponents for loudness.¹²⁰ Noise sensitivity reflects a psychophysiological process with neurocognitive and psychological features. Noise-sensitive individuals have noise “annoyance thresholds” approximately 10 dB lower than noise tolerant individuals.¹²³ Noise sensitivity has been described as increasing a person’s risk for experiencing annoyance when exposed to sound at low and moderate levels.^{4,157}

Noise-Related Annoyance

Noise sensitivity and noise-related annoyance are moderately correlated ($r = 0.32$ ¹²⁰) but not isomorphic. The WHO¹¹² defines noise annoyance as a subjective experience that may include anger, disappointment, dissatisfaction, withdrawal, helplessness, depression, anxiety, distraction, agitation, or exhaustion. A survey of an international group of noise researchers indicated that noise-related annoyance is multifaceted and includes both behavioral and emotional features.¹²⁶ This finding is consistent with Job’s¹²² definition of noise annoyance as a state associated with a range of reactions, including frustration, anger, dysphoria, exhaustion, withdrawal, and helplessness.

Annoyance and Wind Turbine Sounds

As noted elsewhere in this review, Pedersen and colleagues^{58,61,62,65} conducted the world’s largest epidemiological studies of people living in the vicinity of wind turbines. These studies have been discussed in detail in the epidemiological studies section of this review. Other authors have also addressed annoyance in the context of living near wind turbines.^{57,61,125,127,128} Pedersen⁶³ later compared findings from the three cross-sectional epidemiological studies to identify common outcomes. Across all three studies, SPLs were associated with annoyance outside (r between 0.05 and 0.09) and inside of the people’s homes (r between 0.04 and 0.05). These effect sizes were all less than the small effect boundary of 0.10, meaning that sound levels played a minor role in annoyance. The percentages of people reporting annoyance with wind turbine noise ranged from 7% to 14% for indoor exposure and 18% to 33% for outside exposure.^{58,61} These rates are similar to those reported for exposure to other forms of environmental noise.¹²⁹

The dynamic nature of wind turbine sound may make it more annoying than other sources of community noise according to Pedersen et al.⁵⁸ They compared self-reported annoyance from other environmental noise exposure studies (aircraft, railways, road traffic, industry, and shunting yards) with annoyance from wind turbine sound. Proportionally, more subjects were annoyed with wind turbine sound at levels lower than 50 dB than with all other sources of noise exposure, except for shunting yards. Pedersen and Waye^{107,128} reported that the sound characteristics of swishing ($r = 0.70$) and whistling ($r = 0.62$) were highly correlated with annoyance to wind turbine sound. Others have reported similar findings. One author has suggested that wind turbine sound may have acoustic qualities that may make it more annoying at certain noise levels.⁸⁰ Other theories for symptoms described in association with living near wind turbines have also been proposed.¹³⁹

Annoyance associated with wind turbine sounds tends to show a linear association. Sound levels, however, explain only between 9% ($r = 0.31$) and 13% ($r = 0.36$) of the variance in annoyance ratings.^{57,61} Therefore, SPLs seem to play a significant, albeit limited, role in the experience of annoyance associated with wind turbines, a conclusion similar to that reached by Knopper and Ollson.⁴

Nonacoustical Factors Associated With Annoyance

Although noise levels and noise sensitivity affect the risk of a person reporting annoyance, nonacoustic factors also play a role, including the visual effect of the turbines, whether a person derives economic benefit from the turbines and the type of terrain where one lives.⁴ Pedersen and Waye⁶¹ assessed the effect of visual/perceptual factors on wind turbine-related annoyance; all of the variables described above were significantly related to self-reported annoyance after controlling for SPLs. Nevertheless, when these variables were evaluated simultaneously, only attitude to the visual effect of the turbines remained significantly related to annoyance ($r = 0.41$, which can be interpreted as a large effect) beyond sound exposure. Pedersen and Waye¹²⁸ also found visual effect to be a significant factor in addition to sound exposure for self-reported annoyance to wind turbine sounds. Pedersen et al⁵⁸ explored the effect of visual attitude on wind turbine sound-related annoyance. Logistic regression showed that sound levels, noise sensitivity, attitudes toward wind turbines, and visual effect were all significant independent predictors of annoyance. Nevertheless, visual attitudes showed an effect size of $r = 0.27$ (medium effect), whereas noise sensitivity had an r of 0.09. Other authors have also found the visual effect of wind turbines to be related to annoyance ratings.¹³⁰ Results from multiple studies support the conclusion that visual effect contributes to wind turbine annoyance,⁴ with this review finding visual effect to have an effect size in the medium to large range. Nevertheless, given that noise sensitivity and visual attitude are consistently correlated ($r = 0.19$ and $r = 0.26$, respectively),^{58,61} it is possible that visual effect enhances

annoyance through multisensory (visual and auditory) activation of the noise-sensitivity trait.

Economic Benefit, Wind Turbines, and Annoyance

Some studies have indicated that people who derive economic benefit from wind turbines are less likely to report annoyance. Pedersen et al.⁵⁸ found that people who benefited economically ($n = 103$) from wind turbines reported significantly less annoyance despite being exposed to relatively high levels of wind turbine noise. The annoyance mitigating effect of economic benefit was replicated in Bakker et al.⁵⁷ The mitigation effect of economic benefit seems to be within the small effect size range ($r = 0.15$).⁵⁷ In addition, because receiving economic benefit represents a personal choice to have wind turbines on their property in exchange for compensation, the involvement of subject selection factors (ie, noise tolerance) requires additional study.

Annoyance, Quality of Life, Well-being, and Psychological Distress

The largest cross-sectional epidemiological study of wind turbine noise on QOL was conducted in northern Poland.⁶⁷ Surveys were completed by 1277 adults (703 women and 574 men), aged 18 to 94 years, representing a 10% two-stage random sample of the selected communities. Although the response rate was not reported, participants were sequentially enrolled until a 10% sample was achieved, and the proportion of individuals invited to participate but unable or refusing to participate was estimated at 30% (B. Mroczek, personal communication). Proximity of residence was the exposure variable, with 220 (17.2%) respondents within 700 m, 279 (21.9%) between 700 and 1000 m, 221 (17.3%) between 1000 and 1500 m, and 424 (33.2%) residing more than 1500 m from the nearest wind turbine. Several indicators of QOL, measured using the SF-36, were analyzed by proximity to wind turbines. The SF-36 consists of 36 questions divided into the following subscales: physical functioning, role-functioning physical, bodily pain, general health, vitality, social functioning, role-functioning emotional, and mental health. An additional question concerning health change was included, as well as the Visual Analogue Scale for health assessment. It is unclear whether age, sex, education, and occupation were controlled. The authors report that within all subscales, those living closest to wind farms reported the best QOL, and those living farther than 1500 m scored the worst. They concluded that living in close proximity to wind farms does not result in worsening of the QOL.⁶⁷ The authors recommend that subsequent research evaluate the reasons for the higher QOL and health indicators associated with living in closer proximity to wind farms. They speculated that these might include economic factors such as opportunities for employment with or renting land to the wind farm companies.

Individuals living closer to wind farms reported higher levels of mental health ($r = 0.11$), physical role functioning ($r = 0.07$), and vitality ($r = 0.10$) than did those living farther away.⁶⁷ Nevertheless, the implications of the study⁶⁷ are unclear, as the authors did not estimate sound-level exposure or obtain noise annoyance ratings from their subjects. Overall, with the exception of the study by Mroczek et al.,⁶⁷ noise annoyance demonstrated a consistent small to medium effect on QOL and psychological well-being.

A study a year earlier of 39 individuals in New Zealand came to different conclusions than the Polish study.¹³¹ Survey results from 39 residents located within 2 km of a wind turbine in the South Makara Valley in New Zealand were compared with 139 geographically and socioeconomically matched individuals who resided at least 8 km from any wind farm. The response rates for both the proximal and more distant study groups were poor, that is, 34% and 32%, respectively, although efforts were made to blind respondents to the study hypotheses. No other indicator of exposure to wind turbines was included beyond the selection of individuals from within 2 km or

beyond 8 km of a wind turbine, so actual or calculated wind turbine noise exposures were not available. Subjective HRQOL scales were used to describe and compare the self-reported physical, psychological, and social well-being for each group. Health-related quality of life measures are believed to provide an alternative approach to direct health assessment in that decrements in well-being are assumed to be sensitive to and reflect possible underlying health effects. The authors reported statistically significant differences between the groups in some HRQOL domain scores, with residents living within 2 km of a turbine installation reporting lower mean physical HRQOL domain score (including lower component scores for sleep quality and self-reported energy levels) and lower mean environmental QOL scores (including lower component scores for considering one's environment to be less healthy and being less satisfied with the conditions of their living space). The wind farm group scored significantly lower on physical HRQL ($r = 0.21$), environmental QOL ($r = 0.19$), and overall HRQL ($r = 0.10$) relative to the comparison group. Although the psychological QOL ratings were not significantly different ($P = 0.06$), the wind farm group also scored lower on this measure ($r = 0.16$). In the wind farm group, noise sensitivity was strongly correlated with noise annoyance ($r = 0.44$), psychological HRQL ($r = 0.40$), and social HRQOL ($r = 0.35$). These correlations approach or exceed the large effect size boundary ($r > 0.37$ suggested by Cohen).

There were no differences seen for social or psychological HRQOL domain scores. The turbine group also reported lower amenity scores, which are based on responses to two general questions—"I am satisfied with my neighborhood/living environment," and "My neighborhood/living environment makes it difficult for me to relax at home." No differences were reported between groups for traffic or neighborhood noise annoyance. Lack of actual wind turbine and other noise source measurements, combined with the low response rate (both noted by the authors as limitations), limits the inferential value of this study because it might pertain to wind turbine emissions.

Across three studies, Pedersen⁶³ found that outdoor annoyance with turbine sound was associated with tension and stress ($r = 0.05$ to 0.06) and irritability ($r = 0.05$ to 0.08), qualities associated with psychological distress. Bakker et al.⁵⁷ also found that psychological distress was significantly related to wind turbine sound ($r = 0.16$), reported outside annoyance ($r = 0.18$) and inside annoyance ($r = 0.24$). Taylor et al.⁶⁹ found that subjects living in areas with a low probability of hearing turbine noise reported significantly higher levels of positive affect than those living in moderate or high noise areas ($r = 0.24$), suggesting greater well-being for the low noise group.

Personality Factors and Wind Turbine Sound

Personality psychologists use five bipolar dimensions (neuroticism, extraversion-introversion, openness, agreeableness, and conscientiousness) to organize personality traits.¹³² Two of these dimensions, neuroticism and extraversion-introversion, have been studied in relation to noise sensitivity and annoyance. Neuroticism is characterized by negative emotional reactions, sensitivity to harmful cues in the environment, and a tendency to evaluate situations as threatening.¹³³ Introversion (the opposite pole of extraversion) is characterized by social avoidance, timidity, and inhibition.¹³³ A strong negative correlation has been shown between noise sensitivity (self-ratings) and self-rated extraversion,¹²⁵ suggesting that introverts are more noise sensitive. Introverts experience a greater disruption in vigilance when exposed to low-intensity noise than do extroverts.¹³⁴ Extroverts and introverts differ in terms of stimulation thresholds with introverts being more easily overstimulated than extroverts.¹³⁵ Despite these studies, the potential link between broad personality domains and noise annoyance remains unclear.

Taylor et al⁶⁹ explored the role of neuroticism, attitude toward wind turbines, negative oriented personality (NOP) traits (negative affectivity, frustration intolerance), and self-reported nonspecific somatic symptoms (NSS) in reaction to wind turbine noise. Despite one of the few peer-reviewed studies of personality and noise sensitivity, it only achieved a 10% response rate, which raises questions as to the representativeness of the findings. Nonetheless, the study sample reported a moderately positive attitude toward wind turbines in general and seemed representative of the local community. In the study by Taylor et al,⁶⁹ zero-order correlations showed that estimated sound levels were significantly related to perceived turbine noise ($r = 0.33$) and reduced positive affect ($r = -0.32$) but not to nonspecific symptoms ($r = 0.002$), whereas neuroticism and NOP traits were significantly related to NSS (r of 0.44 and 0.34, respectively). Multivariate analysis suggested that high NOP traits moderated the relationship between perceived noise and the report of NSS; that is, subjects with higher NOP traits reported significantly more NSS than did subjects low in NOP across the range of perceived loudness of noise.

Nocebo Response

The nocebo response refers to new or worsening symptoms produced by negative expectations.^{98,136} When negatively worded pretreatment information (“could lead to a slight increase in pain”) was given to a group of chronic back pain patients, they reported significantly more pain ($r = 0.38$) and had worse physical performance ($r = 0.36$).⁹⁸ These effect sizes are within the moderate to large ranges and reflect a meaningful adverse effect for the negative information contributing to the nocebo response. The effect of providing negative information regarding wind turbines prior to exposure to infrasound has been experimentally explored. Crichton et al¹³⁷ exposed college students to sham and true infrasound under high-expectancy (ie, adverse health effects from wind turbines) and low-expectancy (ie, no adverse health effects) conditions. The high-expectancy group received unfavorable information from TV and Internet accounts of symptoms associated with wind farm noise, whereas the low-expectancy group heard experts stating that wind farms would not cause symptoms. Symptoms were assessed pre- and postexposure to actual and sham infrasound. The high-expectancy group reported significantly more symptoms ($r = 0.37$) and greater symptom intensity ($r = 0.37$) following both sham and true infrasound exposure ($r = 0.65$ and 0.48 , respectively). The effect sizes were similar to those found in medical research on the nocebo response. These findings demonstrate that exposing individuals to negative information can increase symptom reporting immediately following exposure. The inclusion of information from TV and the Internet suggests that similar reactions may occur in real-world settings.

A study by Deignan et al¹³⁸ analyzed newspaper coverage of wind turbines in Canada and found that media coverage might contribute to nocebo responses. Newspaper coverage contained fright factor words like “dread,” “poorly understood by science,” “inequitable,” and “inescapable exposure”; the use of “dread” and “poorly understood by science” had increased from 2007 to 2011. These results document the use of fright factor words in the popular coverage of wind turbine debates; exposure to information containing these words may contribute to nocebo reactions in some people.

Wind turbines, similar to multiple technologies, such as power lines, cell phone towers, and WiFi signals, among others, have been associated with clusters of unexplained symptoms. Research suggests that people are increasingly worried about the effect of modern life (in particular emerging technologies) on their health (modern health worries [MHW]).¹⁴⁰ Modern Health Worries are moderately correlated with negative affect ($r = 0.23$) and, like the nocebo response, are considered psychogenic in origin. The expansion of wind turbine energy has been accompanied by substantial positive and neg-

ative publicity that may contribute to MHW and nocebo responses among some people exposed to this information. Health concerns have also been raised about the potential of electromagnetic fields associated with wind turbine operations; however, a recent study indicated that magnetic fields in the vicinity of wind turbines were lower than those produced by common household items.¹⁴⁰

Chapman et al⁵² explored the pattern of formal complaints (health and noise) made in relation to 51 wind farms in Australia from 1993 to 2012. The authors suggest that their study is a test of the psychogenic (nocebo or MHW) hypothesis. The findings showed that very few complaints were formally lodged; only 129 individuals in Australia formally or publically complained during the time period studied, and the majority of wind farms had no complaint made against them. The authors found that complaints increased around 2009 when “wind turbine syndrome” was introduced. On the basis of these findings, the authors conclude that nocebo effects likely play an important role in wind farm health complaints. But the authors do report that the vast majority of complaints (16 out of 18) were filed by individuals living near large wind farms ($r = 0.32$). So while few individuals complain, those who do almost exclusively live near large wind farms. Nevertheless, it is important to note that filing a formal or public complaint is a complex sociopolitical action, not a health-related outcome. Furthermore, analysis of data provided in Table 2 of the Chapman⁵⁴ study shows that the strongest predictor of a formal complaint was the presence of an opposition group in the area of the wind farm. A review of Table 2 shows that opposition groups were present in 15 of the 18 sites that filled complaints, whereas there was only one opposition group in the 33 areas that did not file a complaint ($r = 0.82$). Therefore, the relevance of this study for understanding health effects of wind turbines is limited. Chapman has also addressed the multitude of reasons why some Australian home owners may have left their homes and attributed the decision to wind turbines.⁵⁴ Gross¹⁴⁰ provides a community justice model designed to counter the potential for nocebo or psychogenic response to wind farm development. This method was pilot tested in one community and showed the potential to increase the sense of fairness for diverse community members. No empirical data were gathered during the pilot study so the effect of method cannot be formally evaluated.

Conclusions

Annoyance is a recognized health outcome measure that has been used in studies of environmental noise for many decades. Noise levels have been shown to account for only a modest portion of self-reported annoyance in the context of wind turbines ($r = 0.35$).⁴ Noise sensitivity, a stable psychological trait, contributes equally to exposure in explaining annoyance levels ($r = 0.37$). Annoyance associated with wind turbine noise shows a consistent small to medium adverse effect on self-rated QOL and psychological well-being. Given the coarseness of measures used in many studies, the magnitude of these findings are likely attenuated and underestimate the effect of annoyance on QOL. Visual effect increases annoyance beyond sound exposure and noise sensitivity, but at present there is insufficient research to conclude that visual effect operates separately from noise sensitivity because the two variables are correlated. Wind turbine development is subject to the same global psychogenic health worries and nocebo reactions as other modern technologies.¹³⁹

Economic benefit mitigates the effect of wind turbine sound; however, research is needed to clarify the potential confounding role of (self) selection in this finding. The most powerful multivariate model reviewed accounted for approximately 50% ($r = 0.69$) of the variance in reported annoyance, leaving 50% unexplained. Clearly other relevant factors likely remain unidentified. Nevertheless, it is not unusual for there to be a significant percentage of unexplained variance in biomedical or social science research. For example, a meta-analysis of postoperative pain (a subjective experience),

covering 48 studies and 23,037 subjects, found that only 54% ($r = 0.73$) of the variance in pain ratings could be explained by the variables included in the studies.¹⁴⁴ Wind turbine development is subject to the same global psychogenic health worries and nocebo reactions as other modern technologies. Therefore, communities, government agency, and companies would be well advised to adopt an open, transparent, and engaging process when debating the potential effect of wind turbine sites. The vast majority of findings reviewed in this section were correlational and, therefore, do not imply causality, and that other as of yet unidentified (unmeasured) factors may be associated with or responsible for these findings.

DISCUSSION

Despite the limitations of available research related to wind turbines and health, inferences can be drawn from this information, if used in concert with available scientific evidence from other environmental noise studies, many of which have been reviewed and assessed for public policy in the WHO's Nighttime Noise Guidelines.¹⁰⁴ A substantial database on environmental noise studies related to transportation, aviation, and rail has been published.¹⁴⁷ Many of these studies have been used to develop worldwide regulatory noise guidelines, such as those of the WHO,¹⁰⁴ which have proposed nighttime noise levels primarily focused on preventing sleep disturbance.

Because sound and its components are the potential health hazards associated with living near wind turbines, an assessment of other environmental noise studies can offer a valuable perspective in assessing health risks for people living near wind turbines. For example, one would not expect adverse health effects to occur at lower noise levels if the same effects do not occur at higher noise levels. In the studies of other environmental noise sources, noise levels have been considerably higher than those associated with wind turbines. Noise differences as broad as 15 dBA (eg, 55 dBA in highways vs 40 dBA from wind turbines) have been regularly reported.¹⁴⁷ In settings where anthropogenic changes are perceived, indirect effects such as annoyance have been reported, and these must also be considered in the evaluation of health effects.

We now attempt to address three fundamental questions posed at the beginning of this review related to potential health implications of wind turbines.

Is there available scientific evidence to conclude that wind turbines adversely affect human health? If so, what are the circumstances associated with such effects and how might they be prevented?

The epidemiological and experimental literature provides no convincing or consistent evidence that wind turbine noise is associated with any well-defined disease outcome. What is suggested by this literature, however, is that varying proportions of people residing near wind turbine facilities report annoyance with the turbines or turbine noise. It has been suggested by some authors of these studies that this annoyance may contribute to sleep disruption and/or stress and, therefore, lead to other health consequences. This self-reported annoyance, however, has not been reported consistently and, when observed, arises from cross-sectional surveys that inherently cannot discern whether the wind turbine noise emissions play any direct causal role. Beyond these methodological limitations, such results have been associated with other mediating factors (including personality and attitudinal characteristics), reverse causation (ie, disturbed sleep or the presence of a headache increases the perception of and association with wind turbine noise), and personal incentives (whether economic benefit is available for living near the turbines).

There are no available cohort or longitudinal studies that can more definitively address the question about causal links between wind turbine operations and adverse health effects. Nevertheless, results from cross-sectional and experimental studies, as well as

studies of other environmental noise sources, can provide valuable information in assessing risk. On the basis of the published cross-sectional epidemiological studies, "annoyance" is the main outcome measure that has been raised in the context of living in the vicinity of wind turbines. Whether annoyance is an adverse health effect, however, is disputable. "Annoyance" is not listed in the International Classification of Diseases (10th edition), although it has been suggested by some that annoyance may lead to stress and to other health consequences, such as sleep disturbance. This proposed mechanism, however, has not been demonstrated in studies using methods capable of elucidating such pathways.

The authors of this review are aware of the Internet sites and non-peer-reviewed reports, in which some people have described symptoms that they attribute to living near wind turbines. The quality of this information, however, is severely limited such that reasonable assessments cannot be made about direct causal links between the wind turbines and symptoms reported. For example, inviting only people who feel they have symptoms because of wind turbines to participate in surveys and asking people to remember events in the past in the context of a current concern (ie, postturbine installation) introduce selection and recall biases, respectively. Such major biases compromise the reliability of the information as used in any rigorous causality assessment. Nonetheless, consistent associations have been reported between annoyance, sleep disturbance, and altered QOL among some people living near wind turbines. It is not possible to properly evaluate causal links of these claims in the absence of a thorough medical assessment, proper noise studies, and a valid study approach. The symptoms reported tend to be nonspecific and associated with various other illnesses. Personality factors, including self-assessed noise sensitivity, attitudes toward wind energy, and nocebo-like reactions, may play a role in the reporting of these symptoms. In the absence of thorough medical evaluations that include a characterization of the noise exposure and a diagnostic medical evaluation, confirmation that the symptoms are due to living near wind turbines cannot be made with any reliability. In fact, the use of a proposed case definition that seemed in a journal not indexed by PubMed can lead to misleading and incorrect assessments of people's health, if performed in the absence of a thorough diagnostic evaluation.¹⁴³ We recommend that people who suspect that they have symptoms from living near wind turbines undergo a thorough medical evaluation to identify all potential causes of and contributors to the symptoms. Attributing symptoms to living near wind turbines in the absence of a comprehensive medical evaluation is not medically appropriate. It is in the person's best interest to be properly evaluated to ensure that recognized and treatable illnesses are recognized.

Available scientific evidence does not provide support for any bona fide-specific illness arising out of living in the vicinity of wind turbines. Nonetheless, it seems that an array of factors contribute to some proportion of those living in proximity to wind turbines, reporting some degree of annoyance. The effect of prolonged annoyance—regardless of its source or causes—may have other health consequences, such as increasing stress; however, this cannot be demonstrated with the existing scientific literature on annoyance associated with wind turbine noise or visibility.

Is there available scientific evidence to conclude that psychological stress, annoyance, and sleep disturbance can occur as a result of living in proximity to wind turbines? Do these effects lead to adverse health effects? If so, what are the circumstances associated with such effects and how might they be prevented?

Available research is not suitable for assessing causality because the major epidemiological studies conducted to date have been cross-sectional, data from which do not allow the evaluation of the temporal relationship between any observed correlated factors.

Cross-sectional studies, despite their inherent limitations in assessing causal links, however, have consistently shown that some people living near wind turbines are more likely to report annoyance than those living farther away. These same studies have also shown that a person's likelihood of reporting annoyance is strongly related to their attitudes toward wind turbines, the visual aspect of the turbines, and whether they obtain economic benefit from the turbines. Our review suggests that these other risk factors play a more significant role than noise from wind turbines in people reporting annoyance.

The effect of annoyance on a person's health is likely to vary considerably, based on various factors. To minimize these reactions, solutions may include informative discussions with area residents before developing plans for a wind farm along with open communications of plans and a trusted approach to responding to questions and resolving noise-related complaints.

Is there evidence to suggest that specific aspects of wind turbine sound such as infrasound and low-frequency sound have unique potential health effects not associated with other sources of environmental noise?

Both infrasound and low-frequency sound have been raised as possibly unique health hazards associated with wind turbine operations. There is no scientific evidence, however, including results from field measurements of wind turbine–related noise and experimental studies in which people have been purposely exposed to infrasound, to support this hypothesis. Measurements of low-frequency sound, infrasound, tonal sound emission, and amplitude-modulated sound show that infrasound is emitted by wind turbines, but that the levels at customary distances to homes are well below audibility thresholds, even at residences where people have reported symptoms that they attribute to wind turbines. These levels of infrasound—as close as 300 m from the turbines—are not audible. Moreover, experimental studies of people exposed to much higher levels of infrasound than levels measured near wind turbines have not indicated adverse health effects. Because infrasound is associated more with vibratory effects than high-frequency sound, it has been suggested that the vibration from infrasound may be contributing to certain physical sensations described by some people living near wind turbines. These sensations are difficult to reconcile in light of field studies that indicated that infrasound at distances more than 300 m for a wind turbine meet international standards for preventing rattling and other potential vibratory effects.¹⁴

Areas for Further Inquiry

In light of the limitations of available studies for drawing definitive conclusions and the need to address health-related concerns associated with wind turbines raised by some nearby residents, each author discussed potential areas of further inquiry to address current data gaps. These recommendations primarily address exposure characterization, health endpoints, and the type of epidemiological study most likely to lead to informative results regarding potential health effects associated with living near wind turbines.

Noise From Wind Turbines

As with any potential occupational or environmental hazard, further efforts at exposure characterization, that is, noise and its components such as infrasound and low-frequency sound, would be valuable. Ideally, uniform equipment and standardized methods of measurement can be used to enable comparison with results from published studies and evaluate adherence to public policy guidelines.

Efforts directed at evaluating models used to predict noise levels from wind turbines—in contrast to actual measured noise levels—would be valuable and may be helpful in informing and reassuring residents involved in public discussions related to the development of wind energy projects. Efforts at fine tuning noise models for accuracy to real-world situations can be reassuring to public health

officials charged with evaluating potential health effects of noise. The development and the use of reliable and portable noise measuring devices to address components of noise near residences and evaluating symptoms and compliance with noise guidelines would be valuable.

Epidemiology

Prospective cohort studies would be most informative for identifying potential health effects of exposure to wind turbine noise before and after wind turbines are installed and operating. Ideally, substantially large populations would be evaluated for baseline health status, and subsequently part of the population would become exposed to wind turbines and part would remain unexposed, as in an area where large wind turbine farms are proposed or planned. The value of such studies is in the avoidance of several forms of bias such as recall bias, where study participants might, relying on recall, under- or overreport risk factors or diseases that occurred sometime in the past. As has been noted by several authors, the level of attention given the topic of wind turbines and possible health effects in the news and the Internet makes it difficult to study any population truly “blinded” to the hypotheses being evaluated. The main advantage of prospective cohort studies with a pre- and post-wind turbine component is the direct ability to compare changes in disease and health status among individuals subsequently exposed to wind turbine noise with those among similar groups of people not exposed. These conditions are not readily approximated by any other study approach. A similar but more complex approach could include populations about to become exposed to other anthropogenic stimuli, such as highways, railroads, commercial centers, or other power generation sources.

We note that additional cross-sectional studies may not be capable of contributing meaningfully and in fact might reinforce biases already seen in many cross-sectional studies and surveys.

Sound and Its Components

Several types of efforts can be undertaken to test hypotheses proposed about inaudible sound being a risk for causing adverse health effects. It would be simple, at least conceptually, to expose blinded subjects to inaudible sounds, especially in the infrasound range, to determine whether they could detect the sounds or whether they developed any unpleasant symptoms. Ideally, these studies would use infrasound levels that are close to hearing thresholds and comparable with real-world wind turbine levels at residential distances. Crichton et al^{137,149} have begun such studies, finding that subjects could not detect any difference between infrasound and sham “exposures.” The infrasound stimulus used, however, was only 40 dB at 5 Hz, more than 60 dB lower than hearing threshold and lower than levels measured at some residences near wind turbines.

The possibility of adverse effects from inaudible sound could also be tested in humans or animals in long-term studies. To date, there seem to be no reports of adverse effects in people exposed to wind turbine noise that they could never hear (such reports would require careful controls), nor are any relevant animal studies known to the authors of this review.

Controlled human exposure studies have been used to gain insight into the effects of exposure to LFN from wind turbines. Human volunteers are exposed for a short amount of time under defined conditions, sometimes following various forms of preconditioning, and different response metrics evaluated. Most of these studies addressed wind turbine noise annoyance but no direct health indicator; however, one study addressed visual reaction to the color of wind turbines in pictures,⁷³ and another evaluated physical symptoms in response to wind turbine noise.^{137,149}

Efforts to document a potential effect of infrasound on health have been unsuccessful, including searches for responses to sound from cochlear type II afferent neurons or responses to inaudible

airborne sound from the vestibular system. But in other cases, the relevant experiments (can inaudible sound cause endolymphatic hydrops?) seem not to have been conducted to date. This seemingly improbable hypothesis, however, could be tested in guinea pigs, which reliably develops endolymphatic hydrops in response to other experimental interventions.

Psychological Factors

This review has demonstrated that a complex combination of noise and personal factors contributes to some people reporting annoyance in the context of living near wind turbines. Further efforts at characterizing and understanding these issues can be directed to improvements in measurement of sound perception, data analysis, and conceptualization.

We suggest improvements in the quality and standardization of measurement for important constructs like noise sensitivity and noise annoyance across studies. We also suggest eliminating the use of single-item “measures” for primary outcomes.

Data analysis should ideally include effect size measures in all studies to supplement the significance testing (some significant differences are small when sample sizes are large). This will help improve the comparability of findings across studies.

Integrate noise sensitivity, noise annoyance, and QOL into a broader more comprehensive theory of personality or psychological functioning, such as the widely accepted five-factor model of personality.

SUMMARY

1. Measurements of low-frequency sound, infrasound, tonal sound emission, and amplitude-modulated sound show that infrasound is emitted by wind turbines. The levels of infrasound at customary distances to homes are typically well below audibility thresholds.
2. No cohort or case-control studies were located in this updated review of the peer-reviewed literature. Nevertheless, among the cross-sectional studies of better quality, no clear or consistent association is seen between wind turbine noise and any reported disease or other indicator of harm to human health.
3. Components of wind turbine sound, including infrasound and low-frequency sound, have not been shown to present unique health risks to people living near wind turbines.
4. Annoyance associated with living near wind turbines is a complex phenomenon related to personal factors. Noise from turbines plays a minor role in comparison with other factors in leading people to report annoyance in the context of wind turbines.

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