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# Noise: Windfarms

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**Abstract**

Windfarms consist of clusters of wind turbines, which, when placed in populated areas, are associated with intrusive and unwanted sound. A relatively new noise source; wind turbine noise has characteristics sufficiently different from other, more extensively studied, noise sources to suggest that preexisting noise standards are not appropriate. Though research into the human impacts of wind turbine noise has appeared only in the last decade and in small quantity, the data suggest that, for equivalent exposures, wind turbine noise is more annoying than road or aviation noise. Furthermore, the particular characteristics of wind turbine noise may be likely to cause sleep disruption. As with other impulsive noise sources, time-aggregated noise metrics have limited utility in protecting public health, and a cluster of metrics should be used in order to estimate potential threat. At this time, however, the quantity and quality of research are insufficient to effectively describe the relationship between wind turbine noise and health, and so legislation should apply the precautionary principle or conservative criteria when assessing proposed windfarm developments.

## INTRODUCTION

Planning authorities, environmental agencies, and policy makers in many parts of the world are seeking information on possible links between wind turbine noise and health in order to legislate permissible noise levels or setback distances. Concurrently, larger and noisier wind turbines are emerging, and consent is being sought for progressively larger windfarms to be placed even closer to human habitats. While noise standards can effectively and fairly facilitate decision-making processes if developed properly, the current standards on offer suffer severe conceptual difficulties. Specifically, noise metrics considered by many in the industry as best practice may in fact relate little to health outcome variables such as annoyance or sleep disruption. In this entry, we describe the physical characteristics of wind turbine noise, review the impact of such noise on humans, and critique current approaches to mitigation.

## INDUSTRIAL WIND TURBINES

Industrial wind turbines transform kinetic energy from the wind into electricity, a practice dating back over 100 years. Structurally, wind turbines can be decomposed into three key components (Fig. 1). First, wind turbines possess a rotor, consisting of one or more blades designed to rotate when exposed to wind. The rotor can be thought of as a type of sail, catching wind in order to induce movement. Depending on the axis of blade rotation, wind turbines can be categorized as either horizontal-axis (the most common) or vertical-axis turbines. The second major component is the generator or "dynamo." The generator component includes a gearbox to regulate the speed of the dynamo and components to change blade pitch and plane of rotation with respect to wind direction. The dynamo can be used as a motor to maintain rotation at very low wind speeds. Third, there is a tower supporting the rotor and, typically, the generator. The size of a wind turbine can be specified either as a dimension (e.g., tower height measured from the ground to the top of a blade at its highest point) or as an electrical output (e.g., watts). Currently, turbines range from approximately 2 to 200 m high and from approximately 50 W to 6 MW.

Wind turbines can be erected in isolation or in sets and be located either onshore (i.e., terrestrial) or offshore (i.e., marine), though the latter is associated with higher construction costs. Industrial-scale wind energy generation, involving the saturation of an optimum number of wind turbines in a fixed area of land, gives rise to the concept of the "windfarm" or "wind park." Wind energy developers seek areas that have good consistent wind flow and close access to energy grids. The proliferation in the number of windfarms established globally in the past decade has been largely driven by environmental concerns such as climate change, renewableness and sustainability, and strategic energy considerations relating to the depletion of fossil fuels.[1] However, in the absence of large-scale electricity

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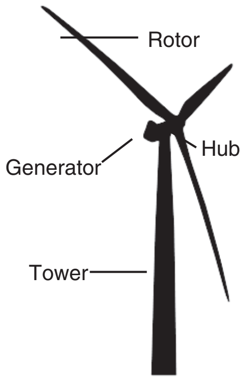


**Fig. 1** Components of a typical horizontal-axis wind turbine.

storage devices (i.e., batteries), the contribution of wind energy to a nation's electricity needs is likely to be peripheral. Another barrier is social acceptance, with reviewed social surveys indicating citizens supporting renewable energy in principle but opposed to having windfarms in their immediate vicinity due to visual impacts on the landscape, shadowflicker from the blades, and fears of noise-induced annoyance and sleep disruption.

## ACOUSTIC PROFILE OF WIND TURBINE NOISE

The sound generated from a windfarm is qualitatively different from any sound source commonly met in the environment, can rapidly switch from being stationary to nonstationary, and can vary by as much as 20 dB within a single minute. When it interferes with human activities, wind turbine sound becomes a type of noise. Analysis of windfarm noise poses distinct challenges, including the identification of acoustic energy that can be directly attributed to the turbines and the detection of special audible characteristics, including distinct tonal complexes and modulation effects. Windfarm noise is often a broadband low-amplitude noise constantly shifting in character ("waves on beach," "rumble-thump," "plane never landing." etc.). In this respect, windfarm noise is not like, for example, traffic noise or the continuous hum from plant and machinery. When assessed, wind turbine noise is often related to either wind speed (m/s) or electrical output (watts) and typically increases with both.

When the wind reaches a blade, it flows both over and under the blade. The part of the airflow with momentum great enough to break away forms trailing vortexes and turbulence behind the blade, producing a set of sound sources. The power of each sound source depends on the strength of the turbulence, which in turn depends on the speed of airflow; the compressibility and viscosity of the air; the design and surface texture (roughness) of the blade; the wind speed; and the velocity of the blade at that point. The faster the blade rotates, the earlier the breakup in the boundary vortexes and the greater the interaction between the vortexes emanating by adjacent wind turbines. An amplification of potential noise occurs when two or more turbines are, or nearly are, synchronous, such that the blade passing pulses coincide and then go out of phase again.[2] With exact synchronicity, there is a fixed interference pattern; with near synchronicity, concurrent arrival of pulses will change over time and place.

Noise emissions from modern wind turbines are primarily due to turbulent flow and trailing edge sound, blade characteristics, blade/tower interaction, and to a lesser degree, mechanical processes. The most commonly used description of wind turbine noise is the A-weighted

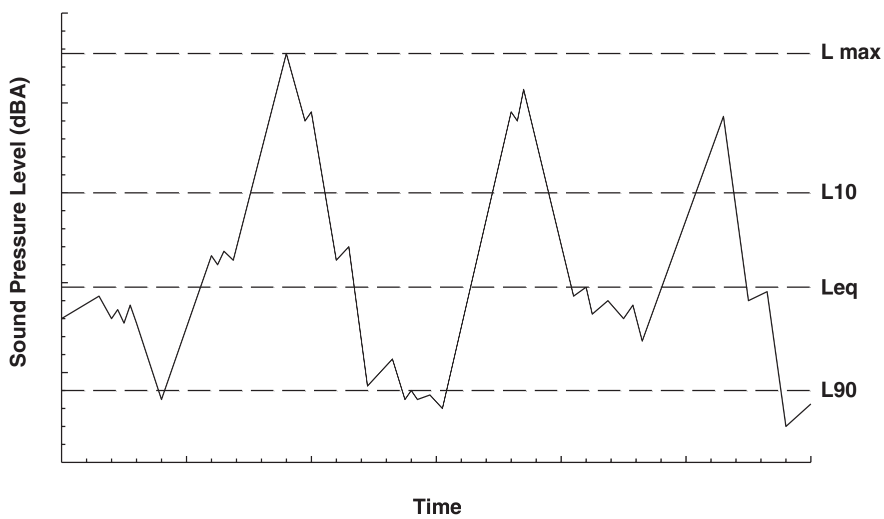


**Fig. 2** Chart illustrating different noise descriptors. L10 is the level exceeded 10% of the time, while L90 is the level exceeded 90% of the time. The time-average (equivalent continuous) sound pressure level, Leq, represents the average acoustic energy across a defined measurement epoch.

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sound pressure level, which is expressed in decibels (notated dBA). The most commonly used noise compliance assessment methods for windfarms involve the "time-average" sound level $L_{Aeq}$ or the background sound level $L_{A90}$. These levels are quite different as the time-averaged ambient sound level includes all noises from near and far. The difference between these levels, and other common levels, is illustrated in Fig. 2. The chart shows that sound levels change over time and that any derived sound level index is a summary of fluctuating levels in that time period. In a relatively short time period, such as 10 minutes, the unique noise events such as bangs or thuds from turbines shifting in the wind may be captured. If the time period is relatively long, for example, an hour, then evidence of unique short-term noise events is reduced because the sound energy is "averaged" over the whole hour, and the single-value A-weighted level will not represent short-term variations in sound character. If extraneous noise (e.g., insect noise) is included in the wind turbine measurement, its contribution to the overall level must be determined, though how this is undertaken remains a challenge.[3]

The A-frequency–weighted sound pressure level or "sound level" is the most common sound descriptor and is reputedly analogous to our hearing at medium sound levels. This is not strictly true, and the A-weighting has a significant restriction in that it does not permit measurement or assessment of low-frequency sound (i.e., 20 to 250 Hz). For more complex situations where dominant tonal components are significant (i.e., special audible characteristics), a procedure for determining tonal adjustment requiring one-third octave band frequency or narrow-band analysis is needed. These assessment procedures require the "C" weighting for low frequency or the unweighted (also known as "Z") response to measure both low-frequency and infrasonic sound. Whereas the dBC metric is able to include low-frequency sounds such as the audible rumble and thump from wind turbines, the dBZ response is more suitable for infrasound measurements (i.e., typically inaudible energy below 20 Hz). Fig. 3 presents a third octave band analysis of outdoor wind turbine noise recorded over a 6-hr period. Other measures include assessments for tonality or low-frequency sound referenced to third octave bands and the "G" weighting for infrasound. Aside from physical measures of amplitude (e.g., dBA), wind turbine noise can be quantified with a variety of other acoustical and objective psychoacoustic measures, including amplitude modulation (for example, 100 msec samples of peak, time-average, or fast response), sound quality (including audibility, dissonance, roughness, fluctuation strength, sharpness, tonality), loudness (for steady, time-varying, and impulsive sounds), and unbiased annoyance.[4]

Certification of wind turbine noise is undertaken in accordance with the International Standard IEC 61400-11:2002.[5] Emission levels are to be reported as A-weighted time-averaged ($L_{Aeq}$) sound levels in one-third octave bands. Audibility is calculated by reference to tones. An informative chapter in IEC 61400-11 states the following: "In addition to those characteristics of wind turbine noise described in the main text, this emission may also possess some, or all of the following: infrasound; lowfrequency noise; impulsivity; low-frequency modulation of broad band or tonal noise; other, such as a whine, hiss, screech, or hum, etc., distinct pulses in the noise, such as bangs, clatters, clicks or thumps, etc." Unfortunately, many of these parameters are not reported by the turbine manufacturer and cannot be predicted with the simple

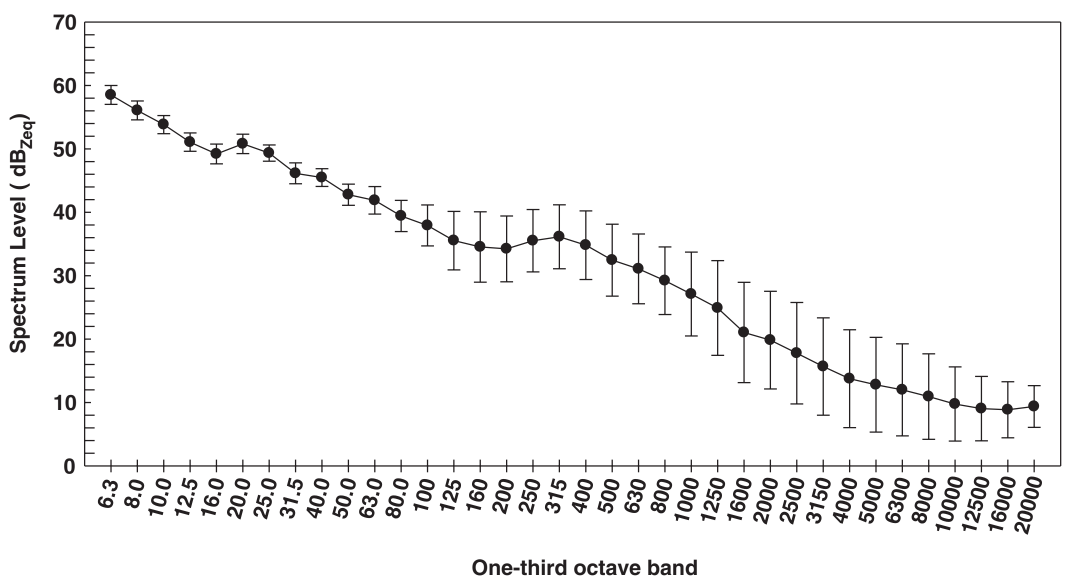


**Fig. 3** One-third octave band analysis of time-average unweighted sound pressurelevel ($dB_{Zeq}$) for wind turbine sound measured from 7:00 PM to 1:00 AM outside of a residence.

**Table 1** Factors affecting the prediction of wind farm noise levels at a receiver.[a]

- The true sound power level of the turbine(s) at the specified wind speed
- The reduction in sound level due to ground effects
- The increase or reduction in sound level due to atmospheric (meteorological) variations and wind direction
- The variation due to modulation effects from wind velocity gradient
- Increase and reduction in sound levels due to wake and turbulence modulation effects due to turbine placement and wind direction
- Increased sound levels due to synchronicity effects of turbines in phase due to turbine placement and wind direction
- Building resonance effects for residents inside a dwelling

[a]A conservative set of noise predictions should take all factors into account.

calculation methods currently available. The prediction of windfarm sound levels is most often referenced to national or international standards that have been based on ISO 9613-2.[6] The propagation method is calculated with the receivers being downwind from the noise source(s). All prediction models have uncertainty to their accuracy of prediction. Table 5 of the ISO 9613-2 standard gives an estimated accuracy for broadband noise of ±3 dB at between 100 and 1000 m. This is due to the inherent nature of the calculation algorithms that go into the design of the model, the assumptions made in the implementation of the model, and the availability of good source sound power data. The ISO 9613-2 method holds for wind speeds of between approximately 1 and 5 m/s, measured at a height of 3 to 11 m above the ground. However, wind turbines are sound sources that operate at higher wind speeds than allowed for under the standard, and an accuracy of ±7 dB can be expected.[3] Ultimately, the received noise levels at residences will vary subject to varying meteorological conditions in the locality (e.g., wind speed and direction, wind shear, temperature, humidity, inversions), among other factors (see Table 1), all of which must be accounted for when measuring or modeling wind turbine noise levels.

## THE HUMAN IMPACTS OF WIND TURBINE NOISE

### A Psychological Description of Wind Turbine Noise

At the psychological level of description, wind turbine noise is most frequently characterized as a swishing or lashing sound or less commonly as thump/throb, low-frequency rumble, or a rustling sound.[7,8] Wind turbines produce noise with an impulsive character[9] and while the actual cause of the swishing or thumping has not yet been fully elucidated, it has been demonstrated that the swishing or thumping pattern is common with larger turbines[10] and may result from a fluctuating angle of attack between the trailing edge of the rotor blade and wind, or wind speed inequalities across the area being swept by the rotor blades.[11] It is thought that the swishing sound may be linked to activity in the 2000 to 4000 Hz band, with the pace of the rotor blades determining the degree of amplitude modulation.[12] Unfortunately, such amplitude-modulated sounds are generally attenuated poorly by background noise, especially so in rural areas.[13] Further, because human sensory systems behave as contrast analyzers, fluctuations in the incoming stimulus field tend to direct attention and so are more easily detected. Thus, amplitude-modulated sounds such as wind turbine noise are readily perceived and difficult to filter out, making them especially intrusive.[14] The loudness of a wind turbine depends on a number of factors, including wind speed, sound-attenuating materials between the turbines and the receiver, other masking sounds, the season, and time of day. The loudness of a modern 2 to 3 MW wind turbine can be compared to a car on a motorway, autobahn, or freeway,[15] with a sound power level of 94 to 104 dBA at a windspeed of 8 m/s.[16] Wind turbine noise is perceived louder at night and during the summer months and when the wind is blowing from the direction of the turbines toward the receiver.[7,8]

### Quantifying the Health Impacts of Wind Turbine Noise

Elucidating a causal mechanism between an environmental event and health is a complicated undertaking, and noise effects are commonly “indirect” as opposed to “direct.” According to the biomedical model of health (Fig. 4a), a direct health effect implies a direct pathological relationship between an environmental parameter (e.g., noise level) and a target organ. An alternative approach (Fig. 4b) distinguishes between direct health effects and psychosomatic illness, the latter indicting that any physiological illness coinciding with the onset of wind turbine noise is caused by a negative psychological response to the noise and not the noise *per se*. Thus, anxiety or anger in the presence of wind turbine noise induces stress and strain that, if maintained, can eventually lead to adverse health effects. A counter argument to this approach is that some individuals are simply more susceptible to noise than other individuals, which fits with the general concept of biological and physical variation. In the field of epidemiology, the differential susceptibilities of individuals are known as risk factors or vulnerabilities, with noise sensitivity being one risk factor related to negative responses to intrusive noise. A second challenge to the psychosomatic approach comes from documented instances of individuals who initially welcomed wind turbines into the community but who later campaigned to have them removed due to undesirable noise exposure.[17] Lastly, the veracity of psy-

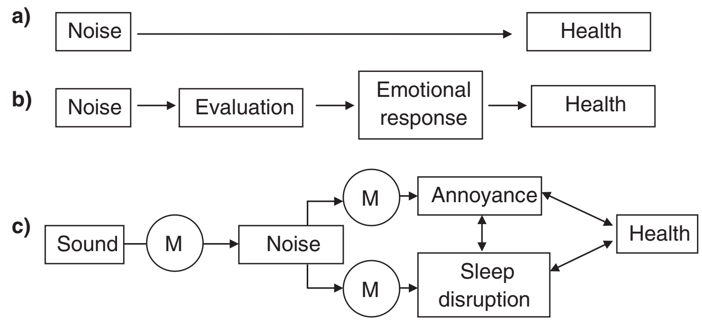


**Fig. 4** Three models representing the relationship between noise and health: the biomedical model (a) stipulating a direct causal relationship and indirect models (b and c) containing moderators and mediators.

chosomatic arguments lessens in the face of feasible biological mechanisms describing the relationship between health and noise.[18]

An alternative and more accepted approach would be to adopt the World Health Organization's (WHO's) definition of health:[19] "A state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." The forerunner of the biopsychosocial model, the WHO's definition states that optimal human functioning is determined by the interplay of biological, environmental, psychological, and social factors. Fig. 4c displays a model consistent with the WHO's approach, in which the impact of noise is moderated by environmental, psychological, and social factors. A context-relevant model proposed by van den Berg and colleagues,[8] based on previous wind turbine literature, takes a similar shape to that presented in Fig. 4c. They dichotomize moderators (denoted "M" in Fig. 4c) into environmental moderators (e.g., degree of urbanization, house type, and ambient sound level) or psychological and demographic moderators (e.g., age, gender, education, employment status, attitudes to wind energy, noise sensitivity, and whether the individual receives a monetary return from the turbines). Other models linking wind turbine sound and health have been proposed[20] but can be considered extensions of that presented in Fig. 4c.

As a new source of noise, the impact of wind turbine noise is understandably understudied relative to aviation and road traffic noise. Consequently, little data exist with which to assess the impacts of wind turbine noise on health, a state of affairs compounded by rapid development of wind turbine technology, in which data collected for smaller and less powerful turbines are not generalizable to larger, more modern turbines.[9,21] To date, there have been two approaches to collecting wind turbine noise impact data, either epidemiological studies relying on masked surveys or direct clinical case studies.[22] Both approaches typically focus on the emotional impacts of noise (i.e., annoyance), upon sleep disruption, and/or the degradation of well-being and increases in stress that arise from sleep disturbance and annoyance. Irrespective of approach, however, case studies,[23–25] and epidemiological studies[7,8,20] have provided evidence that, like road traffic and aviation noise, wind turbine noise can be associated with negative health outcomes.

## Wind Turbine Noise and Annoyance

People generally respond more negatively to man-made noise than to natural sounds,[26] and this generalization holds true for wind turbine noise.[16] From a psychological perspective, chronic exposure to community noise can impact health through information overload, overarousal, loss of coping strategies, loss of privacy, and loss of perceived control. These mechanisms give rise to a number of subjective responses to noise, of which the most common is annoyance. As a psychological stressor,[27] noise annoyance can express itself through malaise, fear, threat, uncertainty, restricted liberty, excitability, or defenselessness.[28] Furthermore, annoyance may be accompanied by intense anger, especially if one believes that they are being harmed unnecessarily. Thus, the term "annoyance" is often misinterpreted by the layperson as a feeling brought about by the presence of a minor irritant. The medical usage, in contrast, exists as a precise technical term and defines annoyance as a mental state capable of degrading health and well-being,[29,30] and it is classified as an adverse health effect by the WHO.[31]

There have been few studies estimating the health impacts of windfarms, with a series of studies undertaken in Scandinavia contributing the most to current knowledge. A seminal Swedish study undertaken by Pedersen and Persson Waye[7] sought to document the prevalence of wind turbine–induced annoyance and, further, to generate dose–response relationships between the two. Respondents were located between 150 and 1200 metres from the nearest wind turbine and were classified into noise exposure categories (see Fig. 5). A significant relationship between dose (dBA) and annoyance was reported, but the variability in annoyance scores explained by noise level was small (adjusted $R^2 = 0.13$). Those reporting annoyance indicated a daily or nearly-everyday intrusion of windfarm noise. Those describing the noise as "swishing" were more

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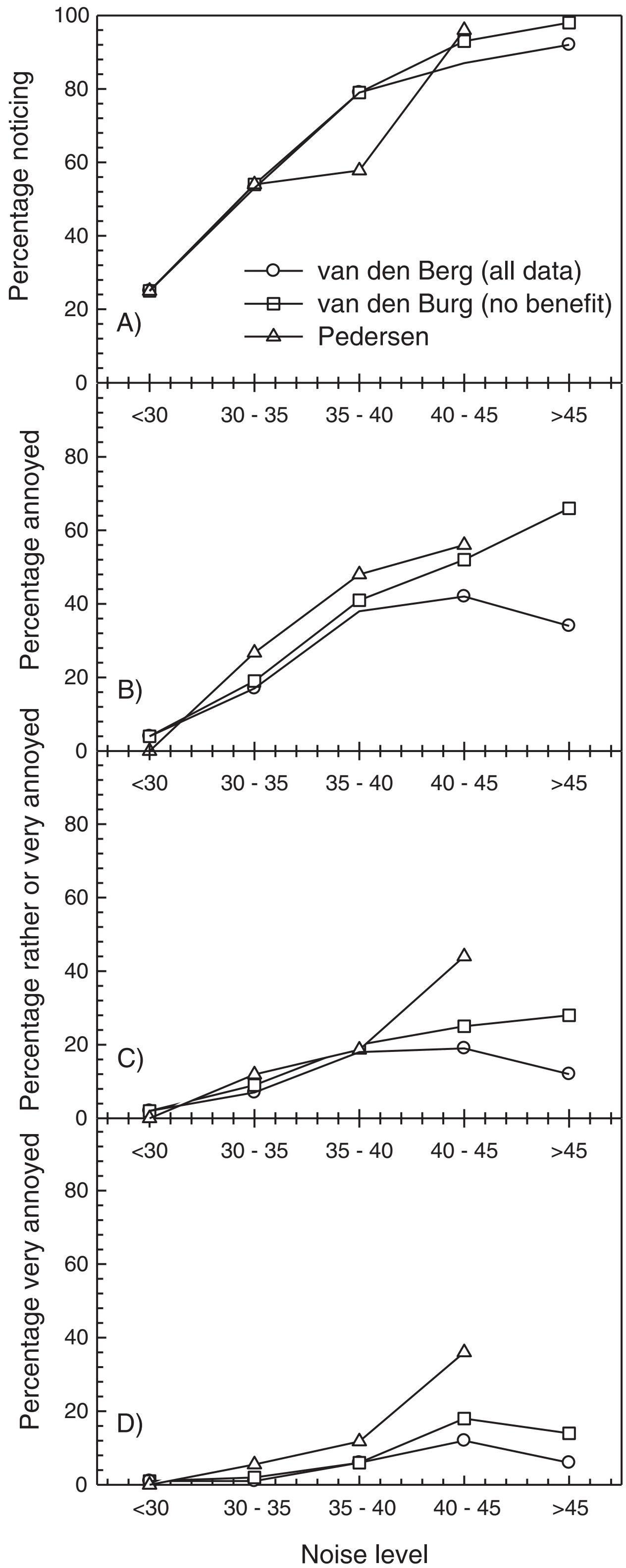


**Fig. 5** Perception of wind turbine noise as a function of noise level for three sets of data:Tables 7.25 (complete data set) and 7.26 (no economic benefit of turbines) from van den Berg et al.[8] and Pedersen and Persson Waye's[7] Table V. Plot A is percentage noticing the noise, while plots B to D are for annoyance. Plot B includes data from plots C and D, and plot C includes data from plot D.

likely to report noise annoyance, a finding replicated in a subsequent study reporting a high correlation ($r$ = 0.664) between the swishing sound and annoyance.[14] Among those who noticed the noise, 11.2% reported being annoyed when indoors. A small but significant correlation was found between noise annoyance and noise sensitivity, with approximately 50% of the rural-dwelling respondents describing themselves as noise sensitive. Those making negative appraisals of the wind turbines, for example, as visually incongruent with the landscape, were at higher risk of an annoyance response. On the basis of their data, the authors undertook follow-up studies[14–16,22] supporting their conclusion that wind turbine noise maybe more potent than other categories of environmental noise (e.g., road or aviation) and appealed for further studies to determine why this might be. In a later report, Pedersen[22] suggests that coping strategy may moderate the relationship between wind turbine noise and stress.

Van den Berg et al.[8]analyzed data from 725 Dutch nationals residing within 2.1 km of a wind turbine and who were exposed to calculated outdoor noise levels between 24 and 54 dB(A). Approximately 60% of the sample could hear the turbines outdoors, while 33% reported that they could hear the wind turbines indoors. Of the 45% ($n$ = 231) who noticed the sound of the rotor blades, 24.7% were not annoyed, 25.8% were slightly annoyed, 19.5% were rather annoyed, and 29.9% were very annoyed. The sound level explained approximately 25% of the variability in annoyance scores, and those who compared the noise to an amplitude modulation (i.e., swishing or lashing) were more likely to be annoyed, though this is not a novel finding.[14,32,33] Fig. 5 plots the data from van den Berg et al., presenting proportions of detection and elicited annoyance as a function of noise level, for their entire dataset (Fig. 5, circles) and for those receiving no economic benefit (Fig. 5, squares). Note that, for those receiving no economic benefit, a monotonic relationship is evident, while a nonmonotonic function occurs when individuals benefiting financially from the turbines are included. Van den Berg[8] reports that this depreciation in annoyance of those benefiting economically can be explained by the control they have over the wind turbines, such that they can impede their operation if noise levels increase. Finally, it was reported that annoyance was positively correlated with stress scores, though a causal relationship could not be inferred.

It is accepted that both the physical parameters of the noise and the psychological characteristics of the listener combine to produce noise annoyance.[34] On the physical side, the relatively high annoyance levels elicited by wind turbine noises (e.g., swishing or thumping) may be explained by the increased fluctuation of the sound, up to 4 to 6 dB for a single turbine operating in a stable atmosphere.[11] Individuals are also highly sensitive to changes in frequency modulation variations of approximately 4 Hz or greater.[4] Noting that amplitude-modulated sound is known to be more annoying than unmodulated sound, Lee et al.,[34] in a laboratory setting, demonstrated that amplitude-modulated wind turbine noise was consistently judged to be more annoying than its unmodulated counterpart. Thus, the dominant acoustic driver of annoyance is likely to be noise dynamics rather than noise level. Other physical parameters linked to annoyance include terrain complexity, with rural terrain associated with greater annoyance than urban areas, possibility due to more complicated terrain exhibiting various focusing or defocusing effects and greater ground reflection.

While there is a strong correlation between the sound pressure level (i.e., amplitude) of a sound wave and the perceived loudness of a sound, there is no one-to-one mapping between sound pressure level and the psychological responses that individuals have to a sound.[35] Many non-acoustical factors determine how annoyed one will become toward a source of noise.[36–38] Thus, the response of the individual to the sound is just as important as the parameters of the acoustic wave, and the "people" side of noise should not be omitted from acoustical reports. Table 2 lists, in no particular order, non-acoustical factors found to influence levels of noise annoyance.[39] In relation to windfarms, the personal factors listed in Table 2 have been found to strongly influence how exposed individuals perceive the noise.[16] In addition, perceptions of amenity, individuals seeking refuge from urban noise, or the lower ambient sound levels typical of the rural environment may explain why annoyance responses are higher in rural as opposed to urban settings.[13,16]

When considering wind turbine noise and annoyance data emerging from the literature, a number of risk factors are evident, including an effect of age and educational status but not gender.[8] Employment status was also linked to wind turbine noise–induced annoyance in one study, possibly due to impeded restoration,[16] but to date, there are no data meaningfully comparing ethnicity or national groups (but see Pedersen et al.[40]). The general public view wind turbines as necessary but ugly,[14] and it is possible that the visual impact of a windfarm can interact with noise level to cause moderate annoyance. This amplification of annoyance is possibly due to a violation of the landscape–soundscape continuum constructed by those who choose to live in areas that later contain windfarms,[41] or alternatively, multisensory engagement may enhance detection and identification of wind turbine noise.[42] The degree of influence of the visual aspects of windfarms has yet to be determined, with laboratory studies suggesting that it is wind turbine noise and not the visual impact that underlies the annoyance response,[41] while epidemiological studies suggest that the visual effects are nontrivial. [40]

**Table 2** Non-acoustical factors influencing the degree of annoyance to noise.

- Perceived predictability of the noise level changing
- Perceived control, either by the individual or others
- Trust and recognition of those managing the noise source
- Voice, the extent to which concerns are listened to
- General attitudes, fear of accidents, and awareness of benefits
- Personal benefits, how one benefits from the noise source
- Compensation, how one is compensated due to noise exposure
- Noise sensitivity
- Home ownership, concern about plummeting house values
- Accessibility to information relating to the noise source

**Source:** From Flin dell and Stallen.[39]

## Wind Turbine Noise and Sleep

The deleterious effects of noise on sleep and the consequences of sleep loss are well documented and are a major concern for governments.[43] In comparison with road, rail, and aircraft noise, there is little research on the effects of wind turbine noise on sleep. However, there is no doubt that wind turbine noise can and does disturb the sleep of those living nearby. Sleep disruption is the predominant symptom in the thousands of anecdotal cases reported in the press and on the Internet and is confirmed by more structured surveys.[25] The quantity, consistency, and ubiquity of complaints has been taken as *prima facie* epidemiological evidence of a causal link between wind turbine noise, sleep disruption, and ill health.[44]

Early investigations into wind turbine noise and sleep are difficult to interpret as researchers used imprecise outcome measures, generally relying on recalled sleep disturbances such as difficulty in initiating or returning to sleep, which tends to underestimate the magnitude of the noise impact and its consequences.[45] One of the earliest studies ($n$ = 128) reported that approximately 16% of respondents living at calculated outdoor turbine noise exposures exceeding 35 dB $L_{Aeq}$ stated that wind turbine noise disturbed their sleep.[7] A New Zealand study of 604 households within 3.5 km of a windfarm found that 42 reported occasional and 26 frequent sleep disturbance.[46] The largest wind turbine noise study to date, "Project WINDFARMperception,"[8] concluded that turbine noise was more of an annoyance at night and that interrupted sleep and difficulty in returning to sleep increased with both indoor and outdoor calculated noise levels. Even at the lowest noise levels, 20% of 725 respondents reported disturbed sleep at least one night per month. In a meta-analysis[40,47] of three European datasets ($n$ = 1764),[7,8,16] there was a clear increase in levels of sleep disturbance with dB $L_{Aeq}$ in two of the three studies. In one study, an increment in self-report sleep disturbance occurred between 35 and 40 dBA, while in the other, it occurred between 40 and 45 dBA.

More recent research into wind turbine noise and sleep includes two studies reported by Nissenbaum, Aramini, and Hanning.[48] In the first, a pilot study, a structured questionnaire was administered to 22 subjects living 370 to 1100 m from twenty-eight 1.5mW turbines and a control group ($n$ = 28) living at least 4.5 km from the nearest turbine. The study group had clinically and statistically worse sleep disturbance, headache, vestibular symptoms, and psychiatric symptomatology. The second study, using validated questionnaires, administered the Pittsburgh Sleep Quality Index (PSQI), Epworth Sleepiness Score (ESS), and Short-form health survey (SF36) to 79 subjects living between 375 and 6600 m from two windfarms. Those living within 375–1400 m reported worse sleep, were sleepier, and had worse SF36 mental summary scores than those between 3 and 6.6 km from a turbine. Psychiatric symptom scores (irritability, stress, anger, hopelessness, and anxiety) were significantly greater, as was a composite mental health score. They were also more likely to report headaches, nausea (31.6% vs. 12.2%), and a willingness to move away. Modeled dose–response curves of both sleep and health scores against distance from nearest turbine (Fig. 6a–c) were significantly related after controlling for gender, age, and household clustering. There was a sharp increase in effects between 1 and 2 km. This study is the first to use appropriate sleep outcome measures[45] and to use a control group. While the sample size is modest ($n = 78$), it is convincing evidence that wind turbine noise adversely affects sleep and health for those living within 1.5 km of turbines.

Mechanisms explaining the effects of wind turbine noise on sleep have been considered, but would benefit from further empirical support.[45] Noise of any description can interfere with sleep by preventing the onset of sleep either at sleep initiation or at the return to sleep after a spontaneous or induced awakening. The amplitude, character, and associations of the noise are all important as is the noise sensitivity of the individual and the psychological response to the noise. In this respect, wind turbine noise seems to be particularly annoying, possessing an impulsive nature with short bursts of low-frequency sound, making it audible 10–15 dBA below background level.[38,49] Nocturnal atmospheric stability ensures that wind turbine noise is maintained while ground level ambient noise diminishes. Indoor noise levels for most noise sources can be reduced by closing windows; however, the low-frequency content of wind turbine noise means that it may be more audible indoors than outdoors. Additionally, during warmer months, windows are more likely to stay open to control thermal parameters, whence the inability to control or modify wind turbine noise will contribute to the annoyance and, presumably, the effect on sleep onset.[16]

Noise may also cause awakenings and arousals. Arousal is a brief lightening of sleep that is not recalled. Sleep becomes fragmented and, if enough arousals occur, induces the same consequences as reduction of total sleep time. Awakenings are arousals of sufficient degree for wakefulness to be reached and long enough (greater than 10 sec) to be recalled. Arousals are more likely than awakenings,

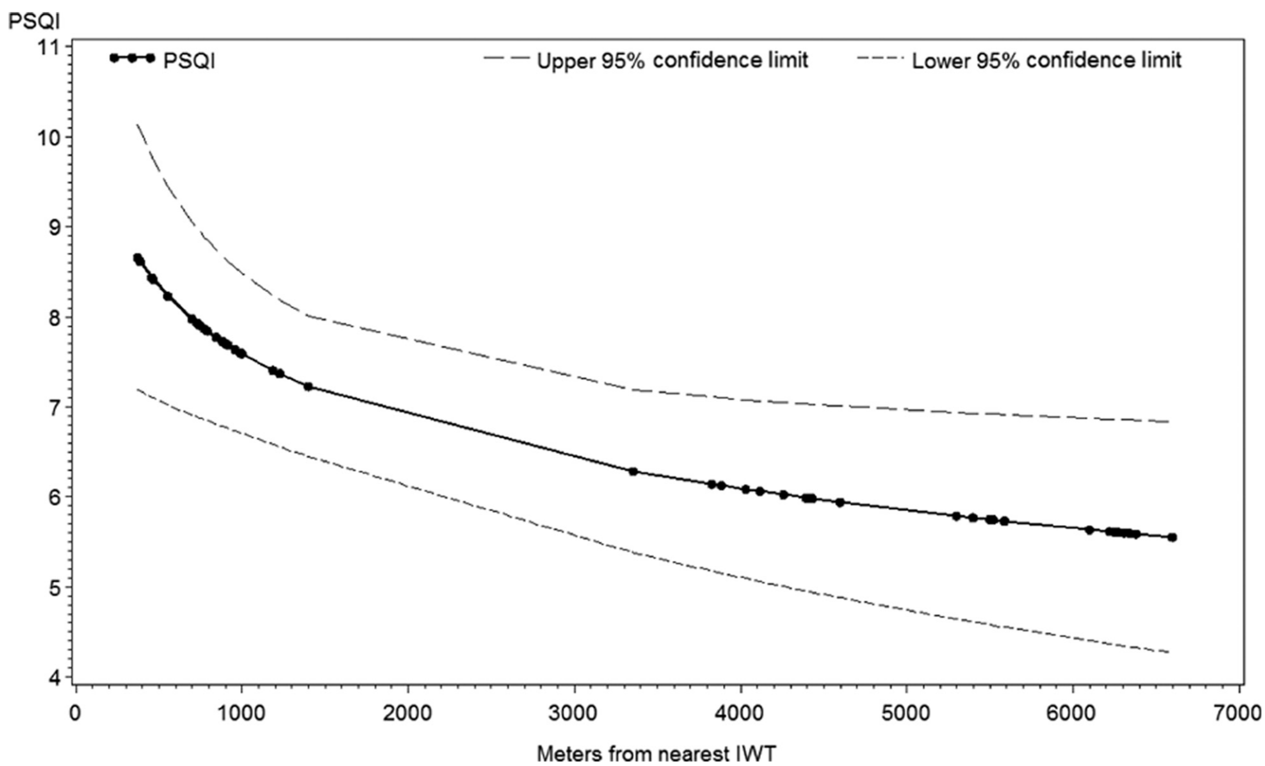


**Fig. 6a** Mean Pittsburgh Sleep Quality Index (PSQI) scores as a function of setback distance. The dashed lines are 95% confidence intervals.
**Source:** From Nissenbaum, Aramini, and Hanning.[48]

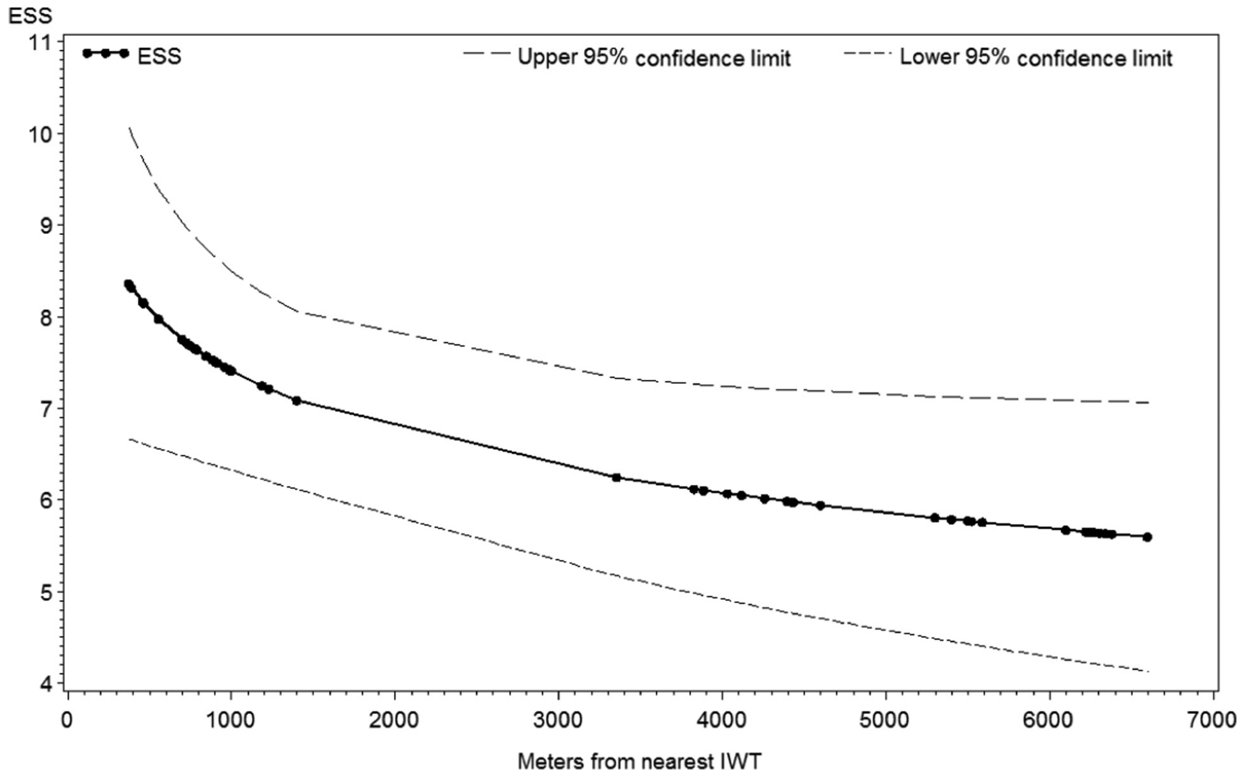


**Fig. 6b** Mean Epworth Sleepiness Scale (ESS) scores as a function of setback distance. The dashed lines are 95% confidence intervals. **Source:** From Nissenbaum, Aramini, and Hanning.[48]

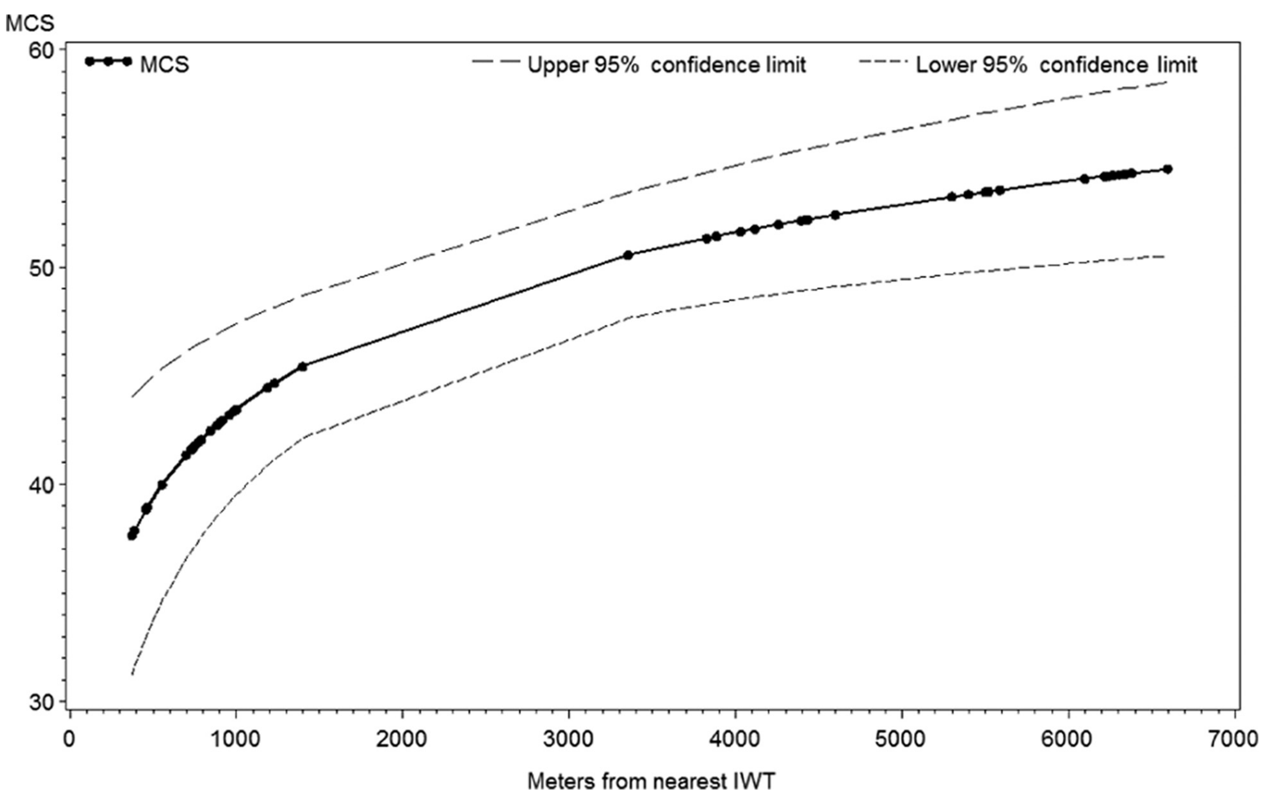


**Fig. 6c** Mean SF36 mental component score (MCS) as a function of setback distance. The dashed lines are 95% confidence intervals. **Source:** From Nissenbaum, Aramini, and Hanning.[48]

and thus, relying on reported awakenings underestimates the magnitude of the noise effects. The likelihood of an arousal depends upon the volume, character, and duration of the noise as well as the sleep stage and individual propensity (i.e., noise sensitivity). In an investigation into hospital noise, dose–response curves were created for different noises in different sleep stages.[50] Noises with characteristics designed to alert (e.g., telephone, alarms) were more likely to arouse. These noises tend to be impulsive in character, as does wind turbine noise. Noises that were classified as continuous broadband noises (e.g., traffic noise) were less likely to arouse. Another study[51] has shown that subjects with fewer sleep spindles (electrophysiological markers characteristic of stage II sleep) are more easily aroused by noise (Fig. 7). Sleep spindles are taken as a marker of sleep stability and may provide a physiological marker of sleep quality.

To date, there are no electrophysiological studies of wind turbine noise on sleep. However, it is reasonable to expect that, in common with road, rail, and aircraft noise, it will induce arousals, fragmenting sleep, as well as preventing the onset of and return to sleep. The sleep measures used in the study by Nissenbaum, Aramini, and Hanning[48] (i.e., ESS and PSQI) are average scores, determining sleepiness and sleep quality, respectively, over a period of weeks. Thus, occasional sleep disturbance would not alter scores as the sleep loss would have been compensated quickly over one or two nights. The study results imply strongly that sleep was being disturbed to some degree on sufficient nights to prevent compensation occurring, thus leading to persistent daytime symptoms.

## Wind Turbine Syndrome

Wind turbine syndrome refers to a cluster of symptoms, which Pierpont,[24] who coined the phrase, claims are associated with exposure to wind turbine noise. Using direct clinical case studies, Pierpont describes the following symptoms to be characteristic of many individuals residing in close vicinity of wind turbines: insomnia, headaches, dizziness, unsteadiness, nausea, exhaustion, anxiety, anger, irritability, depression, memory loss, eye problems, problems with concentration and learning, and tinnitus. Pierpont hypothesizes that wind turbines may affect the vestibular system, that part of the inner ear that plays an important role in the maintenance of balance and stable visual perception. Wind turbines may compromise this system in two ways: first, by the visual disturbance of the moving blades and shadows (i.e., the flicker), and second, by direct vibration of the vestibular system. Such a model would explain why some residents in the close proximity of wind turbines (i.e., less than a kilometer) complain of vertigo, dizziness with nausea, and migraines. Wind turbine syndrome awaits further validation from the medical and scientific establishments, specifically the confirmation of a cause-and-effect relationship between wind turbine noise and vestibular function.

## Wind Turbine Noise and Low-Frequency/ Infrasound Components

Recent enquiry has focused on the impacts of low-frequency (20–200 Hz) and infrasonic frequencies (typically taken as

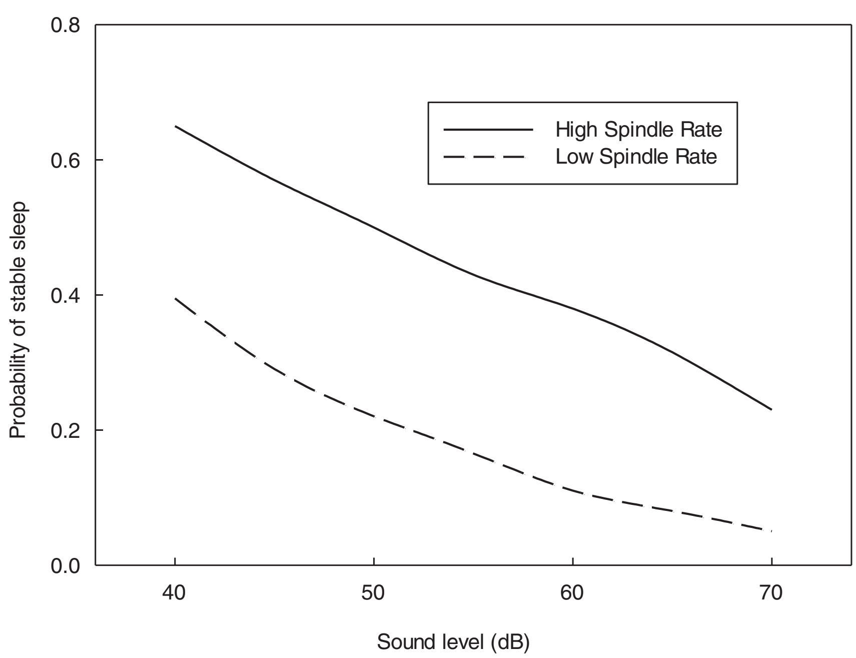


**Fig. 7** Sleep stability as a function of sound level for noise-resistant (high-spindle) and noise-sensitive (low-spindle) groupings. **Source:** Estimated from Dang-Vu et al.[51]

below 20 Hz) being emitted by wind turbines. Infrasound is characterized by fluctuating pressure sensations at the eardrum, is atonal and countable, and is of a level proportional to wind speed.[21] Low-frequency acoustic waves emitted by wind turbines may be amplified by ground reflection and originate from varying lift forces as the rotors travel through spaces differing in wind speed and density.[21] Compared with medium (i.e., 250 to 4000 Hz) and high frequencies (above 4000 Hz), low-frequency energy decays slowly with distance, is less attenuated by conventionally designed structures, causes certain building materials to vibrate, and can sometimes resonate within rooms and undergo amplification. The effect of air absorption must also be taken into account, in which higher frequencies are attenuated at a greater rate as a function of distance, resulting in a shifting of the spectrum toward lower frequencies. The relationship between low-frequency wind turbine noise and building type creates an interesting proposition in which the low-frequency sound may be louder inside a dwelling than out,[21,52] and the assumption that walls and windows attenuate sound by 15 dB may not be applicable to frequencies below 200 Hz.

Research has shown that low-frequency noise increases cortisol levels in those who are sensitive to noise[12] and disturbs rest and sleep at levels below noise otherwise free from lower-frequency components.[31] Low-frequency noise and infrasound are known disturbers of sleep; however, the contribution, if any, of the low-frequency noise emissions of wind turbines to the sleep disturbances they induce remains to be scientifically determined. Beyond infrasound, the phenomenon of vibroacoustic disease is worthy of note. Humans chronically exposed to infrasound may exhibit elevated cortisol levels and generalized cell damage: a condition known as vibroacoustic disease.[53] A number of human and animal models explaining how infrasound can lead to cardiovascular and respiratory disease have been proposed[54] and applied to wind turbine noise.[55] The phenomenon of vibroacoustic disease is supported by correlational evidence coupled with a thoroughly detailed mechanism. However, further research is required to establish the veracity of this approach to human health within and beyond the wind turbine context.

## MITIGATION

There are multiple ways in which to reduce the impacts of audible and inaudible wind turbine noise. The first, and often the most effective, method is to control audible noise at the sound source. Thus, mechanical solutions invite technologies designed to attenuate wind turbine noise or to shift its spectral character in order to eliminate salient tonal characteristics. To safeguard health is more difficult, however, because wind turbine noise is largely aerodynamic in origin,[7] and it is not possible to obtain solutions that completely attenuate the noise at its source. Having minimized the noise through the implementation of technology, other approaches are often required, normally involving the application of noise standards to limit exposure levels or the determination of "safe" setback distances to mitigate noise impact. Still other approaches involve the positioning of wind turbines around preexisting noise generators,[15] in remote areas away from human habitations, or using social processes to determine wind turbine location.[27,56]

### Regulating Permissible Noise Level

Permissible or safe exposure levels are often set in national noise standards, which may or may not be specific to wind turbine noise. These standards may serve one of two purposes, or sometimes both, with noise compliance guidelines naturally emerging from the two. The first purpose relates to methodologies for the physical quantification of the noise. This may involve standardized procedures for measuring noise from preexisting windfarms or detailing accepted mathematical models affording noise predictions of a planned windfarm. The second purpose is to determine what exposure levels can be considered safe and to clearly state criteria to this effect. However, there are a number of flaws inherent in wind turbine noise standards, including the metrics used to represent the noise, oversimplified modeling approaches that yield unrealistically low predictions of noise levels representing "best case" conditions,[5] or stimulus-oriented approaches that fail to account for human factors.[3,57]

There exists, in respect to levels-based noise standards, disagreement as to the relevance of physical measures such as dBA to human response,[58] not only for windfarm noise (Pedersen, 2008b) but also for traffic and aviation noise. Of the few parametric studies that have been published,[7,8] only marginal dose–response relationships between wind turbine noise intensity and health measures have emerged. For example, Pedersen[22] noted that stress was not related to wind turbine noise level but rather noise annoyance. Persson Waye and Öhtrsöm[12] reported that annoyance ratings varied for five distinct recordings of wind turbine noise, even though all five had equivalent noise levels. Others note that both laboratory and field studies have consistently found that the equivalent dBA measure fails to account for the relationship between wind turbine noise and annoyance.[14]

To some degree, then, it must be accepted that there is an uncoupling between wind turbine noise level and human response. A hitherto rarely measured characteristic of wind turbine noise is amplitude modulation, whereby noise levels fluctuate periodically as a function of blade passing frequency. Lee et al.[34] recommend that standardized metrics based on the modulation depth spectrum be developed and used in conjunction with sound levels. Other approaches to measuring amplitude modulation have existed for some time[4,59] but have yet to be seriously applied to the wind turbine noise context. However, the inability to account for amplitude modulation arises primarily due to the time-averaged dBA levels applied by noise standards, and arguably, smaller sampling epochs of around 100 msec should be adopted as best practice in order to record the amplitude modulation inherent in turbine noise.[60,61] The New Zealand Standard[62] applies a penalty for amplitude modulation, but does not describe an objective assessment. Furthermore, using aggregated metrics that average noise level over long periods underestimates the effect of peak levels and crest factors, important when considering sleep disturbance.

For the most part, the acceptable noise limits recommended by noise standards are derived from WHO guidelines.[31,63,64] However, as Fig. 8 demonstrates, using recommended noise levels from guidelines based on transport data risks exposing the population to unacceptable levels of noise. It follows that the Ldn (the "day–night" level in the United States) or Lden (the "day–evening–night" level in Europe) measures, derived from the measured $L_{Aeq}$ sound level can be used in a wind farm context, but with caution.[65] Inspection of Fig. 8 suggests that, relative to transport guidelines, at least a 10 dBA penalty should be placed on wind turbine noise. The differences in annoyance ratings between wind turbine noise and transport noise maybe accounted for by amplitude modulation, the typical location of windfarms (e.g., rural areas), or the over-representation of noise-sensitive individuals. A recent meta-analysis of three epidemiological studies revealed a consistent trend in wind turbine noise exposure and both annoyance and sleep disruption.[22] On the basis of her analysis, Pederson recommends that outdoor levels should not exceed 40 dBA, though this level could be more-or-less depending on situational factors, that is, ambient noise levels or the building's construction materials. When noise is continuous, the WHO[31] stipulates an indoor limit of 30 dBA, though for noises containing lower frequencies (e.g., wind turbine noise), a lower limit still is recommended. Thus, careful examination of the lower end of the frequency spectrum is important when judging appropriate exposure to wind turbine noise, and the use of dBC or spectral analysis in one-third octave bands or narrow bands is necessary.

In the comparison of global wind turbine noise level standards, there exist two chief methodologies, namely, sound levels not to be exceeded (usually in dBA) or a not-to-be-exceeded limit derived from the sum of the preconstruction ambient limit and a constant (e.g., $L_{A90}$+10 dBA). Critique of both these approaches can be found in Thorne.[3] The fact that noise limits differ between, and even within, a country is testament to the impoverished research database guiding their development or the political sensitivities around wind turbine placement. Examples of noise limits are presented in Table 3, and the variability in guidelines is evident. Based on the authors' collective experience, an interim guideline, providing a conservative noise limit capable of protecting the health of the public and suscep-

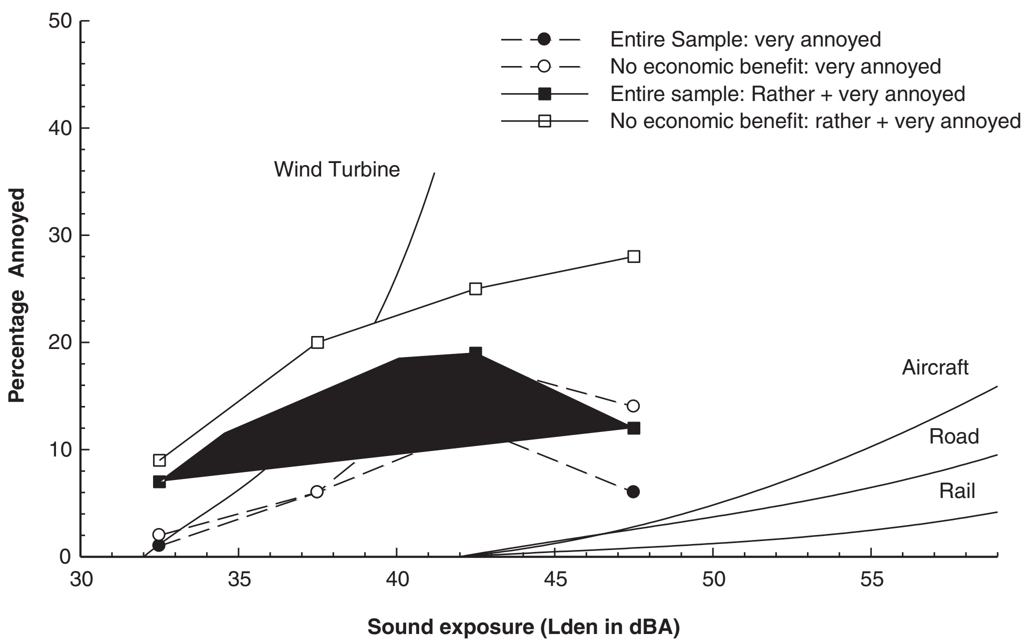


**Fig. 8** Annoyance plotted as a function of noise level for four theoretical models (rail, road, and air parameters: Miedema and Oudshoorm;[66] wind turbine parameters: Pedersen et al.;[7] and four sets of data obtained from Tables 7.24–7.26 of van den Berg et al.[8]). For the data, closed symbols are for the entire sample, while open symbols are for those who identified that they had no economic interest. Circles represent the percentage of "very annoyed" responses, while squares represent the sum of "very annoyed" and "rather annoyed" responses.

**Table 3** A comparison of wind turbine noise guidelines taken from nine countries.

| Country | State | Limit (dBA) | Background plus constant |
|---|---|---|---|
| Australia | Victoria | $L_{A90}$ 35 or 40 | $L_{A90}$ + 5 dBA |
| | South Australia | $L_{Aeq}$ 35 or 40 | $L_{A90}$ + 5 dBA |
| Australia | Queensland | $L_{Aeq}$ 30 indoors | Health and well-being criteria |
| Canada | Ontario | $L_{Aeq}$ 40 to 51 | |
| Denmark | | 40 | |
| France | | | Day: $L_{A90}$ + 5 dBA<br>Night: $L_{A90}$ + 3 dBA |
| Netherlands | | 40 | |
| New Zealand | | $L_{A90}$ 35, 40 | $L_{A90}$ + 5 dBA |
| United Kingdom | | Day: 40<br>Night: 43 | $L_{A90}$ + 5 dBA |
| United States | Illinois | Day: 50<br>Night: 46 | |
| | Michigan | 55 | |
| | Oregon | 35 | |

tible individuals, would be a sound level of $L_{Aeq}$ 35 dBA outside the residence and below the individual's threshold of hearing inside a residence. More specific guidelines are presented in Appendix A of this document.

### Regulating Setback Distances

A setback distance is defined as the minimum distance between a dwelling and the closest wind turbine required to protect the health of the inhabitants. One difficulty is whether such setback distances can be standardized, as they will differ depending on a number of factors, including turbine type, terrain, and climate. Lee et al.[34] report that the perception of amplitude-modulated noise decreases with distances beyond a kilometer, though others claim that amplitude-modulated turbine noise can be heard up to 4 km away from the source.[67] Setback distances maybe based on noise level, which, as discussed in the preceding section, maybe an invalid approach. Instead, a better approach may be to link setbacks to turbine type. Møller and Pedersen,[21] investigating the detection and annoyance of lower-frequency sound emitted from wind turbines, suggest that, for flat terrain, the minimum setback distance for modern turbines (2 to 3.6 MW) should be between 600 and 1200 metres. Other approaches rely on the establishment of dose–response curves relating a health outcome variable (e.g., annoyance or disturbed sleep) and distance (e.g., Fig. 6). Medical professionals have proposed setback distances of 2.4 km[23,24] or 1.5 km.[45] Other research recommends a minimum of 2 km if wind turbines are sited in rough terrain.[3,20]

## CONCLUSION

Windfarms have significant potential for sleep disruption and annoyance due to the intermittent nature and amplitude modulation of their sound emissions, even though exposure may be of low amplitude. The interactions between ambient levels, amplitude modulation, and the tonal character of windfarm noise overlaid within a soundscape are complex and difficult to measure and assess in terms of health and individual amenity. Additionally, currently employed sound level measurement and prediction approaches for complex noise sources of this nature are only partially relevant to environmental risk assessment. Aside from acoustic parameters, other factors such as noise sensitivity or amenity expectations may also predict the human response to wind turbine noise. Unfortunately then, for policymakers, there appears to be no proportional relationship between wind turbine noise levels and health, as these outcome factors will be influenced by characteristics associated with both the noise and the listener.[39]

As a relatively new source of intrusive noise, there is little research to draw upon when judging if a proposed windfarm constitutes a health threat to the exposed public. A liberal approach to assessing health impact will involve the application of previous knowledge obtained from other noise sources (e.g., road, aviation). A conservative approach, consistent with the precautionary principle, will consider wind turbine noise more potent than these other harmful noise sources. Thus, at this time, a constellation of acoustic and social metrics should be taken at preexisting wind farms in order to assess potential threat. Peak and crest noise levels, level metrics assessing low-frequency contributions (e.g., dBC), and amplitude modulation indices constitute the acoustic measures of importance. It should also be remembered that predicted levels derived from computer models represent estimates and not precise values, are constrained by numerous assumptions, contain substantial uncertainty, and as such should not constitute the sole criteria for wind turbine positioning. What form the social measures will take is yet to be elucidated, but research suggests that noise sensitivity[67] and procedural fairness[27] are the best approaches to minimize the health impacts and facilitate social acceptance of windfarms.

## ACKNOWLEDGMENTS

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## APPENDIX A

'Proposed Wind Turbine Siting Sound Limits', a revision by Thorne, R, of the Kamperman James criteria (2008) to include updates to ISO 1996-2 and UK Court of Appeal (Hulme re: Den Brook).

1. Audible Sound Limit
   - **a.** No wind turbine or group of turbines shall be located so as to cause an exceedance of the pre-construction/operation background sound levels by more than 5 dBA. The background sound levels shall be the $L_{A90}$ sound descriptor measured during a pre-construction noise study during the quietest time of evening or night. All data recording shall be a series of contiguous ten (10) minute measurements. $L_{A90}$ results are valid when $L_{A10}$ results are no more than 15 dBA above $L_{A90}$ for the same time period. Noise sensitive sites are to be selected based on wind development's predicted worst-case sound emissions in $L_{Aeq}$ and $L_{Ceq}$ which are to be provided by the developer.
   - **b.** Test sites are to be located along the property line(s) of the receiving non-participating property(s).
   - **c.** A 5 dB penalty is applied for tones as defined in IEC 61400-11 at the turbine and ISO1996-2 at any affected residence.
   - **d.** A 5 dB penalty is applied for amplitude modulation as defined following. When noise from the wind farm has perceptible or audible characteristics that are perceived by the complainant as being cause for complaint, or greater than expected, the measured sound level of the source shall have a 5 dB penalty added. Audible characteristics include tonal character measured as amplitude or frequency modulation (or both); and tonality (where the tonal character/tonality of noise is described as noise with perceptible and definite pitch or tone). Amplitude modulation is the modulation of the level of broadband noise emitted by a turbine at blade passing frequency. Amplitude modulation will be deemed greater than expected if the following characteristics apply:
     - **i)** A change in the measured $L_{Aeq}$, 125 ms turbine noise level of more than 3 dB (represented as a rise and fall in sound energy levels each of more than 3 dB) occurring within a 2 second period.
     - **ii)** The change identified in (i) above shall not occur less than 5 times in any one minute period provided the $L_{Aeq}$, 1 minute turbine sound energy for that minute is not below 28 dB.
     - **iii)** The changes identified in (i) and (ii) above shall not occur for fewer than 6 minutes in any hour.

Noise emissions are measured outside a complainant's dwelling and shall be measured not further than 35 metres from the relevant building, and not closer than within 3.5 metres of any reflective building or surface, or within 1.2 metres of the ground.

2. Low Frequency Sound Limit
   - **a.** The $L_{Ceq}$ and $L_{C90}$ sound levels from the wind turbine at the receiving property shall not exceed the lower of either:
     - **i)** $L_{Ceq}$ -$L_{A90}$ greater than 20 dB outside any occupied structure, or
     - **ii)** A maximum not-to-exceed sound level of 50 dBC measured as the background sound level ($L_{C90}$) from the wind turbines without other ambient sounds for properties located at one mile or more from State Highways or other major roads or measured as the background sound level ($L_{C90}$) for properties closer than one mile.
     - **iii)** These limits shall be assessed using the same night-time and wind/weather conditions required in 1(a). Turbine operating sound emissions ($L_{Aeq}$ and $L_{Ceq}$) shall represent worst case sound emissions for stable night-time conditions with low winds at ground level and winds sufficient for full operating capacity at the hub.

3. General Clause
   - **a.** Sound levels from the activity of any wind turbine or combination of turbines shall not exceed $L_{Aeq}$ 35 dB within 100 feet of any noise sensitive premises.
   - **b.** The monitoring shall include all the sound levels as required by these noise conditions and shall include monitoring for the characteristics described in Annex A of IEC 61400-11including infrasound, low-frequency noise, impulsivity, low-frequency modulation of broad-band or tonal noise, and other audible characteristics. Wind speed and wind direction shall be measured at the same location as the noise monitoring location.

4. Requirements
   - **a.** All instruments must meet ANSI or IEC Class 1 integrating sound level meter performance specifications.
   - **b.** Procedures must meet ANSI S12.9, IEC61400-11 and ISO1996-2
   - **c.** Procedures should meet ANSI, IEC and ISO standards applicable to the measurement of sound or its characteristics.
   - **d.** Measurements must be made when ground level winds are 2m/s (4.5 mph) or less. Wind shear in the evening and night often results in low ground level wind speed and nominal operating wind speeds at wind turbine hub heights.

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**e.** IEC 61400-11 procedures are not suitable for enforcement of these requirements except for the presence of tones near the turbine.

5. Definitions
   ANSI S12.9 Quantities and Procedures for Description and Measurement of Environmental Sound, Parts 1 to 6.
   IEC 61400-11 *Wind turbine generator systems—Part 11: Acoustic noise measurement techniques.*
   ISO 1996-2 *Acoustics—Description, measurement and assessment of environmental noise—Part 2: Determination of environmental noise levels*.
   $L_{A90}$, $L_{A10}$ Statistical measures calculated under ANSI S12.9.
   $L_{Aeq}$, $L_{Ceq}$ Time average levels calculated under ANSI S12.9 or ISO 1996-2.
   Noise sensitive premises includes a residence, hotel, hostel or residential accommodation premises of any type.

6. References
   ANSI S12.9-2008, Quantities and Procedures for Description and Measurement of Environmental Sound—Part 6: Methods for Estimation of Awakenings Associated with Outdoor Noise Events Heard in Homes, 2008.
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   IEC 61400-11Wind Turbine Generator Systems—Part 11: Acoustic Noise Measurement Techniques, 2nd ed. (International Technical Commission, Geneva, 2002 plus Amendment 1 2006).
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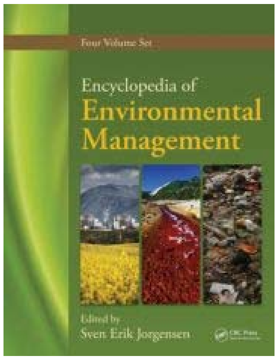


# Encyclopedia of Environmental Management (Print Version)

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- Covers current problems associated with nanotechnology, applications of GMOs, and climate change
- Presents not only an overview of the problems, but also tools to help identify, diagnose, and solve them
- Proposes solutions using the tool boxes of environmental technology, ecological technology, cleaner technology, and environmental legislation
- Includes a topical table of contents that lets readers quickly search for entries by the type of environment problem and methodology they are interested in
- Provides in-depth insights from more than 500 top experts in their fields
- Includes extensive references to guide readers who want more information

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- What is the "big picture," or what background knowledge do we need?
- How can we diagnose the problem, both qualitatively and quantitatively, using monitoring and ecological models, indicators, and services?
- How can we solve the problem with environmental technology, ecotechnology, cleaner technology, and environmental legislation?
- How do we address the problem as part of an integrated management strategy?

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