Wind turbines: is there a human health risk?

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Introduction

Humans have been using wind power since 500-900 A.D. when the first windmills were developed in Persia (Dodge, 2006). Wind, a form of solar energy, is altered in its flow pattern by the earth's land and water surfaces. Through these flow patterns, humans have developed highly sophisticated techniques and machinery to harness wind energy for several purposes such as sailing, pumping water, cutting lumber, and even generating electricity. One such machine is the wind turbine, which is a rotary device that extracts and converts the kinetic energy from the wind into mechanical power and then transforms this power into electricity through the use of a generator.

In the 2011 State of the Union address, President Obama set a new goal for America's energy future and stated that 80% of electricity should come from clean energy sources by 2035, including wind energy. As the use of wind energy and the emphasis on renewable energy have continued to grow, concerns have been raised regarding the impacts of these wind turbines on human health and well-being.

Wind Turbine Trends in the U.S.

By the end of 2011, the U.S. had over 46,900 megawatts (MW) of installed wind power, yet wind power accounts for less than 3% of the country's total net electric generation (U.S. Energy Information Administration [EIA], 2011a, 2011b, 2011c, 2011d). According to the American Wind Energy Association (AWEA), a 35% increase in new wind power capacity occurred over the past five years (AWEA, 2011, 2012). And at the end of 2011, it was also determined that 38 states had utility-scale wind installations with 14 of those having more than 1,000 MW of wind power capacity (AWEA, 2011, 2012). Furthermore, the top five states with the highest number of wind project installations through the first quarter of 2012 were Texas (10,648 MW); Iowa (4,419 MW); California (4,287 MW); Illinois (2,852 MW); and Minnesota (2,718 MW) (AWEA, 2012; EIA, 2011b, 2011d). As of today, the U.S. represents more than 20% of the world's installed wind power (AWEA, 2012).

For several years, wind energy has been the fastest growing source of new electric power generation (EIA, 2011b). Compared to the prior year, in 2006, 2007, 2008, 2009, and 2010 the generation from wind power increased by 49.3%, 29.6%, 60.7%, 33.5%, and 28.1%, respectively (Figure 1) (EIA, 2011b). The current wind energy capacity in the U.S. has generated enough electricity to power the equivalent of nine million homes (EIA, 2011a). And since 1999 the wind power in the U.S. has increased exponentially from 2,472 to 46,918 MW in 2011 with GE Energy being the largest domestic wind turbine manufacturer (AWEA, 2009; EIA, 2011d).

Typically in the U.S., small turbines have been used to power a single home or business and larger turbines have often been grouped into wind farms that can provide power to the electrical grid. The smaller wind turbines have a capacity of less than 100 kilowatts while larger commercial sized turbines may have a capacity of 5 MW.

Sound and Human Perception

The two components of sound, which allow for its perception and recognition, are frequency and pressure. The indicator of pressure or loudness is the decibel (dB), which is a logarithmic ratio of sound pressure level to a reference level. Likewise, the frequency or pitch of sound is expressed in Hertz (Hz), a unit defined as the number of cycles per second.

Human hearing of sound loudness ranges between 0 dB, a threshold of sound for humans, and 140 dB, a sound level that is very loud and painful for most humans (Baker & National Agricultural Safety Database, 1993; Navy and Marine Corps Public Health Center, 2009). Sound pressures are not all perceived as being equally loud by the human ear. This is because the human ear does not respond equally to all frequencies and the perception is less sensitive to lower and higher frequency sounds. For young individuals, the frequency range of human hearing has been found to be between 20 and 20,000 Hz with an inverse relationship between the upper frequency range and age (Berglund, Hassmen, & Job, 1996). Again, since the human ear does not have a flat spectral sensitivity or frequency response, sound pressures have regularly been frequency weighted so that the measured level corresponds to loudness as perceived by the average human ear.

Several weighting networks, such as A-weighting or C-weighting, have been defined by the International Electrotechnical Commission (IEC) in the IEC 60651 and American National Standards Institute (ANSI S1.1-1994) standards (British Wind Energy Association [BWEA], 2005; Hansen & World Health Organization [WHO], 1995). These networks filter the contributions of the varying frequencies to the overall sound level by reducing or increasing the sound pressure as a function of frequency (Hansen & WHO, 1995). Thus, A-weighting, labeled dB(A), approximates the response of the human ear to moderate sound levels and has been the most commonly used network (BWEA, 2005). C-weighting (dB[C]) is used to measure peak levels and G-weighting (dB[G]) is specifically designed for infrasound (BWEA, 2005).

Ultrasound or sound frequencies above 20,000 Hz and infrasound, which is approximately between 0 and 20 Hz, are generally considered to be inaudible (Berglund et al., 1996). Low frequency sound (LFS) in the range of 10-20 Hz and 100-250 Hz includes a field of audibility (Table 1) (Berglund et al., 1996; Leventhall, 2007). The audibility of LFS is often dependent on the individual. Furthermore, in order for infrasound to be audible at frequencies lower than 20 Hz, a very high-pressure level is required. Infrasound detection by the human ear has been theorized to result from nonlinearities of conduction in the middle and inner ear, which produces a harmonic distortion in the higher frequency range in addition to subjective reactions and through the resonance of other body organs (Berglund et al., 1996).

Wind Turbine Sound

One type of sound generated from wind turbines is a mechanical sound, which originates from the mechanical components of the turbines (e.g., gearbox). Aerodynamic sound is the other type of sound; the source of this sound is the flow of air around the blades and tower that produces a "whooshing" sound in the range of 500 to 1000 Hz (Hau, 2006). Manufacturers have improved the engineering of wind turbines and have been able to reduce the mechanical sound. Thus, the aerodynamic sound is now typically the dominant component of wind turbine sound (Pedersen & Waye, 2004; Rogers, Manwell, Wright, & Renewable Energy Research Laboratory, 2006). A great deal of variability exists in the whooshing sound, which is dependent upon mechanical and atmospheric conditions.

Many of the modern wind turbines are now upwind and the size of the turbine is variable. The earlier turbines were often downwind devices with the blades and rotor positioned on the downwind side of the tower. LFS with a range of 20 to 100 Hz was most commonly produced by downwind turbines when the turbine blade encountered localized flow deficiencies due to the flow around a tower (Rogers et al., 2006). The new upwind turbines minimize LFS and infrasound (Musial, Ram, & National Renewable Energy Laboratory, 2010; Szasz & Fuchs, 2010).

Wind Turbine Syndrome

"Wind Turbine Syndrome: A Report on a Natural Experiment" was self-published in late 2009 by Nina Pierpont, MD, PhD, a pediatrician, who coined the term "Wind Turbine Syndrome." In the book, Dr. Pierpont theorized how a multitude of symptoms such as headache and dizziness resulted from wind turbines generating LFS that "scrambled" the body's balance, motion, and position sensors. The reported symptoms, gathered from a case series study design, were based on a collection of subjective responses from 37 participants (age <1 to 75 years) comprised from 10 families who resided (1,000 to 4,900 ft.) near wind turbines erected since 2004 in Canada, Ireland, the United Kingdom, Italy, and the U.S. The study participants, who were not masked from the purpose of the study, were interviewed by telephone by Dr. Pierpont to collect a narrative account, symptom checklist, and past medical history (Pierpont, 2009). Accordingly, this "Wind Turbine Syndrome" phenomenon has instigated a heightened level of panic and fear with respect to living near wind turbines.

The purpose of our article is to provide a summary of the peer-reviewed literature on the research that has examined the relationship between human health effects and exposure to sound in the lower frequency range as well as sound generated from the operation of wind turbines. An objective of this review is to infer conclusions through weighing the evidence from this research about the theory of "Wind Turbine Syndrome" and this possible association.

Methods

In 2009, we were commissioned to write a white paper by the Wisconsin Public Service Commission on the scientific literature regarding health effects associated with wind turbines and LFS (Roberts & Roberts, 2009). This article expounds on the research of that white paper and further examines the currently available research in the peer-reviewed literature that addresses the possible association between human health effects and LFS or noise generated by wind turbines. The PubMed search engine, maintained by the U.S. National Library of Medicine, was the source of this peer-reviewed literature and the search terms used were as follows: (1) "Infrasound AND Health Effects"; (2) "Low-Frequency Noise AND Health Effects"; (3) "Low-Frequency Sound AND Health Effects"; (4) "Wind Power AND Noise"; (5) "Wind Turbines"; (6) "Wind Turbines AND Noise."

It should be noted that the word "sound" and "noise" are terms that can be used interchangeably. "Noise" often implies an unwanted sound and often depends on the intensity of the sound. The classification of a "sound" or "noise" may also depend on cultural factors, the receiver, or the time and circumstance (Berglund et al., 1996). Likewise, both terms were used as search criteria for this research review.

Results

When this literature search was conducted, 16, 59, 40, 18, 20, and 3 articles using the "Infrasound AND Health Effects"; "Low-Frequency Noise AND Health Effects"; "Low-Frequency Sound AND Health Effects"; "Wind Power AND Noise"; "Wind Turbines"; and "Wind Turbines AND Noise" search terms were identified, respectively. A portion of these search results contained overlapping articles and many of the articles in the search output were not relevant because they focused on animal and not human responses or the sound studied was above the established range of LFS. Likewise, of the original 156 articles, nearly 30 articles (n = 28) were identified that addressed any human health effects associated with LFS and that were relevant to wind sound using the previously mentioned search terms.

Research on Human Health Effects and LFS

LFS is often accompanied by vibrations (Maschke, 2004). High levels of LFS, at a frequency of 50 to 80 Hz, can excite body vibrations (e.g., chest resonance vibration) (Leventhall, 2007). Additionally, these chest wall and body hair vibrations have also been shown to occur in the infrasonic range (Mohr, Cole, Guild, & Vongierke, 1965; Schust, 2004). A human tendency often occurs to confuse vibration with sound on its own, which results in people "hearing" more sound than is actually present. Likewise the reverse has been shown to occur as evident by the association found between motion sickness and LFS even without accompanying vibration (Berglund et al., 1996; Yamada, Sueki, Ha giwara, Watanabe, & Kosaka, 1991).

Castelo Branco and Rodriguez first documented vibroacoustic disease among airplane technicians, commercial and military pilots, mechanical engineers, restaurant workers, and disc jockeys for exposure to large pressure amplitude and low frequency sound ([greater than or equal to] 90 dB sound pressure level, [less than or equal to] 500 Hz) (Castelo Branco & Rodriguez, 1999; Maschke, 2004). Vibroacoustic disease was described as a thickening of cardiovascular structures, such as cardiac muscle and blood vessels. Castelo Branco and Rodriguez revealed that workers who were exposed to high-level LFS for more than 10 years exhibited extra-aural symptoms (Castelo Branco & Rodriguez, 1999; Maschke, 2004; Takahashi, Yonekawa, & Kanada, 2001). A causal association and a dose response relationship were not established.

Takahashi and co-authors have explored the effects of both human body vibration and LFS (Takahashi et al., 2001; Takahashi, Kanada, Yonekawa, & Harada, 2005; Takahashi, Yonekawa, Kanada, & Maeda, 1999). In a small study, six male subjects were exposed to pure tones in the 20 to 50 Hz frequency range, and vibration was measured on the chest and abdomen of the subjects. It was determined that sound-induced vibration was inversely correlated with the body mass index of the subject. Takahashi and co-authors concluded that the health effects of LFS depended on the physical constitution of the human body, yet it was still unclear if or how vibrations measured on the body surface related to vibrations in the body's internal organs (Takahashi et al., 1999). No conclusions could be determined as to the possible chronic health effects caused by long-term exposure to LFS (Takahashi et al., 1999).

Takahashi and co-authors also examined the level of unpleasantness of human body vibration and LFS and identified a significant correlation between the measured body surface vibration induced by the LFS and the rating of unpleasantness (Takahashi et al., 2005). Inukai and co-authors found a similar association previously (Inukai, Nakamura, & Taya, 2000). The research findings of Takahashi and co-authors and Inukai and co-authors supported the notion that hearing sensation was an influential component in the perception of unpleasantness or annoyance among those exposed to LFS (Inukai et al., 2000; Takahashi et al., 2005). It was also found that the perception of unpleasantness was independent of the audibility of the sound. Inukai and coauthors qualified three factors: (1) sound pressure, (2) vibration, and (3) loudness in addition to hearing sensation to be predictors for the human psychological responses to LFS, such as unpleasantness or annoyance (Inukai, Taya, Miyano, & Kuriyama, 1986; Takahashi et al., 2005).

Cardiovascular and respiratory effects have also been a focus of research with respect to LFS exposure. Studies have shown changes in heart rate in subjects who were exposed to LFS (Berglund et al., 1996; Yamada, Watanabe, Kosaka, Negishi, & Watanabe, 1986). Respiratory effects such as suspended or reduced respiration, gagging, and coughing have been documented in humans after exposure to LFS, but only with a sound pressure of 150-154 dB (Berglund et al., 1996; von Gierke & Nixon, 1976).

Studies conducted by Karpova and coauthors and Slarve and Johnson indicated that study subjects reported aural complaints after exposure to industrial infrasound below 20 Hz (Karpova et al., 1970; Slarve & Johnson, 1975). Increased diastolic blood pressure, decreased systolic blood pressure, and significantly decreased respiration rate were a few examples of reported nonaural effects (Karpova et al., 1970; Schust, 2004). Karpova and co-authors reported complaints of fatigue, feelings of apathy, loss of concentration, somnolence, and depression following exposure to LFS. Furthermore, a relationship between fatigue and tiredness after work and increasing LFS exposure was found among 439 employees working in offices, laboratories, and industries in a later study (Schust, 2004; Tesarz, Kjellberg, Landstroem, & Holmberg, 1997).

Some studies have looked at the effect of LFS on nighttime sleep in adults and children (Ising, Lange-Asschenfeldt, Moriske, Born, & Eilts, 2004; Maschke, 2004). Ising and co-authors found that children (aged 5-12 years) who were highly exposed to truck noise at a maximum of 100 Hz had a significantly increased morning saliva cortisol concentration compared to a control population. This increased cortisol concentration indicated an activation of the hypothalamus-pituitary-adrenal axis and thus an indication of restless sleep and a further aggravation of bronchitis in the children (Ising et al., 2004). Adult case studies have reported that LFS affects sleep quality and results in insomnia and concentration problems (Berglund et al., 1996; Waye, 2004). In a cross-sectional study of 279 individuals, however, it was determined that no significant differences were detected in reported sleep among those exposed to a high level of LFS compared to those exposed to a medium level of LFS from ventilation and heat pumps (Waye & Rylander, 2001).

Annoyance, which will be discussed later, seemed to play a role in these findings. Fatigue, difficulty falling asleep, and feeling tense and irritable were reported significantly more often among those individuals who were annoyed by LFS than those who were exposed to the same sound but did not report being annoyed. Lastly, a study that exposed sinusoidal tones, or pure tones at a single frequency of 10, 20, 40, and 63 Hz with sound pressure levels ranging from 75 to 105 dB for 10 Hz and 20 Hz and 50 to 100 dB for 40 Hz and 63 Hz to six participants found no significant difference between the exposure and control nights in sleep efficiency index, number of changes in sleep state, or changes in the proportion of each sleep stage evaluated by electroencephalogram recordings (Gage, 2010; Inaba & Okada, 1988; Waye, 2004).

Research on Wind Turbines, Health Effects, and Annoyance

Health Effects

Most recently some research has been done specifically on sound produced by wind turbines and the possible association of a human health risk (Salt & Kaltenbach, 2011; Smedley, Webb, & Wilkins, 2010). Salt and Kaltenbach concluded that A-weighting wind turbine sound was not appropriate because A-weighted sounds present a misleading representation of whether the sound affects the human ear or if it is physiologically mediated by the outer hair cells (OHC). OHC have demonstrated stimulation by LFS as low as 3 to 4 Hz, but the A-weighted spectrum arrest measurement of all sound components below 14 Hz (Salt & Hullar, 2010; Salt & Kaltenbach, 2011). A proposed alternative to A-weighting is to use G-weighted measurements, a weighting curve based on the human audibility curve below 20 Hz and with a steep cutoff above 20 Hz (Salt & Kaltenbach, 2011). It was determined, however, that with the use of G-weighed sound measurements, the level of infrasound produced by wind turbines is often too low to be heard by the human ear even though the level is still sufficient to cause OHC stimulation (Jakobsen, 2005; Salt & Hullar, 2010; Salt & Kaltenbach, 2011; Schust, 2004).

Other researchers have examined the possible association of sound produced by wind turbines and epileptic seizures. Through modeling, Smedley and co-authors found that, unlike smaller wind turbines, larger 2 MW wind turbines with a blade width of 2m and a height of 120 m were unlikely to rotate fast enough to induce epileptic seizures due to shadow flicker (Smedley, Webb, & Wilkins, 2010).

Annoyance

The World Health Organization (WHO) considers annoyance an adverse health effect of noise in addition to sleep disturbance, performance effects, and psychological effects such as irritability (WHO, 2001). Annoyance was also defined as a feeling of displeasure with varying tolerance levels. WHO characterized annoyance as a feeling that increases with noise impulses as opposed to a steady noise (WHO, 2001). Likewise, the primary, and most frequently reported, perceived effect of LFS is annoyance as opposed to the loudness or noisiness (Berglund et al., 1996; Broner, 1978).

To date, four epidemiological studies have specifically examined the effects of sound generated by wind turbines on human health (Pedersen, van den Berg, Bakker, & Bouma, 2009; Pedersen & Waye, 2004, 2007; Shepherd, McBride, Welch, Dirks, & Hill, 2011). Pedersen and Waye identified a dose response relationship between calculated A-weighted sound pressure levels from wind turbines and noise annoyance in a cross-sectional study (N = 351) that was conducted in five dwelling areas in Sweden. The study respondents were annoyed by the upwind wind turbines, which had a blade passage frequency of 1.4 Hz, at a higher level than other community noises, such as road traffic (Pedersen & Waye, 2004). Noise annoyance was also found to be related to visual or aesthetic interference and attitude or sensitivity toward the wind turbine (Pedersen & Waye, 2004).

In another Swedish cross-sectional study (N = 754), the relationship between wind turbine noise and self-reported health and well-being factors was also examined (Pedersen & Waye, 2007). No correlation existed between A-weighted sound pressure levels from wind turbines and any health or well-being factors, such as the respondent's status of chronic disease, diabetes, or cardiovascular disease (Pedersen & Waye, 2007). Nevertheless, 31 out of 754 respondents stated that they were annoyed by the wind turbine noise and among this subset 55% reported being tired or that their sleep was disturbed (Pedersen & Waye, 2007). These findings were statistically significantly higher in comparison to those respondents who were not annoyed. Noise annoyance was also found to be associated with a negative attitude toward the visual impact of wind turbines in this study (odds ratio [OR] = 14.4, 95% confidence interval [CI]: 6.37-32.44) as well as another field study conducted (N = 725) in The Netherlands (OR = 2.8, $p < .001$) (Pedersen et al., 2009; Pedersen & Waye, 2007). Living in a rural area compared to an urban area increased the risk of perceiving wind turbine noise and annoyance, especially at sound levels above 40dB(A) (Pedersen & Waye, 2007).

Most recently Pedersen analyzed the self-reported health status among the participants in both the aforementioned Swedish and Dutch cross-sectional studies (Pedersen, 2011). The prevalence of diabetes was found to be weakly associated with A-weighted sound pressure levels due to wind turbines (OR = 1.13, 95% CI: 1.00-1.27) in addition to outdoor (OR = 1.70, 95% CI: 1.14-2.56) and indoor (OR = 1.62, 95% CI: 1.10-2.40) annoyance (Pedersen, 2011).

Finally, a cross-sectional study in New Zealand reported a lower mean physical health-related quality of life (HRQOL) domain score ($F [1, 194] = 5.816$, $p = .017$) among "The Turbine Group" as compared to "The Comparison Group" (Shepherd et al., 2011). HRQOL measured general well-being and well-being in the physical, psychological, and social domains (Shepherd et al., 2011).

Discussion

A rapid growth of wind generation capacity has occurred throughout various parts of the world. In 1970, virtually no wind power existed as a source of renewable energy in the U.S. Despite this rapid growth over that last 40 years, a very minimal amount of effort has been put into researching the human health impacts of wind power development until recently. The National Research Council (NRC) published a report in 2007 that reviewed the positive and negative environmental impacts of wind energy development, including effects on landscapes, views, wildlife, habitats, air pollution, and greenhouse gases. NRC noted that the potential impacts on human health and well-being were those from noise and from shadow flicker, economic and fiscal impacts, and the potential for electromagnetic interference with television and radio broadcasting, cellular phones, and radar (NRC, 2007). NRC also stated that the effects of sound below 20 Hz on humans have not been well documented or understood, but then concluded that the noise produced by wind turbines is generally not a major concern beyond one half-mile (NRC, 2007).

At present, a specific health condition or collection of symptoms has not been documented in the peer-reviewed, published literature that has been classified as a "disease" caused by exposure to sound levels and frequencies generated by the operation of wind turbines. It can be theorized that reported health effects are a manifestation of the annoyance that individuals experience as a result of the presence of wind turbines in their communities. As described previously, it has been found in the peer-reviewed literature that the presence of wind turbines or wind turbine sound is statistically significantly associated with being annoyed. Thus, the annoyance response that many residents and others have experienced as a result of being exposed to LFS may act as a mediator to other adverse physical effects. In this proposed mediation model and as illustrated in Figure 2 (Pathway I), annoyance can be the third variable (M), which intervenes in the relationship between the wind turbine LFS, the independent variable (X), and a physical health outcome, the dependent variable (Y), such as headache and dizziness. Alternatively, it can also be theorized that annoyance is the dependent variable (Y), which has been mediated by a physical health outcome, or a third variable (M), as result of LFS exposure generated by wind turbines (Figure 2 [Pathway II]).

Takahashi and co-authors and Inukai and co-authors characterized a pathway to annoyance or unpleasantness through body surface vibrations induced by LFS (Inukai et al., 2000; Takahashi et al., 2005). Although the sample size was small in their studies, a significant correlation was found between the measured body surface vibration and the rating of unpleasantness. This finding supports this alternative theory, which is that the response of annoyance resulting from LFS exposure can occur after an adverse physical effect, such as body surface vibration, has already occurred.

The underlying complaint of annoyance is not a disease, but instead a universal human response to a condition or situation that is not positively appreciated by the human receptor. Annoyances are highly variable in type (e.g. noise, smell, temperature) and vary from person to person. One can be annoyed by the action of others in addition to their own individual actions. WHO considers annoyance an adverse health effect of noise. Based on this definition and the incomprehension of the role of annoyance in the association between LFS and physiological or physical symptoms, exploring whether or not wind turbine sound is a human health risk through additional research is warranted. Such research should be conducted by a method that minimizes biases among the study participants (e.g., use of objective vs. subjective metrics) and in the selection of participants (e.g., randomization). None of the epidemiological studies, to date, have collected objective measurements, such as blood pressure readings or other biomarkers, to support or attenuate the subjective responses provided in questionnaires by the participants.

In addition to using objective measurements, it would also be beneficial to identify some participants who are not visually impacted by wind turbines because their level of annoyance may be minimized or mitigated, which would in effect create a control-like quality of a portion of the participant sample. Lastly, studies on this highly debated subject matter should employ a single or if possible a double-blinded process of data collection. For example, Pedersen and co-authors (2004, 2007, 2009) concealed the study purpose from the participants in their studies, which was essential because the variability of annoyance and its link to undesirable factors make it a prime indicator for the possibility of recall bias. Like so many outcomes, the effects of LFS on annoyance are challenging to establish because of differences in confounding and biases between exposed and non-exposed populations to LFS, which is precisely why further research is recommended.

Our review explored and summarized the peer-reviewed literature on the research that has examined the relationship between human health effects and exposure to LFS and sound generated from the operation of wind turbines (Table 2 on pages 14 and 15). One of the main limitations of our study involved the use of the search terms. Although all efforts were employed to create search terms that were the most inclusive as well as overlapping, a chance existed that some articles were missed in the search. In order to abate this shortcoming, additional searches were conducted in multiple time periods. Furthermore, the only search engine that was used was PubMed, which created a limitation to accessing foreign articles. By using the reference list of retrieved articles, some additional articles, but not all, were identified. Finally, the use of human only as opposed to animal-based research articles was limiting. Animal models and research can often be very useful in gaining an understanding of the pathway from exposure to health outcome especially when the epidemiological data are scarce.

Conclusion

The answer to the question of whether or not exposure to wind turbine sound is a human health risk is still under review and warrants further research. Although limited, research has demonstrated that LFS can elicit adverse physical health effects, such as vibration or fatigue, as well as an annoyance or unpleasantness response. The current research on exposure to wind turbine sound and the mere presence of wind turbines have also demonstrated a significant annoyance response among study participants. But the association and particular pathway between LFS specifically generated from wind turbines, annoyance, and adverse physical health effects have yet to be fully characterized. What is known is that communities are experiencing a heightened sense of annoyance and fear from the development and siting of wind turbine farms, which seems to be more than just "NIMBYism" (not in my back yard). Hence, the research on the potential health effects, including annoyance-associated health effects, claimed as a result of exposure to sound generated by wind turbines is essential to determine if an actual risk exists. An actual risk versus a perceived risk is very much the same for some communities. High-quality research and effective risk communication can advance this course from one of panic to one of understanding and exemplification for other environmental advancements and developments. As we push to a more sustainable environment, efforts will continue to use and rely on alternative and renewable energy sources, such as wind.

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TABLE 1

Sound Frequency Spectrum

Frequency (Hz)				
0	10	20	100-250	20,000
Infrasound (with body resonance)	Infrasound	Low frequency sound	Non-low frequency audible sound	Ultrasound
Range of infrasound		Range of human hearing		Inaudible

Note. Adapted from Berglund et al., 1996.

TABLE 2

Reviewed Literature

Year	Author	Title
1965	Mohr, G.C. et al.	Effects of low frequency and infrasonic noise on man
1970	Karpova, N.I. et al.	Early response of the organism to low frequency

		acoustical oscillations
1975	Slarve, R.N. & Johnson, D.L.	Human whole-body exposure to infrasound
1978	Broner, N.	The effects of low frequency noise on people--a review
1986	Inukai, Y. et al.	A multidimensional evaluation method for the psychological effects of pure tones at low and infrasonic frequencies
1986	Yamada, D. et al.	Physiological effects of low frequency noise
1988	Inaba, R. & Okada, A.	Study on the effects of infra and low frequency sound on the sleep by EEG recordings
1996	Berglund, B. et al.	Sources and effects of low-frequency noise
1997	Tesarz, M. et al.	Subjective response patterns related to low frequency noise
1999	Castelo Branco, N.A. et al.	The vibroacoustic disease--an emerging pathology
1999	Takahashi, Y. et al.	A pilot study on the human body vibration induced by low frequency noise
2000	Inukai, Y. et al.	Unpleasantness and acceptable limits of low frequency sound
2001	Waye, K.P. & Rylander, R.	The prevalence of annoyance and effects after long-term exposure to low-frequency noise
2001	Takahashi, Y. et al.	A new approach to assess low frequency noise in the working environment
2004	Ising, H. et al.	Low frequency noise and stress: Bronchitis and cortisol in children exposed chronically to traffic noise and exhaust fumes
2004	Maschke, C.	Introduction to the special issue on low frequency noise
2004	Pedersen, E. & Waye, K.P.	Perception and annoyance due to wind turbine

		noise--a dose-response relationship
2004	Schust, M. et al.	Effects of low frequency noise up to 100 Hz
2004	Waye, K.P.	Effects of low frequency noise on sleep
2005	Jakobsen, J.	Infrasound emission from wind turbines
2005	Takahashi, Y. et al.	A study on the relationship between subjective unpleasantness and body surface vibrations induced by high-level low-frequency pure tones.
2007	Pedersen, E. & Waye, K.P.	Wind turbine noise, annoyance, and self-reported health and well-being in different living environments
2009	Pedersen, E. et al.	Response to noise from modern wind farms in The Netherlands
2010	Salt, A.N. & Hullar, T.E.	Responses of the ear to low frequency sounds, infrasound, and wind turbines
2010	Smedley, A.R. et al.	Potential of wind turbines to elicit seizures under various meteorological conditions
2011	Pedersen, E.	Health aspects associated with wind turbine noise--results from three field studies
2011	Salt, A.N. & Kaltenbach, J.A.	Infrasound from wind turbines could affect humans
2011	Shepherd, D. et al.	Evaluating the impact of wind turbine noise on health-related quality of life

Year	Study Design
1965	Experimental: Subjects (noise-experienced officers) were exposed to high intensity broad-band, narrow-band, and pure-tone low frequency noise (1-100 cps [cycle/second = hertz]) for two minutes to observe the effect on cardiac rhythm, hearing threshold, visual acuity, fine motor control, spatial orientation, speech intelligibility, and subjective tolerance.
1970	Experimental: Subjects were exposed to industrial

infrasound (5, 10 Hz/100, 135 dB) for 15 minutes.

1975 Experimental: Subjects were exposed to infrasound ranging 1 to 20 Hz for a period of eight minutes up to levels of 144 dB re 20 micropascal.

1978 Review: The effects of low frequency noise are reviewed.

1986 Experimental: Subjects were exposed to pure low and infrasonic (3-40 Hz) tones generated by loudspeakers in a pressure chamber and then rated the tones on a response device.

1986 Experimental: Subjects were exposed to both rattling noises and to unspecified signals at frequencies between 16 and 125 Hz, at levels between 60 and 100 dB in a test chamber and electrophysiological measurements were collected.

1988 Experimental: Subjects were exposed to sinusoidal tones at 10, 20, 40, and 63 Hz with sound pressure levels ranging 75 to 105 dB for 10 and 20 Hz and 50 to 100 dB for 40 and 63 Hz.

1996 Review: The sources of human exposure to low-frequency noise and its effects are reviewed.

1997 Cross-sectional: The relationship between low frequency noise exposure and subjective symptoms were studied in a group of persons working in offices, laboratories, and industries.

1999 Cross-sectional: Analyzed the medical files of 140 patients (male aircraft technicians) with vibroacoustic disease (VAD) in order to classify VAD by a function of time.

1999 Experimental: Subjects were exposed to pure tones in the frequency range of 20 to 50 Hz using a designed measuring method with a miniature accelerometer and vibration was measured on the chest and abdomen of subjects.

2000 Experimental: Subjects were exposed to pure tones at 16 one-third octave band center frequencies between 20 and 500 Hz and then rated the tones on a five-category scale, of which the highest two categories were "quite unpleasant" and "very unpleasant."

2001 Cross-sectional: A cross-sectional questionnaire and noise measurement survey was undertaken among randomly chosen persons exposed to noise (low frequency or middle frequency noise) from heat pump/ventilation installations in their homes.

2001 Experimental: Subjects were exposed to 15 kinds of low frequency noise stimuli (5 frequencies x 3 sound pressure levels) reproduced by 12 loudspeakers installed in the wall in front of the subject in order to collect measurements of noise-induced vibration on the body surface and to estimate the equal acceleration level contours of the vibration.

2004 Cross-sectional: To examine the correlation of respiratory diseases to traffic related air pollution and noise, nitrogen dioxide as an indicator for vehicle exhausts and the mean nighttime noise level were measured outside children's windows.

2004	Review: An introduction and overview of human exposure to low-frequency noise.
2004	Cross-sectional: In order to evaluate the prevalence of annoyance due to wind turbine noise and to study dose response relationships, responses were obtained through questionnaires and doses were calculated as A-weighted sound pressure levels.
2004	Review: This review concentrates on the effects of low frequency noise up to 100 Hz on selected physiological parameters, subjective complaints, and performance.
2004	Review: An overview of the effects of low frequency noise on sleep.
2005	Review: A critical survey of all known published measurement results of infrasound from wind turbines.
2005	Experimental: Subjects were exposed to high-level low-frequency pure tones and body surface vibrations were measured at the chest and the abdomen. At the same time, the subject rated the unpleasantness that he had just perceived during the exposure to low-frequency noise stimulus.
2007	Cross-sectional: In order to evaluate the prevalence of perception and annoyance due to wind turbine noise among people living near the turbines, a cross-sectional study was carried out in seven areas in Sweden across dissimilar terrain and different degrees of urbanization through a postal questionnaire and measurements of outdoor A-weighted sound pressure levels were calculated for each respondent.
2009	Cross-sectional: To assess possibly unacceptable adverse health effects, a field study exploring the impact of wind turbine sound on people living in the vicinity of wind farms was carried out in The Netherlands in 2007.
2010	Review: An overview of the responses of the ear to low frequency sounds, infrasound, and wind turbines.
2010	Experimental: To determine the risk of seizures from wind turbines in persons with photosensitive epilepsy, the light-dark contrasts of turbine shadows for worst case conditions were modeled.
2011	Meta analysis: Data from three cross-sectional studies comprising A-weighted sound pressure levels of wind turbine noise and subjectively measured responses from 1,755 people were used to systematically explore the relationships between sound levels and aspects of health and well-being.
2011	Review: An overview of the responses of the ear to infrasound generated by wind turbines.
2011	Cross-sectional: To compare the health-related quality of life of individuals residing in the proximity of a wind farm to those residing in a demographically matched area sufficiently displaced from wind turbines, a cross-sectional study was conducted in semirural New Zealand.

Year	Study Population

1965	Male and female volunteers (N = 5)
1970	Male volunteers (N = 3)
1975	Male Volunteers (N = 4)
1978	N/A
1986	Male and female volunteers (N = 17)
1986	Male and female volunteers/ complainants (N = 21)
1988	Male and female volunteers (N = 6)
1996	N/A
1997	Male and female workers (N = 439)
1999	Male workers (N = 140)
1999	Male volunteers (N = 6)
2000	Male and female volunteers (N = 39)
2001	Male and female volunteers (N = 279)
2001	Male volunteers (N = 9)
2004	Male and female volunteers (N = 68)
2004	N/A
2004	Male and female volunteers (N = 351)
2004	N/A
2004	N/A
2005	N/A

2005	Male volunteers (N = 9)
2007	Male and female volunteers (N = 754)
2009	Male and female volunteers (N = 725)
2010	N/A
2010	N/A
2011	Male and female volunteers (N = 1,755)
2011	N/A
2011	Male and female volunteers (N = 197)