Wind Turbine Noise and Human Health: A Four-Decade History of Evidence that Wind Turbines Pose Risks*

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Abstract

Many expert-review panels and some individual authors, in the U.S. and internationally, have taken the position that there is little literature to support concerns about adverse health effects (AHEs) from noise emitted by industrial wind turbines (IWTs). In this review, we systematically examine the literature that bears on some of the particular claims that are commonly made in support of the view that a causal link is non-existent. Investigation of the veracity of those claims requires that multiple topics be addressed, and the following specific topics were targeted for this review: (1) emissions of infrasound and low-frequency noise (ILFN) by IWTs, (2) the perception of ILFN by humans, (3) the evidentiary bases for establishing a causative link between IWTs and AHEs, as well as the physiological bases for such a link, (4) recommended setback distances and permissible noise levels, (5) the relationship between annoyance and health, (6) alternative causes of the reported health problems, (7) recommended methods for measuring infrasound, (8) foundations for establishing a medical diagnosis of AHEs due to IWTs, (9) research designs useful in establishing causation, (10) the role of psychological expectations as an explanation for the reported adverse effects, (11) the prevalence of AHEs in individuals exposed to IWTs, and (12) the scope and quality of literature addressing the link between IWT noise and AHEs. The reviewed evidence overwhelmingly supports the notion that acoustic emissions from IWTs is a leading cause of AHEs in a substantial segment of the population.

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Introduction

Whether infrasound and low-frequency noise (ILFN) from industrial wind turbines (IWTs) is detrimental to human health is currently a highly controversial topic. Advocates of industrial-scale wind energy assert that there is no credible scientific evidence of a causal relationship, while many reputable professionals believe that there is sufficient scientific evidence to establish a causal link between IWTs and detrimental health effects *for a non-trivial percentage of individuals who reside in communities hosting IWTs*. The veracity of claims regarding the effects on human health is being debated on a global scale by the wind industry; individuals living near IWTs; attorneys and expert witnesses in courts of law; print and web-based media; documentary films (which currently include *Windfall*, *Wind Rush*, and *Down Wind*); and scientists and other professionals in government reports, on the Internet, and in scientific and professional papers presented at society meetings and published in peer-reviewed journals.

The debate surrounding IWTs extends to many controversial issues, including physical safety, visibility, shadow flicker, and threats to property values and wildlife. Many problems involving wind turbines, including mechanical failures, accidents, and other mishaps, have been discussed on the Internet. At least one website has extensively catalogued these incidents,[1] and the large number of incidents reported by that site is described by its webmaster as grossly underestimating the actual number of documented incidents. The most vigorous debate, however, centers on ILFN and its effects on human health.

The overall purpose of this article is to provide a systematic review of legitimate sources that bear directly and indirectly on the question of the extent to which IWT noise leads to the many health complaints that are being attributed to it. The authors accessed most articles and reports referenced in this review by employing Google, Google Scholar, and PubMed as the primary search engines. Our basic aim was to provide a comprehensive and representative—though not exhaustive—review of the literature that is relevant to many of the claims made by wind industry advocates. An exhaustive review is an elusive and impractical goal, given the large volume of directly and indirectly related work done in this area over the past several decades and the current pace of such work.

The role of evidentiary facts

Adverse impacts on people and property are among the most contentious issues that are typically the focus of legal proceedings involving IWT noise. Based on the forensic and research experiences of the authors, we believe that a resolution of the controversial aspects of this debate will require not just relevant scientific research, but rather a series of legal judgments based on the effective evaluation and interpretation of the existing research. In fact, much research and some already-rendered legal decisions show convincingly that some segments of the population suffer damaging effects from exposure to wind turbine noise (WTN). What is needed among the scientific community, local and national governmental agencies, and political leaders, is honest discourse about methods for reducing carbon emissions in ways that do not turn some rural communities into *sacrifice zones*.[2, 3]

Many symptoms and complaints of adverse health effects (AHEs) related to IWTs have been self-reported by individuals living near wind turbines and described in published case reports. There is a group of core symptoms and complaints, however—including sleep disturbance, headache, dizziness, vertigo, and ear pressure or pain—that are remarkably common worldwide. Dr. Nina Pierpont was the first to report these core symptoms in a case series,[4] and she termed these core symptoms *Wind Turbine Syndrome*. For the sake of brevity, we will on occasion refer to Wind Turbine Syndrome as a substitute for this group of common symptoms and complaints, even though the phrase itself is currently not utilized as a medical diagnostic entity.

Numerous reviews of the literature have already been published that allege that there is no credible link between WTN emissions and AHEs. Those reviews have typically been sanctioned by state or provincial government agencies that have missions to support the development of wind energy, and which in turn appoint *expert panels* whose members hold views that regularly favor the wind industry and, therefore, may have conflicting interests. Too often, in the opinion of the authors, such reviews are biased in support of political policy decisions that promote the financial interests of wind developers, and perceived financial benefits to local communities, over the common good. None of those reviews has been specifically targeted toward describing or explaining the relationship between exposure to complex, dynamically modulated infra- and low-frequency sound from wind turbines or other industrial sources (e.g., noise-induced Sick Building Syndrome) and AHEs. Our primary objective in this article is to review the existing scientific and professional literature that is frequently overlooked in such reviews conducted by wind energy proponents. Such literature can be useful in legal proceedings in questioning and articulating the available evidence of risks to people who live in the footprint of utility-scale wind energy projects.

Some of the published reviews have been criticized for their failure to meet the standards noted by Horner,[5] who reminds us that readers should regard literature reviews with caution, and employ an audit strategy in evaluating their completeness, accuracy, and objectivity. Authors, including ourselves, have an inherent obligation to ensure that such reviews cite all known legitimate sources that serve as the basis for their views of the issues and reflect accurately the contents of all references cited.

Some courts of law in the U.S. and other countries now tend to rely heavily on testimony that adheres to the principle that proof of evidence of causation of AHEs from IWTs be based on the peer-reviewed literature. Presumably, that practice in the U.S. stems at least partially from advocacy by the Office of Management and Budget[6] that internal and external government science documents be peer-reviewed government-wide for the purpose of increasing the quality and credibility of scientific information generated by the federal government. Peer-review standards are considered paramount in that effort.

While the peer-review process has many virtues, it also has its shortcomings, which are well known. For example, not all journals or individual reviews of submitted manuscripts are of equal quality, as specific journals and specific reviewers may have ideological or philosophical biases, which may or may not be surmised from the journals' mission statements. Nonetheless, the peer-review process is one of the most widely acknowledged ways to control the quality of published works. We contend, however, that there are other credible sources of information, even though those sources may not have been subjected to as rigorous a peer-review process as that employed by many scientific journals. Such sources include papers presented at meetings of scientific and professional societies; reports and other documents commissioned by state and local governmental agencies, especially if such documents are authored by independent researchers; legal testimony given under oath by qualified scientists and professionals; and some information available on the Internet, especially if written by professionals who have reputable track records in their disciplines. Although we will emphasize the peer-reviewed literature in this article, we will also cite some of these additional sources as authoritative. Our citing of selected non-peer-reviewed reports, with a few exceptions, is based on our familiarity with the professional reputations of the authors of those reports, normally earned through publication of a solid body of work in the peer-reviewed literature and by acceptance of their work by other professionals and peers. Typically, individuals so referenced enjoy positive national or international recognition in their respective fields of expertise.

We begin this review by calling attention to a quote from geophysicist Marcia McNutt, who once headed the U.S. Geological Survey and is now editor of the prestigious journal *Science*. McNutt has been quoted as stating: "Science is not a body of facts. Science is a method for deciding whether what we choose to believe has a basis in the laws of nature or not."[7] In fact, science consists of a variety of overlapping methodological approaches, which must be interwoven to discover answers to complex problems. That conviction has guided our attempt to re-examine the controversial topic at hand.

Review of wind industry claims and positions

Our review is organized by summarizing the past and present literature that addresses each of 12 selected statements, listed below, that encapsulate specific claims, or positions, commonly taken by advocates for the wind industry:

1. Infrasound is not an issue, as infrasound generated by wind turbines is not perceptible to humans.
2. There is nothing unique about wind turbine noise, as infrasound and low-frequency noise are commonly produced by the body and by many environmental sources.
3. There is no evidence that wind turbine noise, audible or inaudible, is the cause of adverse health effects in people, and there are no physiological mechanisms to explain how inaudible acoustic energy can be harmful.
4. Setback distances of 1,000-1,500 ft. (approximately 0.3-0.5 km) are sufficiently safe to protect humans from harm, regardless of height or other physical characteristics of the IWTs.
5. Annoyance is a nuisance, but it is not a health issue.
6. Noise cannot account for all of the complaints of people living in the vicinity of wind turbines; there must be another, unknown reason for the complaints.
7. Infrasound from wind turbines is sufficiently correlated to the A-weighted sound emissions to allow an A-weighted model to be used to predict how much infrasound is present in homes.
8. Wind Turbine Syndrome has not been accepted as a diagnostic entity by the medical profession, so medical professionals cannot diagnose or treat it.
9. Peer-reviewed epidemiological literature is the only acceptable basis for proving a causative relationship between wind turbine noise and adverse health effects.
10. The nocebo effect, a manifestation of psychological expectations, explains why people complain of adverse health effects when living near wind turbines.
11. Only relatively few people, if any, are adversely impacted by wind turbine noise, and the majority have no complaints.
12. There is no evidence in the literature to support a causative link between wind turbine noise and adverse effects.

Statement 1: Infrasound is not an issue, as infrasound generated by wind turbines is not perceptible to humans.

The argument that infrasound as a cause of AHEs is not an issue has been advanced in the published literature primarily by Dr. Geoff Leventhall,[8, 9] with support from several other researchers. Those researchers have dismissed the influence of infrasound on human health by describing it as not exceeding the thresholds of audibility, and therefore ineffectual, without noting that those thresholds were established using steady pure tones instead of the complex, dynamically modulated tones emitted by wind turbines. Leventhall claims that infrasound from wind turbines is not a problem and that it is misunderstood largely because of mischaracterization by the media and by "those with limited knowledge" (p. 29). He states that there may be noise problems associated with wind turbines, but that such problems are due to *audible* swishing sounds due to interactions of the blades with the tower. Supporters of wind energy have generally followed Leventhall's lead, although his own research has shown conclusively that exposure to modulated ILFN produced by large industrial equipment, including heating, ventilating and air-conditioning (HVAC) systems, leads to mental fatigue, lack of concentration, headaches, reduced performance, and work dissatisfaction. Indeed, there is a long history of noise-induced *Sick Building Syndrome*, stemming from investigations in the 1970s-1990s of the effects of low-frequency noise on knowledge workers (see James[10] and Schwartz[11] for reviews of that research). Leventhall[12] stated:

> "Low frequency noise causes extreme distress to a number of people who are sensitive to its effects. Such sensitivity may be a result of heightened sensory response within the whole or part of the auditory range or may be acquired. The noise levels are often low, occurring in the region of the hearing threshold, where there are considerable individual differences" (p. 4).

Later in the same document, he states:

> "There is no doubt that some humans exposed to infrasound experience abnormal ear, CNS (central nervous system), and resonance induced symptoms that are real and stressful. If this is not recognised by investigators or their treating physicians, and properly addressed with understanding and sympathy, a psychological reaction will follow and the patient's problems will be compounded. Most subjects may be reassured that there will be no serious consequences to their health from infrasound exposure and *if further exposure is avoided* (emphasis added) they may expect to become symptom free" (p. 60).

Leventhall has also stated that the ear is designed to protect us from infrasound and that, in essence, *If you can't hear it, you can't feel it.*[13, 14] The idea that ILFN from wind turbines does not affect health was further reinforced in a 2009 white paper co-authored by Leventhall and sanctioned by the wind industry,[15] to be reviewed later.

The position that infrasound from wind turbines is not harmful to humans because it is not perceptible to the human ear also has support from Møller & Pedersen,[16] who investigated noise emissions from 48 wind turbines with electrical output capacities of between 2.3 and 3.6 MW. They stated:

> "The turbines do emit infrasound (sound below 20 Hz), but levels are low when human sensitivity to these frequencies is accounted for. Even close to the turbines, the infrasonic sound pressure level is much below the normal hearing threshold, and infrasound is thus not considered as a problem with turbines of the investigated size and construction" (pp. 3742-3743).

Evans et al[17] found that levels of infrasound measured at two residential locations near wind projects in South Australia were within the range of infrasound levels experienced in other urban and rural environments. Although Colby et al[15] and Bolin et al[18] dismiss wind turbines as a cause of AHEs, they acknowledge that turbines emit ILFN. A number of authors indicate that large turbines emit more such noise than smaller turbines (see, for example, Bolin et al[18] and Møller & Pedersen.[16]) George Kamperman (personal communication, 2009) has concluded that the amount of low-frequency noise generated by IWTs increases by 3–5 dB for every megawatt of electrical power generated.

Evidence that IWTs produce perceptible levels of infrasound, in addition to audible low-frequency noise above 20 Hz, has been available since the 1980s. In their seminal research on large-scale wind turbines, which was funded by the U.S. Department of Energy, Kelley et al[19] measured noise levels emitted by a DOE/NASA MOD-l wind turbine operating near Boone, North Carolina, in response to noise complaints. They concluded that:

> "…one of the major causal agents responsible for the annoyance of nearby residents by wind turbine noise is the excitation of highly resonant structural and air volume modes by the coherent, low frequency sound radiated by large wind turbines. Further, there is evidence that the strong resonances found in the acoustic pressure field within rooms actually measured indicates a coupling of subaudible energy to human body resonances at 5, 12, and 17-25 Hz, resulting in a sensation of whole-body vibration" (p. 120).

Those conclusions were further strengthened in a subsequent report.[20] In a second follow-up report, also funded by the Department of Energy, Kelley[21] electronically simulated three interior environments resulting from low-frequency acoustical loads radiated from both single and grouped upwind and downwind turbines. (These terms refer to the placement of the rotor and blades with respect to the tower. With upwind designs, the more contemporary design, the airflow strikes the blades before striking the tower, and with downwind designs, the airflow strikes the tower before striking the blades.) Relatively low levels of low-frequency acoustic noise from a single, 2-MW MOD-1 wind turbine led to annoyance of residents of the surrounding community, largely through interaction with residential structures. Most importantly, Kelley found that the turbines radiated their peak sound power in the infrasonic range, typically between 1 and 10 Hz. An extensive investigation revealed that the reported annoyance was the result of a coupling of the turbine's impulsive low-frequency acoustic energy into the structures of some of the surrounding homes, and that annoyance was "frequently confined to *within the home itself*" (p. 1). Despite these early findings that IWTs generate infrasonic levels that produce acoustic energy, vibrations, and resonances that affect people in their homes, the wind industry has chosen to regard them as insignificant or only applicable to obsolete, downwind wind turbine designs.

The basis for discounting the research by Kelley and associates is predicated on the assumption that pressure changes of equal levels to wind turbines occur in natural environments and do not cause any similar complaints. The authors find that their own experiences with rapidly changing pressures have caused similar experiences. If these rather short-duration sensations were to continue over days, weeks, and months, as they do for people living near wind projects, they would likely find them to be unacceptable.

The primary argument of people who deny any effects is encapsulated by Leventhall[9] in his *Child on a Swing* example:

> "A child on a swing experiences infrasound at a level of around 110dB and frequency 0.5Hz, depending on the suspended length and the change in height during the swing" (p. 30).

The inference is that because children often swing on swings, there are no adverse sensations. That fails to acknowledge that the experience of swinging is one that elicits many visceral sensations that are pleasant to the child as long as the sensations stop when the swing stops. The example, however, misses one major point. The duration and motion of the swing provide a smooth, sinusoidal pressure change that has two high pressure points (at the top of each swing) that occur over a period of several seconds or so. This is a completely different experience to that of pressure pulses lasting 100 msec or less. If one considers a swing with a period of 3.5 sec, there is a pressure change at 1.75 sec, resulting in a frequency of 0.57 Hz. The pressure changes are approximately 120 dB peak-to-peak, or 110 dB rms. The overall G-weighted value in this example is -60 dB, with a smooth pressure change, resulting in a net 50 dBG for the child, versus the 75 dBG experienced as a pulse for a person living near a wind turbine (calculations provided by Malcolm Swinbanks, personal communication, 2010).

The assertion that wind turbine infrasound immissions, especially when received in the bedroom of a quiet home, must be at or above the threshold of hearing to cause adverse effects has been disproved, as noted above in the works of Kelley and colleagues in the 1980s.[19, 20, 21] The significant finding of the Kelley studies is that when the intruding infrasound is dynamically modulated short-duration pulses (generally under 100 msec and as short as 4 msec), the thresholds of sound pressure levels (SPLs) for non-auditory perception are in the range of 60 to 70 dB. In the work by one of the authors of this paper (James, with Mr. Wade Bray, INCE, of Head Acoustics, GMBH), infrasound pulsations were measured from a GE 1.5-MW wind turbine with a blade-pass frequency of 1 Hz that reached a level as high as 100 dB.[22] The people living in the home 'felt' the pulsations when the crests of the pressure waves were as low as 60 dB at 1 Hz. During similar measurements, Swinbanks, who has reported that he is sensitive to infrasound pulsations, was present at the test site. His experience was that he could feel the pulsations outside the home at similar SPLs.

Subsequent to the papers by Kelley and colleagues, several other studies have also reported the thresholds for significant experiences at similar thresholds, all substantially below the threshold for audibility of steady pure tones. In many of those tests, the rms SPL of the dynamically modulated blade-pass tone and its harmonics has been as low as 40 dB when using narrow-band analysis with windows of 40 to 80 sec, providing the crest of the pressure waves are 10 to 15 dB higher than the rms levels. These studies include the works of Robert Rand, INCE, and Stephen Ambrose, Bd. Cert., INCE, in their study of homes of complainants in Falmouth, Massachusetts;[23] Walker, Hessler, Hessler, and Schomer, in their work at the Shirley Wind project in Brown County, Wisconsin, for the Wisconsin Public Health Service;[24] and most recently, Steven Cooper's study of the Cape Bridgewater project in Victoria, Australia.[25] All of these studies report similar findings, namely that perception, generally non-auditory in character, begins when the rms SPLs of the modulating tones are as low as 40 dB rms, with increasing impacts as the rms levels rise to 50, 60, and to 70 dB and higher levels. In all these studies, the dynamic modulation of the blade-pass tones produce pressure peaks that are often 10 dB or more, sometimes much more, than the rms values.

In the opinion of the authors, a paper prepared by Swinbanks for the 2015 conference on wind energy in Glasgow, Scotland, shows the impact of dynamically modulated infrasound on a sensitive individual—himself—along with high-quality measurements of the environments in which he experienced the sensations.[26] That paper shows that a highly respected acoustician and scientist with expertise in infra- and low-frequency sound also responds to this acoustic energy in a way that is similar to the many complaints from others, both in the location of his tests and at other wind energy projects around the world. In the paper, Swinbanks reports that he was able to differentiate the pulsations in the test data from at least six separate wind turbines in a project consisting of 46 1.5-MW GE models. He also reports that he was able to perceive the effects of the pulsations in his home's basement, approximately 3 km from the nearest operating wind turbine, with the SPLs of the blade-pass frequency and harmonics summing to about 55 dB rms. At closer locations, he measured positive-going pressure peaks of 87 dB with corresponding negative-going peaks of equal level. It is worth noting that at the Glasgow conference, Swinbanks presented the paper as a poster session,[27] as he was informed by the conference moderator that time restraints prevented him from presenting his paper to conference attendees.

In the 2012 investigation of infrasound at the Shirley Wind project, where local regulations require that the Nordex 2.5-MW turbines be sited at least 1,250 ft., or 381 m, from residences, Walker et al reported infrasound levels at one of the three test homes.[24] WTN was not audible outside the residence where infrasound was greatest, supporting the position that infrasound is at the root of at least some of the complaints. The blade-pass frequency and harmonics were clearly evident from the measurements inside that one home, and the family had moved far away for a solution.

Following the Shirley Wind team study, several members of the community conducted a series of micro barometer measurements inside homes ranging from 1,280 ft. to approximately 6 mi. from the wind turbine towers. Infrasonic tones at blade-pass frequencies and harmonics were found at all test sites, including test sites at distances of several miles or more from towers under downwind conditions. Testimony to Wisconsin's Brown County Board of Health by people with homes more than 4 mi. from the nearest wind turbines reported AHEs during the times the turbines operated. In mid-October 2014, the Brown County Board of Health went on record declaring that wind turbines at the Shirley Wind site "…are a human health hazard."[28] That action, which appears to be a precedent in the U.S., meant that Duke Energy's Shirley Wind utility were forced to prove to the Board that the utility was not the cause of the health complaints documented in the study and voiced by community residents. The outcome could result in a shut-down order, but no final decision had been made in that case at the time of this writing. Other examples of legally ordered turbine shutdowns include those in Massachusetts[29, 30] and Portugal.[31]

We will return to the issue of perceptibility of infrasound later in this paper, as we describe the physiological bases for perceptibility.

Statement 2: There is nothing unique about wind turbine noise, as infrasound and low-frequency noise are commonly produced by the body and by many environmental sources.

To begin, when the spectral characteristics of IWT noise, as depicted in several papers,[24, 32, 33] are compared to the spectra of subsonic jet transport planes,[34] five different types of aircraft,[35] and road traffic noise,[36] it is clear that noise generated by wind turbines has a number of unique acoustical characteristics. These comparisons reveal dissimilarities in spectral and peak levels in both the higher and lower frequency regions, including the low-frequency and infrasonic range.

Leventhall[37] was one of the first to describe how low-frequency noise is a special noise problem, particularly to sensitive people in their homes. He indicated that annoyance to low-frequency noise increases rapidly with level, often starting just above the threshold of audibility, and that about 2.5% of the population may be 12 dB more sensitive than the average person to low-frequency noise. He also noted that the World Health Organization (WHO) places a special emphasis on low-frequency noise as an environmental problem and source of sleep disturbance, even at low levels. The WHO[38] acknowledges that a noise consisting of a large proportion of low-frequency components may considerably increase AHEs and should be limited to below 40 dBA. Cummings[39] notes that sound levels of 40 dBA trigger high levels of community pushback.

Jung et al[40] experimentally identified the characteristics of acoustic emissions from large upwind wind turbines, with emphasis on ILFN. The sound spectral density showed that the blade-passage frequency component is clearly dominant, revealing up to 6-7 harmonics that generally occupy the infrasonic frequency region of 1 to 10 Hz. They voiced a concern that the low-frequency noise of the 1.5-MW and 600-kW wind turbines in the frequency range over 30 Hz would very likely lead to psychological complaints from ordinary adults.

In responding to a bylaw to restrict wind turbine infrasound in the town of Plympton-Wyoming, Ontario, Leventhall[41] declared that “Infrasound has become the Godzilla of acoustics” (p. 2). He concluded that science does not support the conditions in the bylaw, which was largely aimed at restricting blade-passing tones, because “There is no evidence that the very low level of blade passing tones affects humans, whilst there is evidence that it does not” (p. 7). Based on the kinds of evidence just discussed, we strongly disagree.

WTN has been described as having a character that makes it far more annoying and stressful than other sources of noise at the same A-weighted level, including traffic and industrial noise.[42, 43, 44, 45] Harrison[42] concluded that IWTs cause annoyance in about 20% of residents living within a distance considered acceptable by most regulatory authorities, and that for many of the 20%, the annoyance and sleep disturbance lead to AHEs. Thorne[46] has pointed out that human perception of noise is based primarily on sound character rather than sound level, and that wind turbines are unique sound sources that exhibit special audible and inaudible modulated and tonal characteristics. He states that sound levels of 32 dBA Leq outside a residence and/or above an individual's threshold of hearing inside the home are markers for serious AHEs, especially among susceptible individuals.

Structural and human responses to low-frequency noise, including noise from wind turbines, have been described by Hubbard.[47] Hubbard and Shephard[48] illustrated the special characteristics of WTN by explaining its sources, pathways, and receptors. Thorne[46, 49] described wind turbines and *wind farms* as a unique source of sound and noise, like no other noise source or set of noise sources. The sounds are often of low amplitude and shifting in character, making it difficult for people who have never been exposed to such sounds to understand the problems of those who complain about the sounds. Shepherd et al[50] have described WTN as having characteristics sufficiently different from other, more extensively studied, noise sources to justify the application of standards different from pre-existing noise standards.

The preponderance of evidence on this point leads to the conclusion that WTN has special acoustic characteristics that distinguish it from other industrial sounds. A primary feature is that it consists of measureable energy down to below 1 Hz.[24, 51, 52] Its sound pressure level decreases rapidly with increasing frequency from about 0.5-5 Hz. It varies in amplitude over time,[9, 49, 51, 53, 54, 55, 56, 57, 58] it tends to have an intermittent tonal quality,[49, 52, 59] and its characteristics vary with distance and direction.[52, 53] It can result in an impulsive sound,[21, 40, 49, 60] even at long distances.[52] According to Lee et al,[53] the swishing sounds of turbines can be perceived from all directions, but at long distances from a turbine, low-frequency amplitude-modulated sounds can be heard only in particular directions and when the SPL is sufficiently high. This effect may make the WTN seem more impulsive at long distances despite an overall SPL that is relatively low.

Furthermore, ILFN from any source, including IWTs, is well known to penetrate walls and other barriers (e.g., Minnesota Department of Health[55]); is typically more disruptive indoors than outdoors;[46, 47, 61, 62, 63] and is not easily masked by atmospheric sounds, including road traffic and other sources of infrasound.[63, 64, 65, 66] The perception of low-frequency noise depends on density level, modulations, bandwidth, purity of blade-pass tones and harmonics, discrete beating tones, or other time-varying properties, and can occur even at near-infrasonic frequencies if any of these factors is present; otherwise, it might pass unnoticed.[57, 67, 68] James[69] describes the infrasound occurring when wind turbine blades rotate past the tower as a short pressure pulse that consists of a well-defined array of tonal harmonics below 10 Hz. If the pressure peaks are received at the same time, they sum in a linear manner that significantly raises the overall SPL. Often, however, there are many wind turbines rotating at similar speeds, but not synchronized in time. This can lead to another form of modulation as the wind turbine infrasound is perceived as rising and falling, intermittent, or pulsating with variable intensity.

A common argument of wind industry proponents—one that is sometimes raised in legal proceedings—is that humans themselves generate infrasound by virtue of their own heartbeat and breathing, at levels that can be substantially higher than an external noise source such as wind turbines. In a rebuttal to a formal statement to this effect by the Association of Australian Acoustical Consultants (AAAC), Salt has provided a definitive explanation of why the two sources of infrasound (internal vs. external) cannot be equated. In a letter addressed to the AAAC,[70] Salt stated:

> "Stimulation of the ear occurs not directly by pressure (which is why deep sea divers can still hear) but by induced motions of the inner ear fluids, which in turn move sensory tissues and motion-sensitive cells….when low frequency and infrasound enters the ear via the stapes, it causes fluid movements throughout the entire ear between the stapes in the vestibule, through scala vestibuli and scala tympani to the compliant round window membrane at the base of scala tympani. It is these fluid movements that drive sensory tissue movements and cause stimulation. In contrast, pressure fluctuations generated by the body, such as by heartbeat and respiration, enter the ear via the cochlear aqueduct, not through the stapes. The cochlear aqueduct enters the ear adjacent to the round window membrane in the very basal part of scala tympani, so the fluid flows are localized in this tiny region of the ear. As the rest of the ear is bounded by a bony shell which is not compliant, fluid flows in the rest of the ear are substantially lower so that displacements of sensory tissues are negligible. Infrasound generated by the body, because it enters through the aqueduct, therefore does not cause stimulation of the ear."

Statement 3: There is no evidence that wind turbine noise, audible or inaudible, is the cause of adverse health effects in people, and there are no physiological mechanisms to explain how inaudible acoustic energy can be harmful.

In fact, there is ample evidence that noise in general, and especially low-frequency noise, has long-term consequences for human health.[71, 72] For example, long-term exposure to ordinary traffic noise has been associated in a dose-dependent manner with higher risk of myocardial infarction.[73]

Two landmark reports embodying diametrically opposing perspectives with regard to the impact of WTN on health appeared almost concurrently in 2009. One was published as a book by Dr.

Nina Pierpont,[4] a Fellow of the American Academy of Pediatrics who holds an MD degree from Johns Hopkins University School of Medicine and a PhD degree in Population Biology from Princeton University. The other report was written by a panel of seven experts (three physicians, two acousticians, an audiologist, and an audiologist/hearing scientist) commissioned by the American Wind Energy Association and the Canadian Wind Energy Association. The latter report[15] is commonly referred to as the AWEA/CanWEA report, or white paper. These respective reports, more than any others, quickly became the rallying cry for so-called anti-wind and pro-wind advocacy groups in the media, in the public discourse, and in court proceedings.

In her book, Pierpont[4] coined the term *Wind Turbine Syndrome* to describe a range of symptoms reported for 38 family members (adults and children) of 10 families who lived near wind turbines. Based on telephone interviews, she treated her observations and analyses as a case-series research design. She described the syndrome as consisting of 10 classes of symptoms (enumerated below), many of which she attributed to overstimulation of the vestibular system of the inner ear by ILFN. The wind industry, in its AWEA/CanWEA report and elsewhere, has vigorously criticized her study for being non-scientific and non-peer-reviewed. In fact, Pierpont's book was critically reviewed by far more than the usual number of reviewers for a peer-reviewed journal article. While it is true that case series are prone to selection bias, and can at best suggest hypotheses, many discoveries of new phenomena begin with a case study or case series. Furthermore, an increasing body of scientific evidence supports Pierpont's observations of a relationship between WTN and AHEs. More recent laboratory research, described later in this review, suggests that a variety of health symptoms may be due to ILFN stimulation of both vestibular and cochlear components of the inner ear.

Prior to Pierpont's book,[4] Dr. Amanda Harry[74] and Dr. Robyn Phipps and colleagues[75, 76] had documented the occurrence of ill effects from IWTs by use of questionnaire-based surveys of the health complaints of people living near wind projects in Cornwall, England, and Palmerston North, New Zealand, respectively. These authors concluded that a substantial number of people living near wind turbines suffer from health problems and that the cause of the disturbances was the complexity of the noise and vibration. Harry[74] observed that the symptoms were evident for people living within a mile from the wind development and recommended that no wind turbine should be sited closer than 1.5 mi. from the nearest residents. She noted that the guidelines used at the time to site wind turbines were developed when the turbines were 20% the size of the current ones. She concluded that annoyance from noise adversely affects human well-being, and that developers are wrong when they state that WTN is not a problem. Phipps et al[75] noted that 45% of households living within 2 km of the wind farm and 20% of households living up to 8 km away reported hearing noise from the turbines. Phipps[76] reported on the negative consequences of noise that were evident in her own survey and in the works of others, warning that residents do not readily habituate to the presence of WTN.

The AWEA/CanWEA report[15] has been widely used by the wind industry as a basis for its denial of AHEs from IWTs. However, the report is the product of a hand-picked group of experts, at least some of whom were known to hold positions favorable to the report's sponsors, it was never peer-reviewed, and it shows signs of bias, such as conclusions not supported by the research referenced in the report. That white paper concluded that sound from wind turbines, including sub-audible low-frequency sound, does not pose a risk of hearing loss or any other AHE in humans, whether those health effects are described as Wind Turbine Syndrome or otherwise. It also concluded that some people may be annoyed at the presence of sound from wind turbines, including its fluctuating nature, but described annoyance as unrelated to health. Although there is indeed no evidence that IWTs causes hearing loss, the report's conclusion that ILFN does not cause AHEs, and its dismissal of annoyance as a serious entity, have been heavily criticized as erroneous. Horner et al[77] cite many specific examples of the AWEA/CanWEA report's failure to use proper documentation, concluding that it lacks scientific merit and that it is neither authoritative nor convincing. They criticized the report's conclusion that the issue of AHEs stemming from IWTs is settled and that no more research is required, a conclusion that is rarely voiced by scientists. Horner[78] has characterized the report as offering nothing new in its treatment of annoyance, as annoyance has long been known to result from the stress effects of exposure to noise, and he criticized the report for downplaying the relationship between annoyance and health. Phillips[79] has indicated that the report mischaracterized the research designs used by epidemiologists. Despite widespread denial by wind industry advocates of a causal relationship between IWTs and AHEs, the vast majority of peer-reviewed papers have shown that IWTs significantly disturb sleep in at least some residents at distances and noise levels that are typical where IWTs are installed. Furthermore, not a single well-designed scientific study has found WTN to be harmless.[80, 81]

A panel of seven independent experts was commissioned by the Massachusetts Departments of Environmental Protection and Public Health to identify any documented or potential health impacts of risks that may be associated with exposure to IWTs and to facilitate a discussion of IWTs and public health based on scientific findings. The panel generated a report[82] concluding that scientific evidence is lacking to show that WTN leads to AHEs and that a more comprehensive assessment of WTN in populated areas is needed for establishing and refining siting guidelines and for developing best practices. Closer investigation was recommended near homes where outdoor A- and C-weighted levels differ by more than 15 dB, a strategy for detecting the presence of ILFN (e.g., Kamperman & James[83]). The Massachusetts report has been criticized as misrepresenting the evidence it cites, as well as underestimating evidence indicative of AHEs from IWTs.[84, 85] Schomer and Pamidighantam[86] have described the report as a critique of the literature relating to wind turbine acoustic emissions and health effects, and one with problems similar to those it criticizes.

Some laypersons have remarked disparagingly in the media on the factual evidence—including observations and scientific reports—that shows a relationship between IWTs and AHEs. Shahan,[87] for example, confidently states: “To date, there is no scientific evidence that anything such as ‘Wind Turbine Syndrome’ actually exists.” A common argument of wind energy advocates is that studies show that wind turbines do not lead to AHEs, or that studies that draw such a conclusion are not sufficiently scientific to establish causation. Efforts to discredit those who take a skeptical view toward the wind industry commonly use terms such as *opponents*, *detractors*, *anti-wind activists*, or in the case of Shahan,[87] “paid anti-wind ‘experts’ who have a long history of directly testifying against wind energy in various court cases.” Such critics casually ignore the fact that many of the industry experts, including consulting acousticians and physicians, routinely testify on behalf of the industry in such cases, sometimes for substantial fees, and those individuals are rarely described as paid pro-wind experts or activists.

Numerous researchers have reported the existence of a constellation of health symptoms, either directly mirroring or closely related to those described as Wind Turbine Syndrome by Pierpont,[4] in persons living near IWTs. Significantly, the WHO[38] states that there is sufficient evidence that nighttime noise, irrespective of its source, is related to self-reported sleep disturbance and other health problems, and that these effects can lead to a considerable burden of disease in the population.

Sleep disturbance has been identified as a major adverse impact of IWTs.[4, 18, 45, 47, 54, 57, 58, 72, 74, 76, 77, 79, 80, 81, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107] Nighttime exposure to 40-dBA low-frequency noise has been shown to affect cortisol levels, a physiological indicator of stress. Those levels, following awakening, have been found to be associated with subjective reports of lower sleep quality and mood changes.[108] Sleep is a biological necessity, and disturbed sleep is associated with a number of adverse health conditions. The WHO[71] has concluded that there is available, good-quality evidence supporting a causal association between noise and sleep disruption. Sleep disturbance has important implications for public health and may be a particular problem in children.[84, 94, 109]

Even if no other adverse effects were associated with WTN, sleep disturbance alone is a sufficient reason to site turbines at distances that do not disrupt sleep. Many rural communities have background, nighttime sound levels that do not exceed 25 dBA, and observable effects of nighttime, outdoor noise do not occur at levels of 30 dBA or lower.[71] As outdoor sound levels increase, the risk of AH1Es increases, the most vulnerable populations being the first to show their effects. Vulnerable populations include elderly persons; children, especially those younger than age six; and people with pre-existing medical conditions, especially if sleep is affected.[38, 71] According to the WHO, there is ample evidence to link AHEs with prolonged exposure to outdoor sound levels of 40 dBA or higher. It is important to note that the WHO guidelines are based largely on industrial and transportation noise research, and not on wind turbine research. Because multiple studies (covered in this review) have indicated that WTN is significantly more annoying, has higher infra- and low-frequency sound energy, and is modulating, pulsatile, and sometimes tonal, it may impact health to a greater degree than other noises. This means that noise limits in the WHO guidelines may need to be adjusted downward when applied to WTN.

Additional factors increase the probability of sleep disruption due to WTN. The noise can be heard especially well in areas with low background noise levels, which usually occur at night. Also, lower nighttime wind speeds at ground level increase the nighttime contrast between WTN and background sound levels. Using test data taken during daytime wind conditions will result in a large underestimate of nighttime WTN levels, and thus underestimate the potential for sleep disruption.[38, 58]

Researchers who have studied the impacts of ILFN in general and WTN specifically on health, including some who have reviewed and assessed the findings of other researchers, have attributed a variety of symptoms to ILFN exposure. Those symptoms have been variously described by different researchers, with varying degrees of overlap and detail. They are shown, in no particular order, in Table 1.

Clearly, in addition to annoyance, the most commonly experienced and least-contested health symptom suffered by people living near IWTs is sleep disturbance.[110] Both the United Nations Committee against Torture (CAT) and the Physicians for Human Rights[111] describe sleep deprivation as critical to human functioning. According to Physicians for Human Rights:

> "Sleep deprivation ... causes significant cognitive impairments including deficits in memory, learning, logical reasoning, complex verbal processing, and decision-making; sleep appears to play an important role in processes such as memory and insight formation" (p. 22).

Table 1. Health symptoms described by different researchers as linked to exposure to infrasound and low-frequency noise, including exposure to industrial wind turbines.

Author (Year)	Reference	Symptomatology
Pierpont (2009)	4	Sleep disturbance; headache; Visceral Vibratory Vestibular Disturbance (VVVD); dizziness, vertigo, unsteadiness; tinnitus; ear pressure or pain; external auditory canal sensation; memory and concentration deficits; irritability and anger; and fatigue and loss of motivation
Leventhall (2003) Kasprzak (2014)	12 112	Vibration of bodily structures (chest vibration), annoyance (especially in homes), perceptions of unpleasantness (pressure on the eardrum, unpleasant perception within the chest area, and a general feeling of vibration), sleep disturbance (reduced wakefulness), stress, reduced performance on demanding verbal tasks, and negative biological effects that include quantitative measurements of EEG activity, blood pressure, respiration, hormone production, and heart rate
Havas & Colling (2011)	91	Difficulty sleeping, fatigue, depression, irritability, aggressiveness, cognitive dysfunction, chest pain/pressure, headaches, joint pain, skin irritations, nausea, dizziness, tinnitus, and stress
Horner (2013) Paller et al (2013)	78 113	Headaches, nausea, tinnitus, vertigo, and worsened sleep
Jeffery et al (2013)	92	Sleep disturbance; subjective complaints such as headaches, fatigue, temporary feelings of dizziness, and nausea; objective complaints such as vomiting, insomnia, and palpitations; annoyance; and reduced quality of life (QoL)
Jeffery et al (2014)	93	Negative impacts on the physical, mental and social well-being of people
Krogh et al (2012)	96	Annoyance (regarded as an adverse health effect associated with stress), sleep disturbance, headaches, difficulty concentrating, irritability, fatigue, and a variety of more-serious ailments
Minnesota Department of Health (2009)	55	Annoyance, reduced quality of life, sleeplessness, and headache
Howe Gastmeier Chapnik Limited (2010)	114	High levels of annoyance in a non-trivial percentage of persons, with annoyance associated with sound from wind turbines expected to contribute to stress-related health impacts in some persons

Author (Year)	Reference	Symptomatology
Nissenbaum (2013)	81	Sleep disturbances/sleep deprivation and the multiple illnesses that cascade from chronic sleep disturbance, which include cardiovascular diseases mediated by chronically increased levels of stress hormones, weight changes, and metabolic disturbances (including the continuum of impaired glucose tolerance through diabetes); psychological stresses that can result in cardiovascular disease, chronic depression, anger, and other psychiatric symptomatology; headaches, auditory and vestibular system disturbances; an increased requirement for and use of prescription medication; tinnitus; and vertigo
Nissenbaum et al (2012)	97	Increased sleep disruption, reduced mental health
Thorne (2013)	49	Sleep disturbance, headache, tinnitus, ear pressure, dizziness, vertigo, nausea, visual blurring, tachycardia, irritability, problems with concentration and memory, and panic attack episodes
Pawlaczyk-Luszczyńska et al (2005)	115	Problems with vision, concentration, and continuous and selective attention (especially in persons who are highly sensitive to low-frequency noise)
Pedersen (2011)	99	Annoyance (both outdoors and indoors), statistically related to SPLs; sleep interruption, diabetes, and tinnitus (at one of three test sites); annoyance outdoors, significantly related to sleep interruption, tension, stress, irritability (at all three sites), headache (at two sites), and undue fatigue (at one site); annoyance indoors, significantly related to sleep interruption (at all three sites), and to diabetes, headache, undue fatigue, tension, stress, and irritability (at one of three sites)
Roberts & Roberts (2013)	102	Vibration or fatigue, annoyance or unpleasantness
Shepherd & Billington (2011)	103	Annoyance, which has been linked to increased levels of psychological distress, stress, difficulty falling asleep, and sleep interruption
Taylor (2013)	58	Annoyance, stress, sleep disturbance, interference with daily living, headache, irritability, difficulty concentrating, fatigue, dizziness, anxiety, and reduced QoL
Ambrose et al (2012) Rand et al (2011)	61 116	Dizziness, irritability, headache, loss of appetite, fatigue, inability to concentrate, a need to leave the home, and a preference for being outdoors (during investigations of WTN by seasoned researchers, including acousticians)
Thorne (2011)	46	Sleep disturbance, anxiety, stress, and headaches

Author (Year)	Reference	Symptomatology
Palmer (2013)	117	Negative impacts on sleep, job stability, social relationships, care giving, pursuit of hobbies, leisure, learning, and overall health (based on interviews of residents four years after living near operational wind turbines)
Castelo Branco & Alves-Pereira (2004) Castelo Branco (1999)	118 119	Vibroacoustic disease, described as occurring only after extensive exposure to high levels of infrasound

Other sources quoted by the Physicians for Human Rights[111] note that:

> "A review of the medical literature reveals numerous adverse cognitive effects of sleep deprivation including impaired language skills-communication, lack of innovation, inflexibility of thought processes, inappropriate attention to peripheral concerns or distractions, over-reliance on previous strategies, unwillingness to try out novel strategies, unreliable memory for when events occurred, change in mood including loss of empathy for colleagues, and inability to deal with surprise and the unexpected" (pp. 22-23).

Another line of reasoning is that there is a cause-effect relationship between AHEs and ILFN from wind turbines that mirrors that in motion sickness. Kennedy et al[120] made acceleration recordings during 193 standard training mission scenarios for two moving-base flight trainers. The pilots, who were of comparable age and experience in both groups, were interviewed for motion sickness symptomatology and tested for ataxia after leaving the simulators. Motion sickness incidence was high for one of the simulators, but not for the second. Ataxia scores departed slightly from expected improvements following exposure in both simulators. Spectral analyses of the motion recordings showed significant amounts of energy in the *nauseogenic range* of 0.2 Hz. The authors concluded that simulator sickness in moving-base simulations may be, at least in part, a function of exposure to infrasonic frequencies that make people seasick. Later, von Gierke and Parker[121] advanced the notion that motion sickness may involve an intermodal sensory conflict between visceral graviceptor signals and vestibular stimulation. Schomer and colleagues[52, 86] have argued that similarities with motion sickness may explain some of the health symptoms suffered by individuals living near IWTs, given that the inner ear is capable of responding to accelerations of the kind that lead to seasickness. These accelerations correspond to frequencies in the infrasonic range, around and under 1 Hz. Schomer[66] states that some persons affected by WTN may be responding directly to acoustic factors, rather than to non-acoustic factors, as argued by Leventhall.[14]

In a rare show of cooperation between the wind industry and independent acousticians, Pacific Hydro agreed to allow acoustician Steven Cooper, a consultant for The Acoustic Group,[25] unlimited access to its Cape Bridgewater wind project in SW Victoria, which had been in operation for about six years. The company allowed Cooper to make noise measurements and independently investigate the noise complaints of six affected residents at three residences located 650-1,600 m from the nearest turbines while the company controlled the on-off cycling of turbine operation. Given Cooper's credentials as an acoustician, the study was described as an acoustical study, as opposed to a medical study. Noise levels were based on A-, G-, and Z-weighted measurements, as well as 1/3-octave band and narrow-band measurements. Participants vacated their homes at night when necessary for Cooper to perform his acoustic studies, and they provided detailed diary accounts of their observations during on-off cycles. Those accounts included severity ratings of perceptions of noise impacts, vibration impacts, and other disturbances, which were collectively labelled as *sensations*. The sensations included headache; pressure in the head, ears, or chest; ringing in the ears; heart racing; or a sensation of heaviness. Synchronization of the timing of the residents' experiences with turbine operational data revealed heightened sensations inside their dwellings during turbine operation. Sensations were not dependent on the ability to hear or see the turbines, as residents were not aware of any of the turbines' operational characteristics. Cooper found that *sensation*, and not *noise disturbance*, was the major disturbance identified. Furthermore, sensations were most related to several different operating conditions of the turbines: at start-up, when there was an increase or decrease in power output of about 20%, and when the turbines were operating at maximum power and the wind speed increased above 12 m/sec.

Based on narrow-band data, Cooper identified a unique *wind turbine signature* (WTS) in which there was an energy peak at the blade-pass frequency and first five harmonics. Shutdown testing confirmed that the WTS, which included an amplitude-modulated signal, was present when the turbines were operating, but not in a natural environment during a turbine shutdown. Participants rated sensations as proportionally more severe as increases occurred in the magnitude of the low-frequency amplitude-modulated signature. The identification of infrasound components was consistent with earlier observations of Kelley et al.[19] Based on his findings, Cooper recommended that further studies be conducted to determine a threshold level of the WTS that protects against adverse impacts, and that the signature concept be used in medical studies by identifying energy from the operation of wind turbines, as the A-weighted scale inside homes is of no assistance in such studies.

In consideration of the above findings and observations, it is reasonable to conclude that IWTs cause AHEs and other unwanted disturbances. We next examine the physiological mechanisms that may explain how inaudible infrasound can be harmful.

In a recent paper, Berger et el[122] concluded that ILFN levels are insufficient to induce AHEs, given the levels of ILFN typically produced by wind turbines, and that guidelines for audible noise are sufficient to protect human health. Their conclusions were based on measurements of indoor infrasound levels and low-frequency noise levels at distances >500 m that were similar to background levels. While we believe the design and major conclusions of their study to be faulty, their conclusions are consistent with the position taken by Leventhall and other wind energy advocates over the past decade.

In her original description of Wind Turbine Syndrome, Pierpont[4] described a distinctive constellation of symptoms that she believed to be due to stimulation, or overstimulation, of the vestibular organs of balance as a consequence of ILFN from wind turbines. She termed these symptoms Visceral Vibratory Vestibular Disturbance (VVVD). In a follow-up report, Pierpont[100] **s**uggested that the observed symptoms of Wind Turbine Syndrome are due to air-borne or body-borne low-frequency sounds that directly stimulate the inner ear, both the cochlea, or hearing organ, and the vestibular organs of balance and motion detection. As discussed below, research by Salt and associates shows that responses in the cochlea suppress the perception of low-frequency sound but still send signals to the brain, signals whose function is, at present, mostly unknown. The physiologic response of the cochlea to WTN is also a trigger for tinnitus and the brain-cell-level reorganization that tinnitus represents. Although cochlear and vestibular organs are housed within the same bony (otic) capsule, evolutionary adaptations have led to selective activation of auditory or vestibular hair cells. In the presence of certain disorders of the inner ear, however, anatomical defects in the otic capsule can alter the functional separation of auditory and vestibular stimuli, resulting in pathological activation of vestibular reflexes in response to sound.[123] The possibility that high-level ILFN can stimulate the vestibular organs lends credibility to Pierpont's suggestion and may explain the basis for symptoms that mimic other vestibular disorders. Physiologic responses from the otolith organs generate a wide range of brain responses, including dizziness and nausea, seasickness (even without bodily movement), fear and alerting responses such as startle and wakefulness, and difficulties with visually based problem-solving.[100] One candidate for the other destination of cochlear input from the outer hair cells may be the interface between the insula and the medial surface of the transverse (Heschl's) gyrus, where primary hearing is experienced but not recognized as sound; the latter involves adjacent secondary areas.[124]

WTN can increase alerting responses that disturb sleep, even when people do not recall being awakened. This effect is one that clearly disturbs sleep and mental well-being out to 1,400 m (4,600 ft.) from turbines, with diminishing effects out to 3 km (3 mi.), as shown in a cross-sectional study by Nissenbaum et al.[97]

Laboratory studies conducted by Salt and colleagues have provided evidence that clearly establishes the biological plausibility that infrasound can adversely affect health. That work shows that there are mechanisms in the inner ear that are capable of transducing infrasonic energy into a neural signal that can be transmitted to the brain, where the signals can lead to such symptoms as tinnitus, dizziness, pulsations, and sleep disturbance. Those studies by Salt and associates have involved laboratory experiments funded primarily by the National Institutes of Health and conducted mostly on guinea pigs, whose ears are very similar to human ears. Basically, electrodes were inserted into the inner ears to determine which structures respond to specific types of electroacoustic stimulation. Their findings help to explain why sound that is normally inaudible can result in the kinds of negative reactions reported by people who are exposed to wind turbine ILFN. Findings from their research indicate the following:

(1) The inner hair cells (IHCs) of the inner ear, which are primarily responsible for transmitting signals to the brain that are interpreted as sound, are velocity-sensitive, and thus unresponsive to infrasound. The outer hair cells (OHCs), on the other hand, are displacement-sensitive and respond to infrasonic frequencies at levels well below those that are heard (i.e., interpreted as sound). This suggests that most IWTs produce an unheard stimulation of OHCs;[56, 125, 126] specifically, at 5 Hz the OHCs can be stimulated at sound pressures 40 dB below those that stimulate the inner hair cells associated with conscious hearing.[126]

(2) Low frequencies, which are coded in the cochlear apex, require less low-frequency SPL to be amplitude modulated, when compared to higher frequencies, which are coded in the cochlear base. This means that amplitude modulation of audible sounds by wind turbine infrasound may be the basis for complaints of those living near wind turbines, including complaints such as annoyance or feelings of throbbing and rumbling sensations. It also means that infrasound from wind turbines need not be audible to annoy people, since infrasound can amplitude modulate sounds that are within the range of audibility.[54]

(3) There are several ways that infrasound could affect people, even though they cannot hear it: (a) causing amplitude modulation (pulsation) of heard sounds, (b) stimulating subconscious pathways, (c) causing endolymphatic hydrops, and (d) possibly potentiating, or exacerbating, noise-induced hearing loss.[127]

(4) Responses to infrasound reach the brain through pathways that do not involve conscious hearing but instead may produce sensations of fullness, pressure or tinnitus, or absence of sensation. Activation of subconscious pathways by infrasound could disturb sleep.[128]

(5) The presence of other, higher-pitched sounds (between 150-1,500 Hz) can suppress infrasound.[129, 130, 131] Because the ear is maximally sensitive to infrasound when higher frequency sounds are absent, this means that WTN is most disturbing to persons inside their homes at night, when background sound levels are low and higher-pitched sounds are attenuated by walls and other physical structures.

(6) A pathway exists, through the OHCs, for infrasound to reach the brain. There, parts of the brain other than auditory centers become active and the signals are perceived as something other than sound. This pathway to the brain, which also includes the vestibular mechanism of the inner ear, means that it is biologically plausible for infrasound to produce a variety of sensations, including pulsation, annoyance, stress, panic, ear pressure or fullness, unsteadiness, vertigo, nausea, tinnitus, general discomfort, memory loss, and disturbed sleep (with chronic sleep deprivation leading to blood pressure elevation and possibly changes in heart rate).

On the above grounds, Salt dismisses the common perception that *What we can't hear can't hurt us*, and has stated unequivocally that "Wind turbines can be hazardous to human health."[132]

Interestingly, Oohashi et al,[133]using non-invasive physiological measurements of brain responses, found evidence that sounds containing *high-frequency* components *above* the audible range, or ultrasound, significantly affect the brain activity of healthy human listeners. It should not be considered implausible, therefore, that infrasonic stimulation can also activate the brain.

Recent research supports the plausibility of such effects. Bauer et al,[134] using functional magnetic resonance imaging (fMRI), found a significant response down to the 8 Hz, the lowest frequency presented, to be localized within the auditory cortex. Using magnetoencephalography (MEG), significant brain responses could be detected down to a frequency of 20 Hz. The authors hypothesized that a somatosensory excitation of the auditory cortex possibly contributes at these frequencies. In a somewhat related study, He and Krahé[135] demonstrated a significant relationship between EEG reactions under different low-frequency noise exposures and subjective annoyance. Noise sensitivity was also found to be an important factor in most of the observations. The authors of these two studies suggested that EEG, fMRI, and MEG may serve as effective physiological measures to explain negative reactions to low-frequency noise.

Kugler et al[136] measured spontaneous otoacoustic emissions (SOAEs) before and after stimulation with perceptually unobtrusive low-frequency sound (30 Hz) and found significant changes to occur; these changes were positively correlated in frequency and level to pre-exposure status and lasted for about 2 min after stimulation. SOAEs are narrow-band acoustic signals that are spontaneously emitted by the inner ear in the absence of acoustic stimulation, and they can be recorded simply and non-invasively in the ear canal with a sensitive microphone. Otoacoustic emissions, first reported by physicist David Kemp,[137] are a by-product of active biophysical amplification by OHCs in the cochlea, persisting in relatively stable form for years under normal physiological conditions. The main task of the OHCs is to detect and mechanically amplify sound waves. In acting as a cochlear amplifier, OHCs actively generate mechanical energy, which is fed back into the cochlear travelling wave to maximize the sensitivity and dynamic range of the mammalian ear. In humans, non-invasive recordings of different classes of sound-evoked otoacoustic emissions (EOAEs) allow indirect access to OHC function, but only SOAE measurements can probe the cochlea in its natural state. The presence of OAEs signals a healthy ear, and their absence or changes in their response patterns can signal pathological function. The significance of the work by Kugler et al is that it reveals OHC function to be affected by a brief exposure to very low-frequency sound that is largely imperceptible. It also reveals that measures of perception severely underestimate OHC sensitivity. The authors concluded that direct quantifications of inner ear active amplification, as measured in their study, are well suited for assessing the risk potential of low-frequency sounds. In the present context, the study provides further support for the notion that what we can't hear can potentially affect us.

Motion sickness has been mentioned in this article as being among the variety of symptoms suffered by individuals living near IWTs. Recalling the work of Kennedy et al,[120] who found evidence of motion sickness in Navy pilots subjected to acceleration during flight simulation, Schomer et al[138] stated that it is plausible that the ear responds similarly to accelerations of a moving vehicle and acoustic pressures at infrasonic frequencies under 1 Hz, in the nauseogenic range. They suggested that the AHEs experienced as a consequence of exposure to IWTs not only bear a striking resemblance to motion sickness, but that the condition may be induced by stimulation of the otolithic organs in the vestibular system of the inner ear. That type of stimulation is purportedly worse when a person is subjected to pressure changes in a closed cavity, including inside one's home. Further, they describe the type of research needed to verify their hypothesis.

Michaud and colleagues have recently authored a series of papers[139, 140, 141, 142, 143, 144, 145] describing a cross-sectional epidemiological study conducted under the sponsorship of Health Canada, in which they investigated the prevalence of health effects or health indicators among a sample of Canadians exposed to WTN. The studies employed both self-reported and objectively measured health outcomes. The final sample, drawn from communities in Ontario and Prince Edward Island where a sufficient number of dwellings were located near wind turbine installations, included 1,238 participates (606 males, 632 females) living between 0.25 and 11.2 km from operational turbines. One participant between the ages of 18-79 years was randomly selected from each household. The reported response rate was 78.9% and did not significantly vary across sampling strata or provinces. Modelled A- and C-weighted WTN levels reached 46 dBA and 63 dBC, respectively, and the two levels were found to be highly correlated, which suggested that C-weighted values offered no additional information beyond that offered by A-weighted values. Only minor differences across strata were reported for age, employment, and type and ownership of dwelling. WTN exposure was not found to be related to hair cortisol concentrations, blood pressure, resting heart rate, or any of several measured sleep parameters (i.e., sleep latency, sleep time, rate of awakenings, sleep efficiency). Self-reported results obtained through an in-person questionnaire did not provide support for an association between increasing WTN levels and self-reported sleep disturbance, use of sleep medication, or diagnosed sleep disorders. Similarly, no significant association was found between WTN levels and self-reported migraines, tinnitus, dizziness, diabetes, hypertension, perceived stress or any measure of QoL. However, they observed statistically significant exposure-response relationships between increasing WTN levels and the prevalence of long-term high levels of annoyance toward noise, shadow-flicker, visual impacts, blinking lights, and vibrations.

The authors of the present report, along with a number of professional colleagues with acoustical or medical expertise, have carefully analyzed the reports by Michaud and colleagues and have concluded that the research protocol of the Health Canada study reflects shortcomings that severely undercut the conclusions that were drawn in the various reports. To enumerate the major flaws in the Michaud et al reports:

(1) They incorrectly concluded that AHEs were not found when sound levels were below 46 dBA by failing to benchmark their "surrogate control group" against the general population. Proper analysis, using a proper control group, would have resulted in high correlations of these symptoms with decreasing distances to, and increasing noise levels from, wind

turbines. In reports of the sound-exposure data, sound levels of 30-35 dBA were significantly associated with increases in the prevalence rates of symptoms. This indicates that the 40 dBA currently used as the permissible threshold in Ontario and other Canadian provinces is not protective of the public's health and welfare.

(2) Key health symptoms were reported primarily for non-vulnerable populations, in that younger individuals and individuals who had left their homes were excluded from participation. Those exclusions invalidate the study as a reflection of health conditions in the general population.

(3) Evidence provided by the World Health Organization[38] showing that exposure to noise from vehicles, railways, and aircraft is linked to serious physiological and psychological health effects at sound levels of 40 dBA and higher, and that lower levels are needed to protect the more vulnerable members of the population, was ignored in the Health Canada study. The finding that AHEs did not occur below 46 dBA should have been a warning sign to the researchers that their study design, their analyses, or both, were flawed.

Statement 4: Setback distances of 1,000-1,500 ft. (approximately 0.3-0.5 km) are sufficiently safe to protect humans from harm, regardless of height or other physical characteristics of the IWTs.

Many zoning ordinances that regulate IWTs specify the height of the turbine tower from its base to blade tip, plus 10% to 100%, as a setback distance that sufficiently protects residents against a catastrophic event such as a tower failure, a falling blade, or ice throw. Some ordinances specify a distance of twice the base-to-blade tip height, roughly 900 ft., while others arbitrarily specify slightly longer distances such as 1,500 ft. or 0.5 km. Most of the reported health symptoms have been observed at distances much greater than these setback distances. One can deduce, therefore, that *setbacks intended to protect physical health from mechanical or other traumatic failure of a wind turbine component are not adequate to protect general health and well-being*.

While terrain, weather patterns, number and size of turbines, and the turbine array itself can influence the ILFN emitted from IWTs, the two major factors are turbine size and distance from the receiver. Distance is the only practical means of achieving acceptable sound levels, as controlling the noise through the erection of barriers or enclosures near the source or receiver are not feasible or effective. Because infrasound is involved, closing windows, insulating buildings (including residences), and sleeping in basements are not normally helpful in attenuating the noise, and there is less likelihood that the emissions will be masked by wind at ground level.[60, 146] Noise levels must be measured by qualified personnel, and the sound level at the residence—or arguably at the property line—is the key element in protecting the health of residents.

To protect human health, a number of researchers have recommended specific distances, while others have recommended limitations on sound levels, irrespective of the distances needed to achieve those levels. Such recommendations are based on observed or reported complaints of AHEs. Though quite specific, the recommendations vary somewhat widely, as shown in Table 2.

The recommendations in Table 2 include boundaries of distance and noise levels of 0.5-2.5 mi. and 30-40 dB, respectively, that are believed by various professionals to protect human health. Although the use of maximum permissible noise levels appears to be the optimal approach for protecting the greatest number of people, the existence of multiple acoustic and environmental factors complicates our ability to recommend a single distance or noise level that protects most residents. Those factors are covered elsewhere in this review.

Table 2. Recommended minimum siting distances and maximum noise levels of industrial wind turbines, based on the protection of human health.

Author (Year)	Reference	Distance/Level
Pierpont (2009) Kamperman & James (2008)	4 83	Distance of 1.25 mi, or 2 km
Nissenbaum et al (2012)	97	Minimum distance of 0.87 mi, or 1.4 km, based on experimental conditions studied
Harry (2007)	74	Minimum distance of 1.5 km from nearest turbine
Frey & Hadden (2007)	90	2 km between family dwellings and IWTs of up to 2-MW installed capacity, with greater separation for a wind turbine greater than 2-MW installed capacity
Shepherd & Billington (2011)	103	4 km, to protect against amplitude-modulated turbine noise
Position of the National Institute of Public Health-National Institute of Hygiene on wind farms (2016)	147	A minimum distance of 2 km of wind farms from buildings
Cummings (2011)	39	Distance of ½ mi or greater; noise levels within 5-10 dB of existing background conditions; sound levels below 40 dBA, or even 30-35 dBA, as levels of 40 dBA or higher trigger large numbers of noise complaints
World Health Organization (2009)	38	Outdoor sound levels <40 dBA, with vulnerable populations expected to be most affected

Author (Year)	Reference	Distance/Level
Knopper et al (2014)	148	Sound levels <40 dBA, for non-participating receptors
Horner (2013)	78	Sound levels <30 dB
Harrison (2011)	42	Sound levels limited to 35 dBA at nighttime and 40 dBA during daytime hours; 5-dBA and 4-dBA penalties, respectively, imposed for the periodic or impulsive character of turbine noise and for uncertainty in noise prediction
Thorne (2013)	49	Sound levels <32 dB LAeq outside a residence

Statement 5: Annoyance is a nuisance, but it is not a health issue.

In the past few years, the position of the wind industry has changed from a blanket denial of any impact from noise to admitting that IWT noise is annoying to a substantial portion of exposed populations, and that annoyance from ILFN is a well-accepted phenomenon. While Bolin et al[18] and Ellenbogen et al[82] downplay the relationship between annoyance and WTN, the larger research community has documented that ILFN from wind turbines and other sources leads to annoyance.[12, 14, 15, 19, 21, 37, 38, 40, 42, 46, 49, 55, 58, 59, 63, 64, 74, 78, 80, 81, 90, 92, 94, 98, 99, 102, 118, 146, 149, 150]

Several investigators have concluded that annoyance increases in a dose-response relationship as distance from turbines is reduced.[44, 89, 146] A number of studies have concluded that noise annoyance appears to be worse when nearby residents have negative attitudes and when visual annoyance or intrusive sound characteristics are also involved.[e.g., 44, 65, 112, 146, 151] However, the annoyance from visual stimulation and the annoyance from noise may be entirely independent. The two irritants do not have to be linked. The common factor is that as one moves closer to a wind turbine, it is perceived as both larger *and* louder. One recent study,[152] which compared visual, audible noise, and combined visual-auditory representations of wind turbines, found noise sensitivity to correlate with both noise and visual annoyance. That study also demonstrated a reciprocal influence between auditory and visual stimuli, but in essentially a direction opposite that predicted by earlier studies of wind turbine visibility and noise. Interestingly, the study showed that a visual stimulus had a mitigating effect on noise annoyance, while an auditory stimulus had a disturbing effect on visual annoyance. This finding supports the idea that humans perceive the environment holistically and in context of all perceptual information. In suggesting that auditory and visual features are processed in close interaction, it forces us to question the idea that annoyance from WTN arises largely because the turbines are visible. Given our current state of knowledge, it seems reasonable to accept that people can be annoyed by auditory and visual irritants independently, even though there may be interactions between them.

Annoyance occurs in residents living near wind turbines at lower sound levels than for transportation noise, industrial noise, or other sources.[38, 42, 43, 58, 64, 93] Perception and annoyance have been found to be associated with both urbanized and rural terrains.[149] Pedersen et al,[146] in summarizing survey data on annoyance from wind turbines in the Netherlands and Sweden, found that 25% or more of all respondents were annoyed by levels of 40-45 dBA, while about 18-20% were very annoyed by those levels. A total of 18% found outdoor levels of 35-40 dBA to be rather annoying or very annoying outdoors and 8% found those levels to be rather or very annoying indoors. For outdoor levels of 40-45 dBA, 18% and 16% were rather or very annoyed outdoors and indoors, respectively. Because such surveys tend to emphasize *noise* from wind turbines, results often reflect levels of annoyance that relate more directly to audible sounds, as opposed to infrasound.

While few would argue that noise from wind turbines annoys a substantial percentage of nearby residents, there is disagreement over whether it leads to AHEs. Colby et al[15] stated that:

> "…there is no evidence for direct physiological effects from either infrasound or low frequency sound at the levels generated from wind turbines, indoors or outside" (p. 3-8).

They reasoned, therefore, that annoyance is not a pathological entity. Their basic contention was that although wind turbines produce infrasound, it is not harmful because people can't hear it. They contended that while some people may be annoyed by the sound from wind turbines — presumably audible sound—annoyance is primarily due to the fluctuating nature of the noise and personal attitudes. In their view, it is a psychological reaction, as opposed to a direct physiological reaction to sound. As noted above, however, several investigations[44, 89, 146] have found a dose-response relationship to exist between measured or estimated sound levels and annoyance. IWT noise emissions have been found to be a mediator between exposure and sleep disturbance and psychological distress,[89] and to be directly associated with stress.[e.g., 104]

The documented health symptoms from exposure to wind turbines are often stress-related and exacerbated by sleep disorders; they appear to be mediated through both direct and indirect pathways, and the result can be serious harm to human health.[92] There is an association between WTN, stress, and well-being, and this association is a potential hindrance to psycho-physiological restitution.[58, 98] The WHO has described annoyance as a critical health effect, in that in some people it is associated with stress, sleep disturbance, and interference with daily living.[38] A range of symptoms, often described as stress responses, have been associated with

WTN in people living in the vicinity of wind projects. As Pierpont[4] and others have noted, these symptoms include headache, irritability, difficulty concentrating, fatigue, dizziness, anxiety, and sleep disturbance. Regardless of whether the perceived impacts of noise from wind projects are physiological or psychological in nature, they are considered to cause AHEs through sleep disturbance, reducing the quality of life and serving as a source of annoyance that sometimes leads to stress-related symptoms.[71] The potential of environmental noises to induce stress reactions is well known. These reactions are dependent on how the noises are interpreted in the central nervous system; medical effects such as increased blood pressure, for example, are known to result from prolonged noise exposure.[153]

Generally, models that explain the relationship between noise and health fall into two broad categories, based on pathways that are *direct* or *indirect*. Figure 1, which is a modification of a figure from Shepherd et al,[50] depicts three models, one direct and two indirect, that have been described in the contemporary literature. The first (Fig. 1a) represents a direct pathological relationship between an environmental parameter (e.g., noise level) and a target organ that affects health. For example, in this model, noise can affect both cognition and sleep, and thus directly impact health. An alternative approach (Fig. 1b) distinguishes between direct health effects and psychosomatic illness. This approach suggests that any physiological illness coinciding with the onset of WTN may be caused by a negative psychological response to the noise, and not the noise *per se*. Any anxiety or anger resulting from the presence of WTN induces stress and strain that, if maintained, can eventually lead to AHEs. Another explanation that involves an indirect pathway from sound to health effects is one that is consistent with the WHO's definition of health.[38] That model (Fig. 1c) recognizes the role of environmental moderators, or mediators, in the determination of whether a sound is (unwanted) noise, and, if so, whether or not the noise

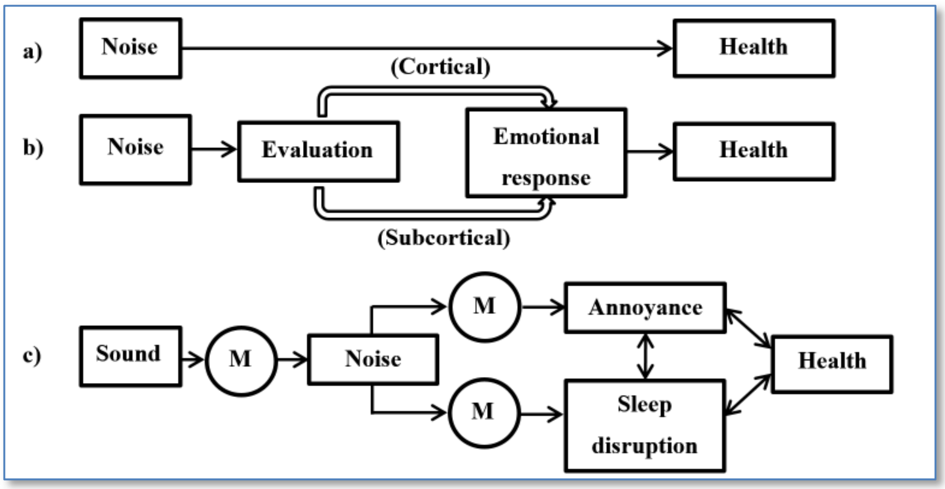

Figure 1. Three models representing the relationship between noise and health: the biomedical model (a) stipulating a direct causal relationship and indirect models (b and c) containing moderators and mediators (Adapted from original source and used with permission of first author, Daniel Shepherd).[50]

negatively impacts health. Mediators include factors such as degree of urbanization, house type, and sound level, and psychological and demographic moderators such as age, gender, education, employment status, attitudes to wind energy, noise sensitivity, and whether the individual receives a monetary return from the turbines. In this model, sleep disruption plays a major role in producing AHEs, with annoyance and sleep disruption being intervening factors between noise and AHEs for some people.

Authors of a recent study,[154] which focused on the province of Ontario, acknowledge both the link between annoyance and health and the possibility that wind projects can exacerbate psychosocial health problems through social processes such as intra-community conflict. They list socially mediated health concerns, distribution of financial benefits, lack of meaningful engagement, and failure to treat landscape concerns seriously, as the core stumbling blocks to a community's acceptance of wind energy development.

Statement 6: Noise cannot account for all of the complaints of people living in the vicinity of wind turbines; there must be another, unknown reason for the complaints.

Havas & Colling[91] have observed that wind turbines generate electromagnetic waves in the form of poor power quality (*dirty electricity*) and ground current, and speculate that these waves can adversely affect those who are electrically hypersensitive. McCallum et al[155] performed magnetic field (EMF) measurements in the proximity of 15 Vestas 1.8-MW wind turbines, two substations, various buried and overhead collector and transmission lines, and nearby homes in the vicinity of Goderich, Ontario, during high-wind, low-wind, and shut-off operational stages. They concluded that there is nothing unique to wind farms with respect to EMF emissions, finding that magnetic field levels in the vicinity of wind turbines were lower than those produced by many common household electrical devices and that levels were well within any existing regulatory guidelines with respect to human health.

Although at least a few of the health symptoms mentioned above have been self-reported by individuals who are exposed to electromagnetism, clinical trials to date suggest the link between health complaints and exposure to electromagnetism to be a purely psychological one, or a nocebo effect, in that self-described sufferers of electromagnetic hypersensitivity are unable to distinguish between exposure and non-exposure to electromagnetic fields.[156] Another review paper[157] found no convincing scientific evidence that symptoms are caused by electromagnetic fields. However, one cannot rule out that the design of the experiments upon which the review papers drew their conclusion may have missed some unique characteristic that could account for the anecdotal evidence. (See our earlier statements describing how failure to identify infrasound pulsations as a causal factor for perception at pressure levels below those needed for audibility have led some to conclude that IWT infrasound causes no harm.) When faced with health complaints from families who live near IWTs, especially when there are repeated instances of symptoms that wax and wane with alternating sequences of exposure and non-exposure, and especially when those families have taken the drastic step of abandoning their homes, it is unreasonable to argue that noise is not the cause of the complaints. Even if other factors such as electromagnetic waves are the root cause of a given complaint, it is still the placement of turbines too close to those residents that is the most likely cause of the problem.

Unfortunately, not as much is known about the effects of electromagnetism as is known about ILFN. At this point in time, therefore, it is reasonable to conclude that more people who live near wind turbines are negatively affected by ILFN than by hypersensitivity to dirty electricity or ground current, as measurable levels of ILFN from wind turbines are highly associated with individual complaints. When Stigwood et al[57] studied and analyzed complaints at over 75 wind developments in the U.K., they found that identifying the problems was straightforward, occurrence was common (i.e., some residents reported problems in all developments), all developments generated excess amplitude modulation (AM), and AM was the cause of the vast majority of the complaints. These findings have recently been reinforced by Cooper's work[25] in Australia.

Statement 7: Infrasound from wind turbines is sufficiently correlated to the A-weighted sound emissions to allow an A-weighted model to be used to predict how much infrasound is present in homes.

This statement is not typically stated explicitly, but it is one that is inherent in the positions commonly taken by wind energy advocates and regulatory bodies through their interpretations and acceptance of research on WTN, which is based largely on A-weighted levels. As noted in many previous papers, including one of our own,[101] the continued use of the A-weighting scale in sound level meters is a major basis for misunderstandings that have led to acrimony between advocates and opponents of locating wind turbines in residential areas. The dBA scale was devised as a means to incorporate into measurements of environmental and industrial SPLs the inverse of the minimum audibility curve[158] at the 40-phon level. It is typically used, though, to specify the levels of noises that are more intense, where the audibility curve becomes considerably flattened, obviating somewhat the need for A-weighting. Use of the A-weighted scale is mandated or recommended in various national and international standards for measurements that are compared to damage-risk criteria for hearing loss and other health effects resulting from occupational or environmental noise exposure. It drastically reduces sound-level readings in the lower frequencies, beginning at 1,000 Hz, and reduces sounds at 20 Hz by 50 dB. For WTN, the A-weighting scale is especially inappropriate because of its devaluation of the effects of ILFN. Many authors have commented on its inadequacy. For example, Pederson and Persson Waye[159] state:

> "There is… support both from experimental and field studies that intrusive sound characteristics not fully described by the equivalent A-weighted sound pressure level contribute to annoyance with wind turbine noise" (p. 4).

A number of researchers have recommended comparing C-weighted measurements to A-weighted measurements when considering the impact of sound from wind turbines.[10, 12, 37, 61, 67, 75, 76, 83, 101] According to these sources, the presence of infra- and low-frequency sound is generally indicated when the difference between levels on the two scales differs by 10-20 dB. When such differences are observed, the use of third-octave or linear-scale measurements is typically recommended (for example, see Shepherd et al[50]). Other weighting scales have been suggested for wind turbine applications, but at present, linear-scale or narrow-band measurements, used in conjunction with a conventional sound level meter (with low-frequency microphone) and micro barometer, offer the best potential for accurately and completely describing the soundscape in the vicinity of IWTs.

As noted above, Cooper[25] has suggested that A-weighted levels, measured inside homes, are not likely to be useful indicators of AHEs. That report concluded that A-weighted levels are not a valid index of protection from AHEs and recommended the further exploration of a newly developed *wind turbine signature* scale, based on the discovery of its capability to quantify the amplitude-modulated peak energy in the infrasonic frequency region. That scale was shown to be directly linked to a variety of adverse bodily sensations when nearby turbines were operating or undergoing transitions in operation.

Although A-weighted sound level measurements have been the *sine qua non* for specifying environmental and occupational noise levels for many decades, we must recognize the inherent inadequacies of applying the A-weighting scale to quantifying noise emitted by IWTs. Bray[160] goes even further by noting that people, and not electronic devices, are the ultimate analysts of data that affect their responses to sound, making the point that people's responses should be given the credence they deserve, and not be devalued when physical measurements fail to confirm them.

Statement 8: Wind Turbine Syndrome has not been accepted as a diagnostic entity by the medical profession, so medical professionals cannot diagnose or treat it.

Currently, Wind Turbine Syndrome is not included in the International Classification of Diseases (ICD) coding system, which is used globally for purposes of establishing categories for diagnosing diseases and other health conditions, and as a basis for reimbursing medical providers for diagnostic and treatment services. Yet, of the 10 symptom sets comprising Pierpont's Wind Turbine Syndrome,[4] at least seven are included as a category or subcategory in the newly revised (ICD-10) coding system. The fact that the syndrome itself is not included may be due to its relatively recent discovery, but is more likely due to the fact that the syndrome consists of symptoms that are highly variable from person to person and affect a minority of the exposed population.

Especially in legal proceedings, it is important to distinguish between the terms *differential diagnosis* and *causation assessment*. It is the latter that is most often the subject of such proceedings. Attorneys and expert witnesses often get the terms confused. Differential diagnosis refers to the identification of disorder(s) that may account for a particular complaint or symptom complex. It rarely deals with the external cause of the disorder. Causation assessment, on the other hand, typically requires an evaluation of whether potential causative agents have irritating properties; a determination of the approximate amount of exposure, or dose, of that agent, and the timing between exposure (and non-exposure) and the occurrence of symptoms; and an assessment of whether alternative potential causes of the disorder can be ruled out. These latter steps are not necessarily considered part of the diagnosis.

Notwithstanding the fact that Pierpont herself is a practicing pediatrician, a couple of recent developments would appear to increase the prospect that medical personnel will soon be able to establish Wind Turbine Syndrome, by that or a similar label, as a clinical entity caused by exposure to WTN. Dr. Robert McMurtry, a physician who is a special advisor to the Canadian Royal Commission on the Future of Health Care, and a long-time advocate for more effective public involvement in healthcare policy, recently published a set of highly specific criteria for establishing such a link. McMurtry[161] originally proposed a case definition that identifies first-, second-, and third-order criteria, as well as specified circumstances and symptoms that must be established before AHEs can be attributed to wind turbine exposure. According to those criteria, probable AHEs are present when:

(1) All four of the following first-order criteria are met: (a) The individual resides within 5 km of IWTs, (b) Health status is altered following the start-up of or initial exposure to, and during

the operation of, IWTs (a latent period of up to 6 months may be allowed), (c) Amelioration of symptoms occurs when more than 5 km from the environs of IWTs, and (d) Recurrence of symptoms occurs upon return to the environs of IWTs within 5 km.

(2) At least three of the following second-order criteria are met (occurring or worsening after the initiation of operation of IWTs): (a) Compromised quality of life, (b) Continuing sleep disruption, difficulty initiating sleep, and/or difficulty with sleep disruption, (c) Annoyance producing increased levels of stress and/or psychological distress, and (d) A preference to leave the residence temporarily or permanently for sleep restoration or well-being.

(3) At least three specified symptoms occur or worsen following the initiation of IWTs, those symptoms referred to as third-order criteria that fall within the following categories: (a) Otological and vestibular disorders, (b) Cognitive disorders, (c) Cardiovascular disorders, (d) Psychological disorders, (e) Regulatory disorders, or (f) Systemic disorders.

To be confirmed as AHEs from WTN exposure, McMurtry indicated that consideration should be given to other stressors present in the community, that sleep studies be carried out if at all possible, and that a licensed physician be able to rule out alternate explanations for AHEs. These alternate explanations include substantial barometric changes from prevailing winds, a stressful home environment, and psychological and/or mood disorders, all of which can normally be ruled out when symptoms subside or disappear when the individual leaves the vicinity of the wind turbines. Apart from these three factors, he indicates that there are very few, if any, other health conditions that can mimic those caused by exposure to wind turbines and at the same time meet the three orders of criteria outlined in his case definition. More recently, McMurtry and Krogh[162] published a revised case definition, in which the third-order criteria—which are commonly present—are not considered essential elements. In both papers, the authors acknowledged that the identification of IWTs as the cause of adverse health symptoms is a complex emerging issue that requires further study to validate the criteria. They proposed key elements that ought to be included in any model used to assess the validity of the case-definition criteria.

McCunney and colleagues[163] have challenged those case definitions as having poor specificity, leading to a substantial potential for false-positive assessments and missed diagnoses. A potential fallacy in this challenge is that the authors unnecessarily conflate the concept of case definition for medical practitioners with that of an epidemiologic research plan. The case definitions presented by McMurtry[161] and McMurtry and Krogh[162] represent guidelines for medical doctors whose individual patients are experiencing new or unusual symptoms. It is erroneous to purport that a physician's mental process can be encapsulated into a set of equations, especially during the earliest stages of developing a case definition. The criticisms of these early case definitions should not deter physicians from attempting to evaluate and treat patients who report AHEs after living in the vicinity of IWTs. This area may indeed benefit from further study. Our view, however, is that such criteria provide an adequate starting point for guiding medical practitioners.

Dr. Steven Rauch, an otolaryngologist at the Massachusetts Eye and Ear Infirmary and a professor at Harvard Medical School, recently declared that he believes Wind Turbine Syndrome to be a real phenomenon.[164] As reported by numerous websites and newspapers, multiple patients have sought treatment from him for AHEs stemming from consistent exposure to IWTs. Rauch compares the syndrome to migraine headaches and believes that people who suffer from migraines are among the most sensitive to the effects of WTN, and he has stated that the wind industry aims to suppress the notion of Wind Turbine Syndrome by blaming the victim.

Given these developments, it is possible that the medical profession may someday embrace Wind Turbine Syndrome—by that or another name—as a clinical entity. This prospect is encouraging, as such acceptance by the profession will facilitate efforts to protect individuals from the harmful health effects of exposure to IWTs. Even though it may be some time before such a diagnostic label is formally acknowledged as an ICD code, it is currently possible for physicians to identify many of the specific symptoms associated with wind turbine exposure and to bill for diagnosing and treating those symptoms, with or without regard for their underlying cause. Paradoxically, it is apparently the case that the most effective treatment for AHEs associated with WTN exposure is non-medical in nature; it is to recommend that patients physically remove themselves from the vicinity of IWTs.

Statement 9: Peer-reviewed epidemiological literature is the only acceptable basis for proving a causative relationship between wind turbine noise and adverse health effects.

This issue runs as a thread through virtually all the other issues addressed in this paper, as it relates to the kind of scientific evidence frequently called for, especially in legal settings, to prove that IWTs are the cause of AHEs. While personal physicians of complainants in legal cases are often considered the only expert witnesses qualified to establish *specific causation*, others can testify to *general causation*, which is the methodology by which scientists determine whether or not an agent is responsible for producing a particular disorder. In general, this requires evaluation of the scientific and medical literature to identify documented instances of health-related conditions arising from exposure to specific agents and, when available, the dose-response relationships between agents and their effects. This process is highly similar to that of *causation assessment*, as explained above, and it does not necessarily require the input of a complainant's personal physician, although such input may be helpful. In legal cases involving WTN, it is critical that expert witnesses in acoustics and health be able to reconcile their positions with the reports and standards of the WHO,[165] the International Organization of Standards (ISO),[166] and the American National Standards Institute/Acoustical Society of America (ANSI/ASA)[167] that have linked low-frequency noise to symptoms of the type involved in complaints. These acoustical documents and research reports are seldom, if ever, included in literature reviews used by the industry to deny potential health risks. If challenged on the validity of the available evidence, acousticians need to be knowledgeable of the relevant acoustical standards and make sure that they are understood by all parties. In reality, the wind industry's almost universal refusal to cooperate with researchers has made it virtually impossible to conduct proper acoustical or epidemiological studies. The industry has been largely unwilling, or claims it is unable, to shut down or modify operations of its turbines for experimental purposes. To date, such a situation has rarely occurred, most notably in the case of the Cape Bridgewater study.[25]

The veracity of Statement 9 is strongly challenged by the classic address by Sir Austin Bradford Hill,[168] Professor Emeritus of Medical Statistics, University of London, to the newly founded Section of Occupational Medicine of the Royal Society of Medicine. In his essay, Hill shared his thinking about association and causal evidence surrounding environmental disease. He posited nine elements that are critical in establishing causation:

(1) *strength* (strength of observed relationships),
(2) *consistency* (consistency, or repeatability, of relationships, based on observations by different persons, in different places, under different circumstances, and at different times),
(3) *specificity* (causation is indicated if the association is limited to specific individuals and to particular sites and types of disease and there are no associations with other factors),
(4) *temporality* (there is a clear temporal relationship between outcomes and periods of exposure and non-exposure),
(5) *biological gradient* (a dose-response relationship exists),
(6) *plausibility* (causation is more likely when certain outcomes are biologically plausible, or possible, a caveat being that plausibility depends on the biologic knowledge of the day; this element is best expressed in the statement: "When you have eliminated the impossible, whatever remains, however improbable, must be the truth" (p. 10),

(7) *coherence* (the cause-and-effect interpretation of data should not seriously conflict with generally known facts of the natural history and biology of the disease),

(8) *experiment* (experimentation or semi-experimental evidence, even if only occasional, can reveal the strongest kind of evidence for causation), and

(9) *analogy* (the recognition that similar cause-effect relationships have occurred under similar conditions).

Hill states:

> "What I do not believe (is) …that we can usefully lay down some hard-and-fast rules of evidence that must be obeyed before we can accept cause and effect. None of my nine viewpoints can bring indisputable evidence for or against the cause-and-effect hypothesis and none can be required as a *sine qua non*. What they can do, with greater or less strength, is to help us to make up our minds on the fundamental question – is there any other way of explaining the set of facts before us, is there any other answer equally, or more, likely than cause and effect?... No formal tests of significance can answer those questions. Such tests can, and should, remind us of the effects that the play of chance can create, and they will instruct us in the likely magnitude of those effects. Beyond that they contribute nothing to the 'proof' of our hypothesis" (p. 299).

Hill makes this final observation in his essay:

> "All scientific work is incomplete – whether it be observational or experimental. All scientific work is liable to be upset or modified by advancing knowledge. That does not confer upon us a freedom to ignore the knowledge we already have, or to postpone the action that it appears to demand at a given time" (p. 300).

Extrapolating from Hill's essay, the totality of our knowledge gained from the available evidence must be considered when examining the link between WTN and AHEs. Fortunately, in addition to experimentation, this evidence includes simple tools that are useful, particularly if we are willing to recognize their collective value. Those tools begin, but do not end, with adverse health reporting.

Dr. Carl Phillips, a specialist in epidemiology and science-based policy making, and a former professor of public health, has stated:[169]

> "In cases of emerging and unpredictable disease risk, adverse event reports are the cornerstone of public health research. Since it is obviously not possible to study every possible exposure-disease combination using more formalized study methods, just in case an association is stumbled on, collecting reports of disease cases apparently attributable to a particular exposure is the critical first step" (p. 304).

He gives familiar examples of hazards revealed by adverse event reporting, including infectious disease outbreaks and side effects from pharmaceuticals. He points out that:

> "Pharmaceutical regulators rely heavily on clearinghouses they create for adverse event reporting about drug side effects (and often become actively concerned and even implement policy interventions based on tens of reports)" (p. 304).

Phillips indicates that the case of wind turbines and health fits the same pattern. He describes adverse event reporting as a special type of case study—sometimes denigrated as anecdotes—that generally reports on the rapid onset of a disease that appears to be related to a particular exposure. He advocates self-reporting of adverse events as a highly useful approach in studying the health effects of wind turbines. In addition, he advocates the use of case-crossover experiments as useful and well-accepted sources of epidemiologic information, stating that they are intuitively recognized by both experts and laypersons seeking to assess whether an exposure is causing specifiable outcomes.

Other forms of evidence, all considered scientific, have been or can be used to determine the impacts of WTN on health. These include case studies, case-series studies, and other pre-experimental, quasi-experimental, true experimental, correlational analysis, and single-subject designs. Single-subject designs, like the case-crossover design used by epidemiologists, can also be applied across multiple individuals to reveal relationships between specific interventions and changes in outcomes in individuals or groups. In both designs, subjects serve as their own controls while crossing over from one treatment to another (A vs. B) during the course of the experimental trial. Both are flexible designs and useful in studying events that are infrequent or sporadic. Numerous individuals living near IWTs have experienced health symptoms that have waxed and waned during repeated cycles of exposure (A) and non-exposure (B), which indicates that the wind industry has unwittingly engaged individuals and families worldwide in a series of quasi-empirical studies for many years, without obtaining informed consent from un-enrolled subjects, typically by downplaying any concerns about potential health impacts. The outcomes from these experiments offer some of the strongest evidence available that there is a causative link between WTN and AHEs in some individuals.

According to the WHO,[170] epidemiology is "the study of the distribution and determinants of health-related states or events (including disease), and the application of this study to the control of diseases and other health problems. Although the randomized clinical trial (RCT) is generally considered the *gold standard* of designs for establishing causation, various methods can be used to carry out epidemiological investigations: surveillance and descriptive studies can be used to study distribution; analytical studies are used to study determinants." Epidemiology uses a systematic approach to study the differences in disease distribution in subgroups and allows for the study of causal and preventive factors.[171] Descriptive epidemiological studies describe the occurrence of outcomes, and analytical studies reveal associative linkages between exposure and outcomes. Descriptive studies include primarily case reports and case-series studies. Analytic designs include experimental studies such as community trials and randomized controlled clinical trials, and observational studies, in which observations can be made retrospectively, concurrently, or prospectively. Observational studies include those in which either grouped (i.e., ecologic) or individual data are collected, the latter normally favored by the scientific community. Those designs involving individual data include cross-sectional, cohort, case-control, and case-crossover studies. Although epidemiological studies rely on statistical analyses of relationships between exposure to specific agents and AHEs in relatively large samples of the population, they are not aimed at revealing the cause of a disease or disorder in specific individuals. A cogent summary of research designs used in *evidence-based medicine* can be found online.[172]

Cross-sectional studies survey exposures and disease status at a single point in time in a cross-section of the population. They measure prevalence, not incidence, of a disease process, and have the disadvantage of difficulty in establishing the temporal sequence of exposure and effect. Also, rare and quickly emerging events may be difficult to detect. Their major advantage is that data can be collected at the same time on all participants, which means the study can be completed in a relatively short time. Notably, several cross-sectional investigations of the effects of WTN exposure have been reported.[44, 97, 98, 99, 104, 149] These studies serve as major contributions to the scientific literature on the subject.

Cohort studies involve an observational design in which a sample of the population is followed to discover new events.[75] They compare individuals with a known risk factor or exposure with others without the risk factor or exposure and aim to determine whether there is a difference in the risk, or incidence, of a disease over time. They tend to be the strongest observational design, especially when the data are collected prospectively, as opposed to retrospectively. Compared to the cross-sectional design, cohort studies tend to require more time, which partially explains the paucity of such studies involving wind turbine exposure.

Case-control designs compare exposures in diseased cases vs. healthy controls from the same general population. Specific disease states must be known prior to initiation, and exposure data must be collected retrospectively. This design can be applied to cases of IWT exposure, despite the fact that it requires the cooperation of affected and unaffected segments of the same population, a circumstance made difficult by attempts on the part of energy companies to maintain confidentiality and privacy as a means to facilitate wind turbine development in areas involving both participants and non-participants.

In case-crossover studies, which are a special type of case-control design, the *case* and *control* components reside in the same individual. This design is especially useful in investigating triggers of a disease process within an individual. In the behavioral sciences, it is commonly referred to as a *single-subject design*, as already described. The case component signifies the hazard period, which is the time period before the disease or event onset (e.g., exposure to IWTs), and the control component signifies a specified time interval other than the hazard period, namely the non-exposure interval. As already mentioned, wind companies themselves have unwittingly subjected residents to the basic conditions of this design, and results clearly suggest that exposure to WTN leads to a variety of health complaints in some individuals and families. Phillips[79] argues that:

> "A case-crossover study is one of the most compelling sources of epidemiologic data. It consists of observing whether someone's outcomes change as their exposure status changes. This is often not possible because the outcomes only happen a single time as a result of long-term exposure (e.g., cancer) or the exposure cannot be changed. But the observed effects of turbine exposure lend themselves perfectly to such studies because the exposure is transient and the effects, while not instantaneous in their manifestation or dissipation, are generally transient over a period of days or weeks at most. Thus, unlike a case of a lifelong exposure or non-transient disease, where we can only make one observation about disease and outcome per person, the effects of turbines allow multiple observations by the same person, including experimental interventions" (p. 305-306).

Turning to experimental designs, the clinical trial is considered the ideal design to test hypotheses of causation. In a clinical trial, the investigator has control of the exposure to an extent similar to a laboratory experiment. The subjects generally are randomly assigned to one of at least two groups, an experimental and a control group. The experimental group receives the treatment (i.e., exposure in the case of wind turbines) and the control group does not; instead, it usually is subjected to a condition that simulates a generic treatment of some type, and the purpose and procedures of the control condition are explained only after the experiment ends.

A fully developed clinical trial of residents who live near wind turbines has never been conducted, and the reasons are fairly clear if we consider the circumstances surrounding such a trial. In a rigorous trial done to establish the link between AHEs and WTN, the investigator would randomly assign hundreds of people selected from the general population—including adults and children, elderly adults, and chronically ill adults—to either an experimental or a control group. Randomization would control for pre-experimental biases toward or against wind energy, as well as for other factors that could confound the outcome. The experimental group would be required to spend a significant period (day and night for weeks or months) in homes located between approximately 1,000 ft. and several miles from the nearest wind turbine. The control group would be required to take up residence several miles or more away from the nearest wind turbine, where they would presumably be free from any effects due to extraneous noise or infrasound. Homeowners who leave their homes, as well as research participants occupying those homes, would have to adjust to new residences and modify their work and school activities, eating patterns, and overall lifestyles. Participants in both groups and at least some of the homeowners who vacate their homes for the experiment would have to be reimbursed for their participation, as well as for the costs incurred as a result of their participation, and the research staff would also have to be paid. To maintain some control across sites, the average age and health status within each group should be equivalent, and data would have to be gathered regarding such factors as turbine size, wind speed and other weather conditions, length of time the turbines were operating, terrain, the exact distance of each participating family from the nearest turbines, and actual noise levels present outside and inside the homes. Scientifically rigorous methods for measuring low-frequency noise and infrasound would have to be agreed upon and used. Although self-report via a survey technique could be part of the experimental design, medical examinations and physiological measurements, including sleep studies, should also be incorporated into the research protocol.

While possible, it is not practical to expect such a study design, in its ideal form, to be implemented. Aside from the difficulty of recruiting and enrolling enough families in enough geographic areas to form statistically strong samples, legitimate ethical questions should be raised regarding the exposure of individuals, especially children and other vulnerable individuals, to potentially hazardous conditions. One might conjecture, however, that consent to participate in such a study could be gained from fully informed adults because the effects of WTN are widely believed to be reversible when a period of non-exposure follows a period of exposure.

Statement 10: The nocebo effect, a manifestation of psychological expectations, explains why people complain of adverse health effects when living near wind turbines.

This statement is the core position of some of the most outspoken critics of the view that IWTs cause AHEs. Any discussion of this statement should begin with an acknowledgment that human behavior and beliefs are highly variable and are often driven by psychological and emotional influences, and not just by observations, logic, intellectual knowledge, or cognitive thought processes. It is not surprising, therefore, that some have adopted the view that negative reactions to wind turbines are based primarily or solely on psychological expectations. Our analysis of the limited literature on the topic leads us to state unequivocally that it is lacking in scientific rigor. Even if the results were as described, the existing studies and observations do not support a conclusion that psychological forces are the only or even primary explanation for most of the negative reactions toward IWTs. Here, we will critically review four papers, all supporting a psychological explanation for the negative reactions.

Chapman et al[173] tested four hypotheses relevant to psychogenic explanations of the variable timing and distribution of health and noise complaints about wind farms in Australia. They obtained records from the wind companies of complaints about noise or degraded health from residents living near 51 wind projects operating between 1993 and 2013 and corroborated those records with complaints documented by three government public agencies, news media records, and court affidavits. Complaints were expressed as proportions of estimated populations residing within 5 km of a wind project. The authors concluded that historical and geographical variations in complaints were consistent with psychogenic hypotheses expressing health problems as "communicated diseases," with nocebo effects likely to play an important role in the etiology of complaints.

Nocebo effects are commonly described as being the opposite of placebo effects. While the *placebo effect* usually refers to a positive reaction to an inert substance—the placebo—the *nocebo effect* refers to a negative reaction to an inert substance—the nocebo. Both effects are psychogenic, but known to exert powerful influences on human physiology, behavior, and attitudes. Essentially, Chapman and his supporters believe that psychogenic reasons are the basis for health complaints about wind turbines, which they believe to be harmless.

Our major criticism of the work of Chapman et al is that wind companies typically engage in practices that discourage local residents to complain. These companies require participating residents to sign contracts before turbines are constructed and before the residents can receive compensation for leasing their land, and they often request non-participating residents to sign contracts prior to initiating a project. Those contracts, which are binding, often include gag clauses that effectively limit resident complaints. The contracts have often stipulated not only that residents refrain from voicing negative views of the wind project, but also that they support the development of future projects. Such conditions create an atmosphere in which is it is highly unlikely that the records of wind companies, governments, courts, or the media will sufficiently reflect all of the complaints that residents have and would voice under less-restrictive circumstances. We argue that the only way to gather accurate data on such complaints is through a survey of either an adequate sample of residents living near multiple wind projects or all such residents, where residents are free of restrictions by the wind companies. Such data would allow a valid determination of the proportion of residents who experience adverse effects. Whether that proportion is large or small, we could all act on the basis of factual evidence, as opposed to incomplete observations.

Another shortcoming of the study by Chapman et al,[173] which is less well documented but a factor observed in legal cases in which the present authors have been involved, is that residents near IWT projects tend to be delayed in their responses to AHEs. Many of them believe their health problems to be linked to other causes before suspecting that the turbines are the cause. Some or most of these individuals were supporters of wind projects prior to experiencing such problems, as Phipps et al[75] noted in New Zealand. The delay factor would mean that the types of records used by Chapman et al would not likely reflect the reactions of many affected residents.

Crichton and colleagues conducted two laboratory investigations, each of which has bolstered the argument that negative reactions to audible and inaudible WTN can be explained by psychological expectations. Crichton et al[174] conducted what they described as a sham-controlled double-blind provocation study, in which participants were exposed to 10 min of infrasound and 10 min of sham infrasound. Fifty-four participants were randomized to high- or low-expectancy groups and presented with audio-visual information, using material from the Internet that was designed to invoke either high or low expectations that exposure to infrasound causes specified symptoms. High-expectancy participants reported significant increases, from pre-exposure baseline assessment, in the number and intensity of symptoms experienced during exposure to both infrasound and sham infrasound. There were no symptomatic changes in the low-expectancy group. Healthy volunteers, when given information about the expected physiological effect of infrasound, reported symptoms that aligned with that information, during exposure to both infrasound and sham infrasound. According to the authors, results suggest that psychological expectations are sufficient to explain the link between wind turbine exposure and health complaints.

Punch[175] has criticized that study as methodologically weak, on the following grounds:

(1) Subjects were never exposed to infrasound that adequately represented that to which residents near wind turbine projects are subjected. It is extremely unlikely that the employed studio woofer was capable of producing a 5-Hz stimulus; the authors did not describe or show a graph of the output spectrum. Even if a true infrasound stimulus was produced by their equipment, 40 dB (presumably SPL) was not sufficient to represent the level of

infrasound commonly produced by IWTs. Even if a sufficient stimulus had been produced to represent wind turbine infrasound, a 10-min exposure would have been meaningless in representing the duration of exposure that is likely necessary to produce any substantial health symptoms.

(2) In effect, subjects were exposed to two sham conditions. If they had been exposed to infrasound that adequately mimicked infrasound from IWTs (preferably actual IWT infrasound), subjects in both the high- and low-expectancy groups would have had a physical stimulus (in the infrasound condition) that could have overridden, or at least moderated, their psychological reactions.

(3) The design limited the study's external validity, the ability to generalize the results to other populations and situations. Most of the individuals who have reported AHEs from WTN, some of whom have abandoned their homes, are not people who were adequately warned of potential health effects prior to their exposures. In fact, most of them were likely told by the wind company to expect no harmful effects. Again, many individuals who report AHEs were advocates of wind energy prior to being exposed. Because the major premise underlying the study is that people complain of WTN based primarily on expectancies that align with prior information, the study is based on a false premise. Also, the recruitment of university students does not represent the type of subjects who are apt to complain about WTN. This population is probably the least vulnerable to the effects of WTN in that few, if any, were very young, very old, likely to have chronic health conditions, or disabled. Also, they are more likely to exhibit a response bias because they are less likely than prospective residents of a wind project to believe that they might be harmed by participating in an experiment. Furthermore, the extensive use of pretesting introduced reactive or interactive effects that could have affected post-test behaviors and ratings. Finally, the use of a laboratory setting and short exposure times, as opposed to a real-life setting in which wind turbine blades are turning at night and the subjects are inside a home, introduced situational effects that limit the ability to generalize the data. The authors admit this shortcoming in their statement:

> "… exposure to infrasound in a listening room purpose (sic) built for sound experiments may not be directly comparable to exposure to infrasound from a wind farm" (p. 4).

(4) This was an experiment whose outcomes could have been predicted, given the conditions employed. Aside from the fact that the outcome had virtually nothing to do with the real-world conditions of exposure to infrasound from wind turbines, none of the factors that influence how expectations can affect perceptions through top-down, or cognitive- based, processing, as opposed to bottom-up, or stimulus-based, processing, were controlled or even

discussed. (Interested readers should refer to Williams[176] for examples of the effects of top-down processing and for a discussion of how such experiments might be improved.)

In a second laboratory study by Crichton and colleagues,[177] similar in design to the first, the authors investigated whether positive expectations can produce a reduction in symptoms and improvements in reported health. Sixty participants were randomized to either positive or negative expectations and subsequently exposed to audible wind turbine sound and infrasound. According to the authors,

> "Participants were … exposed to infrasound (9Hz, 50.4dB) and audible wind farm sound (43dB), which had been recorded 1 km from a wind farm, during two 7-minute listening sessions. Both groups were made aware they were listening to the sound of a wind farm, and were being exposed to sound containing both audible and sub audible components and that the sound was at the same level during both sessions" (p. 2).

Prior to exposure, negative-expectation participants watched a DVD incorporating TV footage about health effects said to be caused by infrasound produced by wind turbines. In contrast, positive-expectation participants viewed a DVD that:

> "…framed wind turbine sound as containing infrasound, sub audible sound created by natural phenomena such as ocean waves and the wind, which had been reported to have positive effects and therapeutic benefits on health" (p. 2).

The authors described the results as indicating that during exposure to audible wind turbine sound and infrasound, symptoms and mood were strongly influenced by subject expectations. Negative-expectation participants experienced a significant increase in symptoms and a significant deterioration in mood, while positive-expectation participants reported a significant decrease in symptoms and a significant improvement in mood. The authors concluded that if expectations about infrasound are framed in more neutral or benign ways, then it is likely that reports of symptoms or negative effects could be nullified.

That second investigation by Crichton and colleagues has some of the same methodological weaknesses as the first, particularly with respect to the use of what was described as experimental infrasound. Again, recordings of WTN were used, and no description of the recording instrumentation was provided, leading us to assume that the instrumentation may have been incapable of accurately reproducing infrasound, and thus its true effects. All participants were informed of the purpose of the study, which was:

> "…to investigate the effect of sound below the threshold of human hearing (infrasound) on the experience of physical sensations and mood" (p. 2).

Preferably, the purpose should have been divulged only after the data were gathered because the description of sounds as those that humans cannot hear would presumably have established a mind-set, or bias, in both groups that the sound would have little impact. That preconception could have confounded any reactions to the different DVD messages. Another criticism of the study is that wind companies frame their turbines in the best possible light, so positive expectations have already been established in the minds of most wind-project participants and non-participants. Despite neutral or positive framing that has sometimes included assurance that the turbine sounds would be no louder than that of a refrigerator (see, for example, Chen & Narins[178]), the consequences of living near IWTs are catastrophic for some residents.

Tonin et al[179] repeated the experimental work of Crichton and her colleagues by using specially modified headphones to produce infrasound, as opposed to the loudspeaker system used in the previous studies, and exposed participants to 23 min of infrasound, as opposed to the 10-min exposures in the Crichton studies. Similar results were reported, suggesting that the simulated infrasound had no statistically significant effect on the symptoms reported by volunteers, while the prior expectations the volunteers had about the effect of infrasound had a statistically significant influence on the symptoms reported, thereby supporting the nocebo effect hypothesis. Some of the same criticisms of the Crichton et al study[174] levelled by Punch[175] also apply to the Tonin et al study, as participants were not being stimulated by sufficient durations or peak levels of infrasound exposure to which residents living near IWTs are exposed, and participants were effectively exposed to two sham conditions, denying them any opportunity to experience realistic infrasonic stimuli that could have overridden or moderated their psychological reactions based on expectancy.

In a related study, Taylor et al[180] assessed the effect of negatively oriented personality (NOP) traits (Neuroticism, Negative Affectivity and Frustration Intolerance) on the relationship between both actual and perceived noise on “medically unexplained non-specific symptoms (NSS)” (p. 338), presumably their euphemism for Pierpont’s Wind Turbine Syndrome.[4] Households within 500 m of 8 0.6-kW micro turbine installations and within 1 km of 4 5-kW small wind turbines in two U.K. cities were surveyed, and 138 questionnaires were completed and returned for analysis. Turbine noise level for each household was also calculated. There was no evidence for an effect of calculated noise on NSS. A statistically significant relationship was found between perceived noise and NSS for individuals high in NOP traits.

That study is similar in concept to those performed by Crichton and colleagues,[174, 177] with virtually the same conclusion—that the link between wind turbines and AHEs has a psychological origin. The study can be criticized on several grounds:

(1) Only smaller wind turbines were investigated; there is virtually no literature demonstrating that such turbines produce noise levels of any consequence to humans. The fact that no relationship was found between "calculated actual noise" from the turbines and participants' attitudes toward wind turbines was thus predictable because the noise levels were either too low to affect attitudes differentially or were completely inaudible.

(2) The authors state:

> "Actual noise turbine level for each household was also calculated" (p. 338).

Calculated levels (from noise maps) are not necessarily actual levels, so this procedure was, at a minimum, mischaracterized.

(3) It should not be surprising to find that individuals with negatively oriented personalities respond negatively to WTN, as they would likely respond negatively to almost any stimulus. However, the findings, as acknowledged by the authors, resulted from reports of participants' retrospective perceptions of noise from turbines and symptoms at the same point in time, possibly resulting in common-method variance and retrospective bias. Also, although the authors reported a statistically significant relationship between NSS and negatively oriented personality, the reported variance explained by those relationships was quite low. That finding suggests that a meaningful (i.e., clinical) significance was not established, in which case one might reasonably question whether symptom reporting in the study was actually linked to negative personality type.

(4) Among other possible confounders, individual differences are likely to have complicated the authors' analyses (see Williams[176] for an explanation).

To conclude this section, we believe that while psychological expectations conceivably can influence perceptions of the effects of WTN on health status, no scientific studies have yet convincingly shown that psychological forces are the major driver of such perceptions. Based on the bulk of literature covered in this review, those drivers are the physical stimuli themselves and the internal physiological reactions they induce.

Statement 11: Only relatively few people, if any, are adversely impacted by wind turbine noise, and the majority have no complaints.

As indicated earlier, most of the studies that have documented specified percentages of the population adversely affected by WTN have been those focusing on annoyance, as opposed to health. While the exact percentage of people whose health is affected by WTN has not been accurately determined, countless reports worldwide suggest that the acoustic energy emitted by

IWTs is harmful to the health of substantial numbers of people. As already noted, Phipps et al[75] found that 45% of households living as far away as 4 km from a wind project and 20% of households living up to 8 km away reported hearing turbine noise. Those figures take into account only the audible noise, of course, and not the inaudible infrasound, and they do not account for any documented adverse impacts.

Estimates of the percentage of people adversely affected by WTN should not be based solely on questionnaire surveys of populations known to be experiencing health problems, due to selection bias. Such surveys can be helpful in arriving at rough estimates of AHEs, however, but only if those surveys also report estimates of the total population from which the affected sample is drawn. The main value of surveys that include only affected individuals (e.g., Harry[74]; Pierpont[4]; The Acoustic Group[25]) is that they strongly suggest that substantial numbers of people living near wind turbines suffer health symptoms. For example, Harry[74] reported that 81% of her 42 survey respondents had health complaints, 76% had visited a doctor regarding those complaints, and 73% reported a reduced quality of life. In a somewhat more representative survey of residents living within 15 km of a wind turbine project—most of whom lived within 3 km—Phipps[76] found that 42 of 614 households who responded to a questionnaire (6.8%) reported occasional sleep disturbance, another 21 (3.4%) reported frequent sleep disturbance, and an additional 5 (0.8%) reported sleep disturbance most of the time due to WTN. Eleven percent of households, therefore, reported suffering at least occasional sleep disruption due to the wind turbines. Fifteen percent of respondents to that survey reported that they had suffered at least occasional reductions in their quality of life since the turbines became operational.

Despite the lack of definitive scientific evidence, we cannot ignore the numerous accounts of such effects reported worldwide on the Internet, in legal proceedings, and in news accounts. Krogh et al[96] have reviewed studies that document such incidents, many of which have involved the abandonment of homes. In a 2010 report commissioned by the Ontario Ministry of the Environment, the engineering firm of Howe Gastmeier Chapnik Limited,[112] despite its general conclusion that Ontario IWTs do not pose a risk to human health, stated:

> “The audible sound from wind turbines, at the levels experienced at typical receptor distances in Ontario, is nonetheless expected to result in a non-trivial percentage of persons being highly annoyed .… research has shown that annoyance associated with sound from wind turbines can be expected to contribute to stress related health impacts in some persons” (p. 39).

In conclusion, we should recall that Phillips[169] advocates self-reporting of adverse events as a critical element in the study of the health effects of wind turbines. As stated earlier, he has noted the importance of case-crossover experiments as useful and well-accepted sources of epidemiologic information. Numerous households around the world have been subjected to this type of quasi-experiment by the wind industry. It is unfortunate that an accurate count of these incidents has never been tallied formally and scientifically. Although that task must be left to future research, we should regard complaints of AHEs from individuals living near wind turbine installations seriously, when they occur, and the wind industry must act responsibly by siting its turbines at distances from residents that protect health and quality of life.

It is widely accepted that the industry has warned that tighter siting restrictions will destroy its prospects for growth. Such growth, however, should not continue in areas where there are probable and potential risks to human health. There are regions of the U.S. and other countries where turbines can operate safely, presumably without such risks. Some examples of those sites are illustrated in Figure 2.

Statement 12: There is no evidence in the literature to support a causative link between wind turbine noise and adverse health effects.

The above review has been aimed specifically at addressing this point, which is often cited as factual by wind industry advocates in the literature and in legal proceedings. Namely, there is an abundant literature, much of it peer-reviewed and authored by highly reputable researchers, indicating that audible and inaudible noise emitted by IWTs adversely impacts the health and well-being of substantial numbers of people who are regularly exposed to wind turbines. It is clear that the literature reviews and papers claiming no AHEs fail to include important studies, international standards, guidance from the WHO, and research conducted on wind turbine noise and other sources of infra- and low-frequency sound. Whether this is through oversight or calculation, only reports that cite scientifically credible references should be considered legitimate sources of information. Our review has shown that it is unacceptable simply to state that the literature contains little or no evidence of a causal link between WTN and AHEs. At a minimum, those effects have been shown to be regularly correlated to living in proximity to IWTs, and there is sufficient evidence that those effects are highly associated with objective measurements of audible noise and infrasound.

Although sleep disturbance and its associated impacts on health and quality of life appear to be the most salient consequences of IWT noise, varying health effects that are unrelated to sleep have also been widely and consistently reported by different investigators. While not everyone who is exposed to IWTs suffers AHEs, it is incumbent on governmental officials and the wind industry to take seriously the health implications of their decisions to locate wind turbines near residential and other populations, especially vulnerable populations, that are or likely to be negatively affected.

Figure 2. Photographic images of sites illustrating onshore landscapes where industrial wind turbines expose humans to minimal health risks due to large setback distances. Note that homes are not seen in the photos. (Source: https://images.search.yahoo.com/search/images?p=wind+turbine+images+california&fr=tightropetb&imgurl=http%3A%2F%2Fwww.freefoto.com%2Fimages%2F39%2F01%2F39_01_1---Wind-Turbine-Generators--Palm-Springs--California_web.jpg#id=36&iurl=http%3A%2F%2Fmedia-cdn.tripadvisor.com%2Fmedia%2Fphoto-s%2F01%2F70%2Ff9%2Fbb%2Ftehachepi-area-california.jpg&action=close).

Conclusion

We have discussed in this paper various elements of acoustics, sound perception, sound measurement, and psychological reactions, and the role these factors play in support of the view that a general-causative link exists between human health and ILFN emitted by IWTs. The available evidence warrants the following conclusions:

(1) Large wind turbines generate infrasound, which is not normally experienced as sound by most human listeners. Some people, however, experience it in the form of pathological

symptoms such as headache, dizziness, nausea, or motion sickness, which appear to be caused by the excitation of resonances inside closed structures and the human body itself.

(2) WTN has unique acoustic characteristics when compared to other environmental noises. These characteristics include low-amplitude, amplitude-modulated, intermittent occurrences of tones that mirror the peak energy of the blade-pass frequency and the first several harmonics. The coupling mechanisms in the inner ear prevent internally generated sound, but not externally generated sound, from being perceived, which means that perception of wind turbine infrasound is far more disturbing than infrasound generated within the human body.

(3) There is voluminous evidence, ranging from anecdotal accounts from around the world to peer-reviewed scientific research, that audible and inaudible low-frequency noise and infrasound from IWTs lead to complaints ranging from annoyance to AHEs in a substantial percentage of the population. Although sleep disturbance is the most common problem cited, a variety of other health problems has been reported by numerous reputable sources. Recent research is largely consistent with Pierpont's original description of Wind Turbine Syndrome. Research on humans and lower animals has shown that it is biologically plausible that inner ear mechanisms, in conjunction with the brain, can process acoustic energy in ways that result in pathological perceptions that are not interpreted as sound. Both balance and hearing mechanisms appear to be involved in evoking these perceptions. The findings that infrasonic stimuli can amplitude modulate higher frequencies in the audible region, and that infrasound may be more perceptible when higher frequencies are absent, are especially compelling in suggesting that what we can't hear can hurt us.

(4) To prevent AHEs, scientists have recommended that distances separating turbines and residences be 0.5-2.5 mi., and 1.25 mi. (2 km) or more has been commonly recommended. Clearly, the short siting distances used by the industry for physical safety do not protect against AHEs. Alternatively, researchers have recommended sound levels typically ranging from 30-40 dBA for safeguarding health, which is consistent with the recommendation of nighttime noise levels by the WHO.

(5) Annoyance is a health issue for many people living near IWTs, which is consistent with both the WHO's definition of health and contemporary models of the relationships among annoyance, stress, and health.

(6) The scientific evidence regarding factors other than amplitude-modulated ILFN as an explanation for most of the health complaints near IWTs, including electromagnetic fields (dirty electricity), is weak; the preponderance of research suggests that ILFN is the most viable explanation for such complaints.

(7) The A-weighted decibel scale, which effectively excludes infrasound and substantial amounts of low-frequency noise, is inadequate to predict the level of outdoor or indoor infrasound, to reveal correlations to infrasound, or to show a definitive relationship with AHEs. Achievement of these goals requires the development of new measurement methods.

(8) Even though Wind Turbine Syndrome is not currently included in the ICD coding system, that system includes most of the acknowledged symptoms of the syndrome. Medical professionals, therefore, have the necessary tools to evaluate and treat it, and that process has already begun on a limited scale.

(9) While some epidemiologically solid research has been done in the area of IWTs and AHEs, evidence from other sources cannot be ignored. Hill noted the nature of such sources in 1965, and Phillips, in 2011, described the importance of other kinds of evidence, including adverse event reports, in establishing a causative relationship. One of the strongest types of evidence is the case-crossover experimental design, which the wind industry has unwittingly imposed for years on multiple families, many of whom have abandoned their homes to escape IWT noise exposure.

(10) While psychological expectations and the power of suggestion conceivably can influence perceptions of the effects of WTN on health status, no scientifically valid studies have yet convincingly shown that psychological forces are the major driver of such perceptions.

(11) Accurate estimates of the percentage of people who are affected by IWTs exist only for annoyance, not AHEs. Multiple reports, however, emphasize the relationships that exist between annoyance, stress, health, and quality of life, and indicate that a non-trivial percentage of people who live near IWTs experience AHEs. Those reports are consistent with thousands of reports worldwide. Although it seems reasonable to conclude that noise from IWTs does not cause AHEs in the majority of exposed populations, and that accurate estimates of AHEs are yet to be established, it is also clear that considerable numbers of people are affected and that they deserve to be heard and protected from adverse health impacts.

(12) The available literature, which includes research reported by scientists and other reputable professionals in peer-reviewed journals, government documents, print and web-based media, and in scientific and professional papers presented at society meetings, is sufficient to establish a general causal link between a variety of commonly observed AHEs and noise emitted by IWTs.

Based on all the evidence presented, our fundamental view is that the controversy surrounding AHEs should not be polarized into two groups consisting of either *pro-wind* or *anti-wind* factions, but rather one in which there is room for a third, *pro-health*, perspective. Essentially, the pro-wind view is that IWTs should be installed wherever feasible, that definitive scientific research is lacking to indicate that turbines cause AHEs, and that if you can't hear it, you can't feel it. The anti-wind view is that IWTs should not be installed anywhere because wind is not an economically viable source of renewable energy, that all government subsidies and development efforts should end, and that what we can't hear can hurt us. A pro-health view is that there is enough anecdotal and scientific evidence to indicate that ILFN from IWTs causes annoyance, sleep disturbance, stress, and a variety of other AHEs to warrant siting the turbines at distances sufficient to avoid such harmful effects, which, without proper siting, occur in a substantial percentage of the population. That view holds that what we can't hear can hurt some of us, and that the precautionary principle must be followed in siting IWTs if such health risks are to be avoided. Industrial-scale wind turbines should not be located near people's homes, educational and recreational facilities, and workplaces. It is our belief that the bulk of the available evidence justifies a pro-health perspective. It is unacceptable to consider people living near wind turbines as collateral damage while this debate continues.

Further scientific investigations of the dose-response relationship between IWT noise and specific health effects in exposed individuals are sorely needed. However, people should be protected by conservative siting guidelines that recognize the concerns raised in this review. Hopefully, such research can and will be planned and executed by independent researchers with the full cooperation of the wind industry. The major objective of such research should be to reveal directions for the industry in balancing the energy needs of society with the need to protect public health.

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