BEFORE
THE OHIO POWER SITING BOARD

In the Matter of the Application of **REPUBLIC WIND, LLC** for a Certificate of Environmental Compatibility and Public Need for a Wind-Powered Electric Generating Facility in Seneca and Sandusky Counties, Ohio.	)))))	Case No. 17-2295-EL-BGN

DIRECT TESTIMONY OF

Kenneth A. Mundt

on behalf of

Republic Wind, LLC

October 21, 2019

I. INTRODUCTION

Q-1. Please state your name, employer, and business address.

A-1. My name is Dr. Kenneth A. Mundt. I am employed by Cardno ChemRisk. My business address is 607 Boylston Street, Suite 301, Boston, Massachusetts 02116-3601.

Q-2. What is your position at Cardno Chemrisk?

A-2. I am an Epidemiologist and Senior Principal Health Scientist at Cardno ChemRisk.

Q-3. How long have you been employed with Cardno Chemrisk?

A-3. I joined Cardno ChemRisk in September 2018.

Q-4. Please describe your current responsibilities at Cardno Chemrisk.

A-4. I am responsible for conducting scientific evaluations of epidemiological and related human health sciences evidence and overseeing other ChemRisk professional staff engaged in these activities. I am also responsible for mentoring professional staff, providing opportunities for skills development and assuring the quality of the work products I oversee. I have additional responsibilities as a member of the ChemRisk Management Committee to participate in business planning and management.

Q-5. Please characterize the scientific work you do at Cardno Chemrisk.

A-5. I specialize in the pragmatic interpretation and integration of epidemiological evidence with other scientific lines of inquiry – primarily exposure sciences, toxicology and risk assessment – in evaluating disease causation and supporting science-based regulation and decision-making. Part of this work involves designing, implementing and overseeing primary epidemiological studies, including the statistical analyses of data and interpretation of findings. Much of my work involves the critical review and synthesis of the published, peer-reviewed literature available on the relationship between various risk factors and exposures and risk of disease in humans. I have become increasingly involved in multidisciplinary risk evaluations in which epidemiological, animal toxicology and mechanistic evidence is critically evaluated on the basis of scientific quality and integrated using weight-of-evidence approaches.

Q-6. Please describe your educational background and professional experience.

A-6. I hold a Bachelor's degree from Dartmouth College, a Master's degree in English from the Graduate School of the University of Virginia, a Master's degree in Epidemiology from the School of Public Health, University of Massachusetts, and a Doctorate in Epidemiology from the School of Public Health, University of North Carolina. I am by training and experience an epidemiologist. I have worked in the field of epidemiology full-time for 30 years. For ten years (1989-1999) I served full-time on the faculty of the Department of Biostatistics and Epidemiology of the School of Public Health, University of Massachusetts, with a joint appointment in Family Medicine (Occupational Medicine Program), University of Massachusetts Medical School. I currently hold adjunct faculty posts in Epidemiology at the University of Massachusetts at Amherst and in Epidemiology as well as in Environmental Health Sciences at the University of South Carolina at Columbia.

I have extensive experience in designing, conducting, interpreting and publishing primary epidemiological research; critical review and synthesis of published epidemiological literature; the graduate-level training of epidemiologists, including classroom teaching, advising and chairing of Masters and Doctoral Committees; and serving in epidemiological advisory, review and editorial capacities at the local, national and international level. My expert epidemiological opinion has been requested and provided in matters addressing an array of human health topics. Many of these pertained to determining or understanding the causes of disease in populations, and applying probabilistically this evaluation to individuals similarly situated. I also have published numerous papers in peer-reviewed human health and medical journals. Please see my CV, attached (Exhibit KM-1). Among these publications, I co-authored "Wind Turbines and Health: A Critical Review of the Scientific Literature" published in the November 2014 issue of the Journal of Occupational and Environmental Medicine, the peer-reviewed, official journal of the American College of Occupational and Environmental Medicine (ACOEM) attached hereto (Exhibit KM-2). Although the review addresses several aspects on the science of wind turbines, my primary role as a co-author was the critical review section on the epidemiology of wind turbines.

Q-7. What is Epidemiology?

A-7. Epidemiology is the field of public health that studies the incidence, prevalence, and distribution of disease -- as well as risk factors that are associated with disease -- in human populations. Epidemiological concepts and methods are highly developed and standardized, and follow basic principles of the scientific method. Epidemiology is the basic science of public health practice, and epidemiologists are therefore public health professionals. As an epidemiologist, I study risk factors for disease in populations, primarily to identify potential causes that can be modified or eliminated in order to prevent disease. Understanding risk at a group or population level provides a probabilistic basis for evaluating risks and for evaluating disease causation. These risks or probabilities also may be informative in evaluating the possible causes of disease at the individual level, which for many diseases (especially those that are chronic and/or have multifactorial etiologies) cannot be known. Scientific approaches aim to be objective and are valued and preferred over subjective approaches to drawing conclusions, which may be unduly influenced by perceptions, beliefs, political motivation, financial gain or loss, folklore, etc.

Q-8. On whose behalf are you offering testimony?

A-8. I am testifying on behalf of the Applicant in the case, Republic Wind, LLC ("Applicant" or "Republic Wind").

Q-9. Have you previously testified before the Ohio Power Siting Board ("the Board")?

A-9. Yes. I previously testified before the Board in two matters involving claimed health effects associated with wind turbine emissions: (1) *Champaign Wind LLC and Ohio Power Siting Board*. Columbus, Ohio. Case No. 12-0160-EL-BGN. Rebuttal Testimony: December 3, 2012. Cross Examination: December 6, 2012; and (2) Buckeye Wind LLC and Ohio Power Siting Board. Columbus, Ohio. Case No. 08-666-EL-BGN. Direct Testimony: November 10, 2009.

Q-10. Have you previously served as an expert witness before any other court, agency, or other body on the subject you plan to offer testimony on today?

A-10. Yes. My expert epidemiological opinion has been requested and provided in numerous matters addressing an array of human disease and health topics, many pertaining to determining or understanding the causes of disease in populations, and in some settings (primarily litigation) applying probabilistically this evaluation to individuals similarly situated to those studied epidemiologically. Please see attached a complete list of matters in which I have provided testimony in the past four years (Exhibit KM-3). Specific to wind development and human health, I have provided expert testimony in several cases, including the following:

- *Application of Cassadaga Wind Project for a Certificate under Article 10 of the Public Service Law*. State of New York Public Service Commission. Case No. 14-F-0490.
- *Association for the Protection of Amherst Island v. Director, Ministry of the Environment and Windlectric, Inc*. Township of Loyalty, Lennox and Addington County, Ontario, Canada. Environmental Review Tribunal (ERT) Case No. 15-084.
- *William Irvin v. Director, Ministry of the Environment and Port Ryerse Wind Farm Limited Partnership.* Town of Simcoe, Norfolk County, Ontario, Canada. Environmental Review Tribunal (ERT) Case Nos. 14-063 and 14-064.
- *Douglas Edward Dingeldein v. Director, Ministry of the Environment and Grey Highlands Nominee (No. 1) Ltd.* Municipality of Grey Highlands, Grey County, Ontario, Canada. Environmental Review Tribunal (ERT) Case No. 15-011.
- *Kimberly and Richard Lance Bryce v. Director, Ministry of the Environment and Suncor Energy Products, Inc.* Municipality of Lambton Shores, Town of Plympton-Wyoming, Warwick Township and Lambton County, Ontario. Environmental Review Tribunal (ERT) Case Nos. 14-065/14-066/14-067.
- *John Gillespie and the Municipality of Bluewater v. Director, Ministry of the Environment and Grand Bend Wind GP, Inc.* Huron County and Perth County, Varna, Ontario. Environmental Review Tribunal (ERT) Case Nos. 14-051/14-052.
- *John Gillespie and the Municipality of Bluewater v. Director, Ministry of the Environment and Goshen Wind, GP, ULC.* Municipalities of Bluewater and South Huron within Huron County. Toronto, Ontario. Environmental Review Tribunal (ERT) Case Nos. 14-059/14-060.

- *Sharon Anne Kroeplin and Kenneth George Kroeplin and Director, Ministry of the Environment / SP Armow Wind Ontario LP*. Municipality of Kincardine, County of Bruce, Ontario. Environmental Review Tribunal (ERT) Case Nos. 13-124/13-125.
- *Shawn Drennan and Tricia Drennan and Director, Ministry of the Environment*. Township of Ashfield-Colbourne-Wawanosh, Goderich, County of Huron, Ontario. Environmental Review Tribunal (ERT) Case Nos. 13-097/13-098.

II. SUMMARY AND SCOPE

Q-11. What is the purpose and scope of your testimony in this proceeding?

A-11. My testimony is intended to assist the Board in the objective interpretation of relevant epidemiological and related scientific evidence pertaining to potential human health impacts of wind turbines. The focus of my testimony is (1) to provide an overview of public health and epidemiology principles germane to an inquiry into the health effects of wind turbines; and (2) to assess health claims that have been attributed to wind turbines in light of my critical review and synthesis of the peer-reviewed, published scientific literature.

Q-12. What documents did you review in preparing your testimony?

A-12. The following documents were provided to me by counsel for Republic Wind:

(a) Application for a Certificate of Environmental Compatibility and Public Need, Republic Wind Farm, Townships of Adams, Pleasant, Reed, Scipio, Thompson and York – Seneca and Sandusky Counties, Ohio, Case No. 17-2295-EL-BGN, December 2018.

(b) Petition to Intervene of Additional Local Residents, Case No. 17-2295-EL-BGN, dated March 20, 2019.

(c) Noise Impact Assessment for Republic Wind – Seneca and Sandusky County, Ohio, report prepared by RSG, dated December 11, 2018.

(d) Shadow Flicker Report, Republic Wind Farm, York Township, Sandusky County, Ohio and Adams, Thompson, Scipio, and Reed Townships, Seneca County, Ohio, prepared by Environmental Design & Research, December 2018.

(e) Staff Report of Investigation. Republic Wind Farm. Republic Wind, LLC. Case No. 17-2295-EL-BGN. July 25, 2019.

(f) Republic Wind LLC Case No. 17-2295-EL-BGN Notice of Project Modifications and Project Information Update. June 28, 2019.

Additionally, included with my testimony is a list of references to which I refer or otherwise rely upon to reach my conclusions. (Exhibit KM-4.)

Q-13. Can you provide a summary of your opinions?

A-13. I have systematically identified, critically reviewed and synthesized the published peer-reviewed epidemiological literature on the possible association between exposure to industrial wind turbine emissions and various human health problems. Following standard methods for comprehensively identifying relevant publications, critically reviewing each on the basis of quality and synthesizing the body of relevant published literature, I conclude that at or below the proposed noise levels for the Wind-Powered Electric Generating Facility in Seneca and Sandusky Counties, Ohio (the "Facility"), the epidemiological evidence does not demonstrate that wind turbine emissions harm human health. As discussed in the epidemiology section of a published critical review I co-authored (McCunney, et al. 2014) and in my updated review and synthesis performed for this matter, many of the available studies on wind turbines and human health are methodologically weak and therefore of limited value in demonstrating causation. Nevertheless, the methodologically stronger peer-reviewed, published studies – including the newest reports from the large and well-conducted Health Canada Community Noise and Health Study, as well as recent registry-based and cohort studies in Denmark – demonstrate no disease or harm to human health associated wind turbine noise. These studies are consistent with findings of a synthesis of the totality of epidemiological evidence, which fails to demonstrate a clear and convincing direct association (and therefore no basis for establishing a causal relationship) between wind turbine noise emissions and any disease or other valid indicator of harm to human health. Therefore, I conclude that claims that wind turbine emissions harm human health cannot be substantiated epidemiologically.

Q-14. What is the basis of your opinions?

A-14. I have utilized standard and widely accepted methods for critically reviewing and synthesizing the peer-reviewed published epidemiological literature based on scientific quality. In contrast with rendering opinions based on select study findings, regardless of their validity, I have formulated my scientific opinions and conclusions based on my assessment of the totality of epidemiological evidence. In addition to the peer-reviewed, published epidemiological literature, I draw upon my education, training and professional experience to formulate my opinions and conclusions, which I hold to a reasonable degree of scientific and epidemiological certainty.

Q-15. What are the noise design goals for the Facility?

A-15. It is my understanding that the Facility has an audible noise design goal of 46 dBA L(8) for nighttime noise outside at non-participating residences.

Q-16. In your opinion, are these design standards consistent with guidelines or levels that are protective of public health?

A-16. Yes. Critical review and synthesis of the epidemiological literature – much of which was based on noise generated by equipment whose designs are noisier and now obsolete – indicates that there is no direct causal link between wind turbine noise and harm to human health. At the design levels proposed, there is no reason to believe that this Facility would be different (other than using modern designs that emit lower sound pressures than historical equipment) and cause harm to public health or safety. Furthermore, according to the noise reports prepared by RSG (the sound consultant for the Facility) the audible noise design goals conform with the guidelines of the World Health Organization (WHO) and the National Association of Regulatory Utility Commissioners (NARUC), both of which are intentionally conservative, and protective.

Q-17. What methods are required to determine the causes of diseases and other health impacts?

A-17. Determining the causes of human diseases generally requires critically reviewing and synthesizing the appropriate epidemiological evidence. Because the quality and validity of research findings is paramount to reaching sound interpretations and conclusions, the scientific and regulatory communities preferentially rely upon and give more weight to epidemiological research that has been peer-reviewed and published in reputable health or medical journals. Not every inquiry about human health is a valid epidemiological study, however, and individual health complaints – even if reflecting actual disease or health experiences – do not constitute scientific evidence that can elucidate causal pathways. Nor are all epidemiological approaches and studies of comparable strength and validity, even if they have undergone peer-review and are published, as the peer-review process does not guarantee scientific quality or the validity of conclusions. Furthermore, most human diseases including their signs and symptoms (which also may be especially common) have multiple causes and risk factors, and the isolation of separate causes is not straightforward, even if possible. A proper critical review and synthesis of epidemiological evidence must reflect, at a minimum, a thorough understanding of epidemiological concepts and methods, and consider the entirety of the published literature (*i.e.*, not selectively relying on studies with findings favourable to some purpose or argument), including evaluation of alternative explanations for the observed correlations. These may include the influence of other, unmeasured causal factors (i.e., confounding), methodological errors leading to bias, or even random error (i.e., chance). Ultimately, correlation does not equate with causation, and observed correlations validly cannot be interpreted as reflecting true causal relationships.

Q-18. What evaluation have you conducted to determine if wind turbine noise impacts human health?

A-18. I have utilized standard and widely accepted methods for identifying, critically reviewing and synthesizing the peer-reviewed, published epidemiological literature to date on noise emissions from industrial wind turbines and human health. My evaluation included as comprehensively as possible all primary epidemiological studies (*i.e.*, original research), as well as scientific reviews that summarize findings across several studies. I also rely upon sections that I authored in "Wind Turbines and Health: A Critical Review of the Scientific Literature" published in the November 2014 issue of the Journal of Occupational and Environmental Medicine, the official peer-reviewed journal of the American College of Occupational and Environmental Medicine (Exhibit KM-2). Although the review addresses the potential health effects of wind turbines from various lines of scientific inquiry and evaluation, my primary responsibility as a co-author was to prepare the epidemiological critical review section.

Q-19. How is your testimony organized?

A-19. Following a brief background on noise and possible human responses including specific health effects, I provide a summary of my critical review and synthesis of the epidemiological literature on health effects of wind turbines, with a focus on the publications generated as part of the Health Canada Study, which I consider to be among the best available. I next provide additional explanations regarding annoyance, which is neither a disease nor an indicator of harm to health, but an expression of displeasure with a stimulus (that others may not find annoying or even enjoy). I then provide a framework for comparing wind turbine noise with other sounds we commonly experience. Last, I provide my general opinion regarding potential health impacts of wind turbines, based on the critical review and synthesis.

The two main messages from my critical review and synthesis, as applied to this matter, as follows:

a. Noise and possible health effects

The Facility noise assessment produced as part of the Application indicates that noise from the proposed turbines will not exceed 46 dBA Leq(8hr) at non-participating residences (including seasonal residences). Sounds generated by industrial wind turbines are similar to sounds generated by any number of devices, human activities or environmental settings – including natural (e.g., surf, wind, rain, insects, etc.) and anthropogenic (traffic, air handling systems, lawn equipment, video games, radio and television broadcasts, etc.) sources. The sound standards established as part of the Application are intended not to cause disease or harm to human health: a synthesis of the epidemiological evidence supports (and cannot refute) this.

b. Noise and Annoyance

While annoyance is not a disease or indicator of harm to health, some individuals express annoyance with any number of other stimuli, for example, smells, extreme temperatures or humidity, flashing lights, and sounds including those produced by wind turbines. Regardless of the source of the stimulus – and whether other may enjoy it – some people may associate feelings of annoyance with perceptions of symptoms or other conditions. However, in cross-sectional surveys of annoyance and symptoms, it is not possible to discern those instances of annoyance (if any) that might lead to a symptom from instances where symptoms might lead to annoyance – or where they both are coincidental. Furthermore, annoyance has been associated with individuals' attitudes toward (for or against) wind turbines, and these attitudes can be influenced by conditioning, i.e., telling people that some stimulus is likely to harm them, even if it is incapable of doing so. In medicine, this is related to the "nocebo" effect (Hauser et al., 2012).

I will address these and other points in greater detail in the next section.

III. <u>LITERATURE REVIEW</u>

Q-20. Can you provide an overview of your literature review?

A-20. I conducted a comprehensive review and synthesis of the peer-reviewed, published epidemiological literature specifically addressing potential health impacts of noise emissions from industrial wind turbines (Exhibit KM-5). I used standard epidemiological methods to identify, review and synthesize the available literature. I identified 68 peer-reviewed published studies from many different countries examining people exposed to noise emissions from industrial wind turbines and possible associations with health effects. The majority of these studies (44) were cross-sectional studies or surveys. There are also six registry-based studies and two prospective cohort studies, as well as several controlled laboratory studies.

Q-21. Can you provide an overview of the Health Canada study on wind turbine noise?

A-21. One of the largest and best-designed cross-sectional studies on wind turbines and health was the Community Noise and Health Study, funded and conducted by Health Canada (i.e., Canadian government scientists) (Feder et al., 2015). The study intentionally did not identify the primary focus on wind turbine noise so that participants would be "blinded" and therefore more likely to provide more objective (i.e., less biased) responses to the study questionnaires. The study included both objective and self-reported measures of health and used actigraphy on a subset of participants to study sleep patterns. Objective measures included individual hair cortisol concentrations (an indicator of stress), blood pressure and resting heart rate, and indicators of sleep activity and disruption. Nine distinct publications derived from the Community Noise and Health Study describe the various methods used and the results of the study. The study enrolled 1,238 randomly selected adults in communities in southwestern Ontario and Prince Edward Island living within 0.25 to 11.22 km of wind turbines during May-September, 2013. The study found no adverse health effects in participants exposed to wind turbine sound levels up to 46 dBA. As observed in other studies, self-reported annoyance -- which is not a disease or indicator of harm to human health -- was correlated with wind turbine noise levels. However, it is not possible to determine from this study whether the noise caused annoyance or if individuals who were annoyed (for any reason including wind turbine noise) tended to self-report more annoyance.

This study has some notable improvements in methodology over previous studies. These improvements primarily include obtaining some objective measurements, in contrast to self-reporting or simply using proximity to wind turbines as a surrogate of exposure. Also, the Health Canada Study researchers relied on "more than 4000 hours of WTN [Wind Turbine Noise] measurements conducted by Health Canada to support the calculation of WTN levels at residences captured in the study scope."

Q-22. What do you recommend to the Board with respect to the Health Canada Study?

A-22. Although the Health Canada Study is cross-sectional by design and therefore cannot address all health questions of interest, its quality rises above most other studies in that objective measurement of wind turbine noise and various indicators of physiological response (e.g., blood pressure and sleep disturbance) were obtained on individual participants, allowing direct evaluation of their potential relationship(s). The Health Canada Study demonstrated no clear or consistent association between wind turbine noise and any health effect, in agreement with the majority of previous studies of reasonable quality. Furthermore, the publications generated from this study were authored by qualified and disinterested government scientists, and published in reputable peer-reviewed scientific journals. Therefore, it is recommended that the Board afford the Health Canada

Study results greater weight in its decision-making regarding wind turbine noise and human health than smaller or poorly designed and conducted surveys.

Q-23. What does the Health Canada study say about sleep disturbance?

A-23. Michaud et al. (2016a) evaluated self-reported sleep quality over the previous 30 days using the Pittsburgh Sleep Quality Index, as well as sleep actigraphy objective measures in a subset of 654 participants. The authors reported that "self-reported and objectively measured sleep outcomes consistently revealed no apparent pattern or statistically significant relationship to WTN levels. However, sleep was significantly influenced by other factors, including, but not limited to, the use of sleep medication, other health conditions (including sleep disorders), caffeine consumption, and annoyance with blinking lights on wind turbines."

Q-24. What does the Health Canada study say about stress, blood pressure and related endpoints?

A-24. Michaud et al. (2016b) used multiple regression modelling to evaluate exposure to WTN and perceived stress scale (PSS) scores, objectively measured hair cortisol concentrations, resting blood pressure, and heart rate. There were no significant associations between WTN up to 46 dBA and any measured health indicators.

Q-25. What does Health Canada say about quality of life?

A-25. Quality of life is a highly subjective general indicator of how good or bad someone considers their life situation, and may include aspects of enjoyment, financial security, health, safety, community amenities, domestic and social support, recreational opportunities, access to services and entertainment, etc. Feder, et al. (2015) evaluated quality of life measures self-reported by the 1,238 randomly selected participants of The Community and Health Noise study. In the main statistical analyses, WTN levels were not related to quality of life and satisfaction with health, or to indicators of physical, psychological, social or environmental well-being. Some quality of life variables correlated with wind turbines, irrespective of wind turbine noise levels. For example, lower scores in the physical and environmental domains "were observed among participants reporting high visual annoyance toward wind turbines." The authors concluded that overall, "results do not support an association between exposure to WTN up to 46 dBA and QOL [quality of life] assessed using the WHOQOL-BREF questionnaire."

Q-26. Are there other studies that you recommend to the Board with respect to health effects of wind turbines?

A-26. Yes, there is a series of publications that evaluated health-related outcomes such as myocardial infarction, stroke, diabetes, hypertension, use of sleep medication and use of anti-depressant medication in the Danish population. These studies involved cohorts of tens of thousands of people followed over a long time period. Some results reflected statistical correlations, including some that would be expected in any study, especially where multiple tests are performed (i.e., 5% of all statistical tests, by definition, will be spuriously statistically significant due to chance alone). However, the totality of the evidence did not find any clear or consistent evidence that exposure to wind turbine noise leads to actual increases in these outcomes.

IV. ANNOYANCE

Q-27. Is annoyance considered an adverse health effect?

A-27. Annoyance is neither a disease nor an adverse health effect. Annoyance is not listed as a disease entity in the 10th Revision of the International Classification of Diseases (ICD-10) – the current compendium of all classified diseases and health effects. I also could not locate a definition for "annoyance" in any medical dictionary. In lay terms, "annoyance" is a feeling of displeasure and synonymous with "irritation." There are many reasons why people become annoyed, much of which has to do with their attitude toward the subject of annoyance.

Q-28. What does the World Health Organization (WHO) say about annoyance?

A-28. WHO's Environmental Noise Guidelines for the European Region (2018) states that [noise] annoyance is "a feeling of displeasure, nuisance, disturbance or irritation caused by a specific sound." Feelings of displeasure or irritation are among the most common reactions to various perceptions or thoughts, including memories, good or bad, but are not diseases or symptoms of a harmful exposure. Ultimately, feelings are subjective and vary widely across individuals and over time in the same individuals. Importantly, what some people find annoying (e.g., dripping faucet, neighbor's dog barking, humming refrigerator, unpleasant smells, etc.) often are inherently benign, but perceived to be harmful.

Q-29. What does the Health Canada study say about annoyance?

A-29. Michaud, et al. (2016c) evaluated associations between reported visual and auditory perception of wind turbines with wind turbine noise levels and reported that increased perception of noise correlated with noise levels, i.e., the louder the wind turbine noise, the more likely people reported hearing it. Reported high levels of annoyance were correlated with multiple sensory perceptions, including increased visual perception of the turbines as well as perceiving turbine noise, blinking lights, shadow flicker and vibrations.

Michaud, et al (2016d) reported that general annoyance with wind turbines, personal benefit, physical safety concerns, property ownership, province, noise levels, and sensitivity to noise were statistically correlated (one way or the other) with reported annoyance. Although not related to wind turbine noise levels, a number of health indicators (migraines, dizziness, tinnitus, chronic pain, and restless leg syndrome) were statistically correlated with annoyance, suggesting that individuals with these conditions may be more easily annoyed with environmental stimuli, or more likely to self-report annoyance.

Voicescu, et al. (2016) reported that self-reported high annoyance with wind turbine shadow flicker was statistically correlated with general annoyance with wind turbines (such as visual perception), concern for physical safety, and self-reported noise sensitivity.

Michaud et al. (2018a) performed principal components analysis (PCA) to develop a single statistical model for overall annoyance related to wind turbines, incorporating responses to noise, blinking lights, shadow flicker, visual impacts, and vibrations. Residential distance to the nearest wind turbine was correlated with aggregate annoyance scores.

Michaud et al. (2018b) evaluated the correlation among aggregate annoyance with wind turbines and self-reported dizziness, tinnitus, migraines, sleep disturbance, depression and perceived stress as well as objectively measured blood pressure and chemical analysis for cortisol levels in hair. Average aggregate annoyance was increased among those with self-reported chronic pain, poor sleep, tinnitus, migraines/headaches, dizziness, high noise sensitivity, and high sleep disturbance. Diastolic blood pressure, perceived stress, and

Pittsburgh Sleep Quality Index scores (scores >5 indicate poor sleep) were also significantly, positively associated with increased aggregate annoyance while quality of life domain scores in physical health, psychological well-being, and environmental factors were significantly, negatively associated with increased aggregate annoyance scores. Hair cortisol concentrations and systolic blood pressure (objective measures) were not related to aggregate annoyance. The authors stated that these observed associations "should not be mistakenly interpreted to mean that annoyance causes adverse health effects (or vice versa)" (Michaud et al. 2018b: p. 258). They further emphasized that their findings were "statistical observations made from data collected at one point in time with no documented historical records for any of the evaluated outcomes or control for other factors that may impact annoyance or health" (Michaud et al. 2018b: p. 258).

Q-30. Is there any scientific literature showing that higher sound levels from wind turbines cause annoyance?

A-30. As discussed in Exhibit KM-5, the literature on wind turbines reports an association (or correlation) between sound pressure levels (especially at higher levels) and self-reported annoyance; however, these findings likely reflect attitudes toward wind turbines, or fears or perceptions associated with other factors such as economic loss or aesthetic degradation, or increased self-reporting of annoyance among people self-reporting other symptoms.

Q-31. Can you explain these findings?

A-31. As discussed in Exhibit KM-5, several controlled laboratory studies of volunteers exposed to recordings of wind turbine noise have been conducted and shed some light on the reported findings from the cross-sectional surveys and the self-reported complaints of annoyance. These experiments, taken together, support the interpretation that self-reports of annoyance and other complaints reflect, at least in part, preconceptions about the ability of wind turbine noise to harm health, damage environmental aesthetics or lead to economic loss, and can be significantly influenced by factors as trivial as the color of the turbine (Crichton et al. 2014a, Crichton et al. 2014b, Crichton et al. 2015, Crichton and Petrie 2015, Maffei et al. 2013, and Ruotolo et al. 2012). As described by Walker et al. (2015) regarding psychosocial stress in wind turbine communities, "Indeed there is some evidence of anticipatory fear, whereby those communities who may be considered future sites of wind turbines (e.g., rural Ontario, Canada) are significantly more worried about the health and well-being impacts of turbines than those who already live with them." It is apparent that community education on the scientific issues is needed to help alleviate concerns and anxiety.

V. Sounds Levels of Wind Turbines and Infrasound

Q-32. The Applicant's proposed design goal for this facility is 46 dBA Leq(8hr) at non-participating residences. How does that compare to noise levels of other common noise sources?

A-32. To better appreciate the maximum sound levels anticipated at points of reception at non-participating residences surrounding the turbines, 46 dBA can be compared with household and other common noise sources, ranging from 10 dBA (sound of the Grand Canyon at night) to 89 dBA (vacuum cleaner) (see Table 1) (Noise Pollution Clearinghouse, www.nonoise.org). Wind turbine noise falls among refrigerators and heating system noise levels. Noise generated from these sources – which constantly surround people – is not associated with adverse health effects.

Table 1: Example Sound Comparisons (http://www.nonoise.org/library/household/index.htm)

Type	Sound Pressure Level (dBA)
Vacuum Cleaner	84-89
Driving Inside a Car, Windows Open, 30 mph	72-76
Driving Inside a Car, Windows Closed, 30 mph	68-73
Clothes Washing Machine	65-70
Dishwasher	63-66
Clothes Dryer	56-58
"Normal" Conversation	55-65
Microwave	55-59
Bathroom Exhaust Fan	54-55
Forced Hot Air Heating System	42-52
Wind Farm – predicted 8-hr night-time average*	*46*
Refrigerator	40-43
Computer	27-45
Typical "Quiet Room"	28-33

Type	Sound Pressure Level (dBA)
Quiet Basement without mechanical equipment; or the sound of rustling leaves	20
Grand Canyon at night (no roads, birds and wind)	10

**wind farm row is added for illustrative purposes.*

The National Institute on Deafness and Other Communication Disorders, part of the National Institutes of Health (NIH), has published similar data (excerpts are reproduced in Table 2). Note that levels under 65 dB are safe for your ears.

Table 2: Excerpts from NIH: National Institute on Deafness and Other Communication Disorders (NIDCD): (https://www.nidcd.nih.gov/listen-text-only-version)

Type of Sound	Decibel Level (dB)	What we hear
Sirens from a fire truck, police car, or ambulance	110–129	You can lose some of your hearing in less than a minute if you're near a police car, fire truck, or ambulance siren.
Motorcycle	80-110	You can lose some of your hearing after an hour on a motorcycle
Movie Theater	70-104	Seeing a movie on the big screen is fun, but it's also loud— often, loud enough to make you lose some of your hearing
Lawnmower	80-100	This level of noise can make you lose some of your hearing, so be sure to wear hearing protection.
Normal talking voice at arm's length	65-80	Chat away! But if you have to yell so people who are nearby can hear you, watch out— the noise around you is probably too loud
Dishwasher running	45-65	This level of noise is safe for your ears. Go ahead and scrub the pots and pans while the dishwasher does its job!
Wind Farm (predicted 8-hr night-time average)*	*46*	
Fridge humming	40	Snack on! This is totally fine for your ears.
Whispering	30	Your secret is safe! This is totally fine for your ears.

**wind farm row is added for explanatory purposes.*

Q-33. What is the sound pressure level of wind turbines?

A-33. Noise from wind turbines includes mechanical noise from the gearbox and generator, and aerodynamic noise from air moving across turbine blades. For modern, properly maintained and operating turbines, the predominant sound is aerodynamic noise. According to a report from the National Research Council, the sound pressure level from a single turbine is usually around 90-110 dB(A) at the source, which creates a sound pressure of 50-60 dB(A) – the sound level of conversational speech – at a distance of 40 meters, or about 130 away, and ranges from 35 to 45 dB(A) at 300 meters (approximately 985 feet) (National Research Council 2007). Note that this was determined more than 12 years ago and would not reflect additional technological improvements. For comparison, this is about the noise level of a refrigerator (see tables above for others), and at the upper end of the typical night-time ambient noise levels in the countryside [20-40 dB(A)]. Low-frequency noise is more likely generated by older, downwind model wind turbines, whereas newer upwind models have been configured to minimize noise, including low frequency noise (National Research Council 2007).

Q-34. What types of sounds do wind turbines produce?

A-34. Wind turbines produce audible sounds, low frequency sound, and infrasound.

The aerodynamic audible sounds from wind turbines have been described as "swishing" or "whooshing" that may make them discernible over other, even louder, sounds under certain conditions. Leventhall (2006) notes that the "swish–swish" is usually 500–1000 Hz, which is above the low frequency range, and that "there is insignificant infrasound from wind turbines and that there is normally little low frequency noise" (Leventhall 2006). Colby et al. (2009) noted that infrasound from wind turbines is not audible and noise in the low frequency range is modest on the scale of commonly encountered low frequency noises. Based on data from field measurements of indoor infrasound at three residences near an operating wind farm, Berger, et al. reported that indoor infrasound was below auditory threshold levels and that low frequency noise levels were comparable to background low frequency noise levels at distances greater than 500 meters (Berger 2015).

Q-35. Have any studies specifically addressed infrasound from wind turbines?

A-35. Yes. Four laboratory studies in five publications specifically examined this issue. Crichton (2014b) exposed 54 university students to one of two presentations labelled as "high-" or "low-expectancy." The "high-expectancy" presentation included first-person television and internet accounts of symptoms attributed to wind turbines, while the "low-expectancy" presentation showed experts stating that infrasound does not cause symptoms. Participants were then exposed to 10 minutes of infrasound and 10 minutes of sham-infrasound. Physical symptoms were reported before and during each 10-minute exposure. The high-expectancy group had increased reports of symptoms and symptom-intensity scores. Furthermore, the high-expectancy group reported more symptoms during both the infrasound and sham infrasound exposure. The low-expectancy participants did not report any significant changes in symptoms. These data demonstrate that the participants' expectations of the wind turbine sounds determined their patterns of self-reporting symptoms, regardless of whether the exposure was to a true or sham wind turbine sound.

Crichton (2014a) examined whether positive or negative health information about infrasound and audible sound generated by wind turbines affected participants' symptoms and health perceptions in response to wind turbine noise. A group of 60 university students was randomly assigned to positive and negative expectancy groups and shown positive expectancy or negative expectancy short videos, respectively. The videos were intended to promote or dispel the notion that wind turbines sounds impacts health. The negative expectancy group received information that exposure to wind turbine sound, particularly infrasound, poses a health risk; the positive expectancy group received information comparisons of wind turbine sound with sub-audible sound created by natural phenomena such as ocean waves and the wind, emphasizing their positive effects on health. Students were then continuously exposed to both infrasound (50.4dB, 9Hz) and recorded audible wind turbine noise (43dB), during two seven-minute listening sessions and assessed for mood and several physical symptoms. Both positive expectancy and negative expectancy groups were made aware they were listening to wind turbine noise, 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. Participants exposed to wind turbine noise experienced a placebo response elicited by positive pre-exposure expectations, with those positive pre-exposure participants who were given expectations that infrasound produced health benefits reporting positive health effects. In contrast, participants in the negative expectancy group reported negative health effects, i.e., a nocebo effect. The authors indicated that reports of symptoms or negative effects associated with wind farms could be nullified if expectations could be framed more positively.

Another study examined the role of noise sensitivity and reported that noise sensitivity was related to annoyance, but again only in the negative expectation group (Crichton et al. 2015). Additionally, Crichton and Petrie (2015) randomly assigned 64 volunteers to watch either positive or negative information about the health effects of infrasound before subjecting them to both audible sound and infrasound from wind turbines. The authors indicated that positive information may help moderate the effect of negative expectations (Crichton, Petrie 2015).

Tonin et al. (2016) investigated symptoms of simulated infrasound produced by wind turbines in a double-blinded study. Infrasound generated by wind turbines at the Shirley Wind Farm in Wisconsin was recorded at three residencies where occupants reported health problems they attributed to wind turbine noise. Seventy-two volunteers (27 female, 45 male) ranging from 17 to 82 years in age, were exposed to either wind turbine infrasound noise or non-wind turbine infrasound noise (sham noise), after watching one of two videos: one video to "heighten expectations," which showed an interview with a couple who were affected by a wind farm, and one to "lower expectations," which showed an academic expert explaining why infrasound is not a problem. Three statistically significant outcomes were reported: 1) in the high expectation groups, the infrasound had a negative effect on the number of reported typical symptoms, 2) baseline concern was significantly correlated with both the mean number and the mean intensity of reported typical symptoms, and 3) age was significantly correlated with the number of reported typical symptoms, with older participants reporting fewer symptoms. The authors concluded that "simulated infrasound ha[d] no statistically significant effect on the symptoms reported by volunteers, but the prior concern that volunteers had about the effect of infrasound ha[d] a statistically significant influence on the symptoms reported" (Tonin et al., 2016).

VI. Other Potential Health Effects Raised

Q-36. What other concerns related to potential health impacts arising from the presence of wind turbines have been raised in these proceedings?

A-36. The intervening parties in this case and public comments have expressed concerns that shadow flicker may lead to health effects such as anxiety and exacerbation of sensory disorders. They have also expressed concerns related to “Wind Turbine Syndrome.” Both of these are discussed below.

Q-37. What are the health impacts allegedly associated with shadow flicker?

A-37. There are no published epidemiological studies of health impacts from shadow flicker generated by industrial wind turbines in the peer-reviewed literature. Two publications identified in PubMed (Harding et al., 2008 and Smedley et al. 2010) postulated that wind turbine shadow flicker at greater than 3 Hz or with blade speeds exceeding 60 rpm could induce seizures in photosensitive individuals; however, no study has demonstrated this. Smedley et al. (2010) reported that “large turbines rotate at a rate below that at which the flicker is likely to present a risk.” However, the intervening parties state that:

> “This strobing of light and shadows on a residence can be extremely annoying, causing anxiety, irritability, and headaches to the residents. As a result, it is generally recognized that residences should not be subjected to any more than 30 hours of shadow flicker per year to protect occupants from adverse health effects. *See, e.g.*, Wind Energy & Wind Park Siting and Zoning Best Practices and Guidance for States (National Association of Regulatory Utility Commissioners, January 2012) at 31” (Petition to intervene of Additional Local Residents).

This reference, however, describes shadow flicker as a nuisance, not an adverse health effect. Further, the National Association of Regulatory Utility Commissioners report cites a review conducted in 2012 for the Commonwealth of Massachusetts (Ellenbogen et al. 2012), stating: “Scientific evidence suggests that shadow flicker does not pose a risk for eliciting seizures as a result of photic stimulation. … There is limited scientific evidence of an association between annoyance from prolonged shadow flicker (exceeding 30 minutes per day) and potential transitory cognitive and physical health effects.” The limited evidence underlying this statement appears to be a single German government experiment conducted by Pohl in 1999 in which a group of volunteers was exposed to 60 minutes of simulated wind turbine flicker; however, the report was not published in any peer-reviewed scientific journal. One review, citing the report of an expert panel convened by the Massachusetts Department of Environmental Protection and Massachusetts Department of Public Health, stated, “Furthermore, the expert panel convened by MassDEP and MDPH

(56) concluded that the scientific evidence suggests that shadow flicker does not pose a risk of inducing seizures in people with photosensitive epilepsy" (Knopper et al., 2014).

Q-38. Do any studies support exacerbation of sensory disorders such as autism from wind turbine emissions?

A-38. I was unable to locate any published peer-reviewed epidemiological study or review that specifically demonstrated that wind turbine shadow flicker or other emissions exacerbate sensory disorders including epilepsy and autism.

Q-39. In their petition to intervene, the Residents' acoustics expert claims that residents in and around the project might be "subjected" to the so-called "wind turbine syndrome." Is "wind turbine syndrome" an accepted medical condition?

A-39. "Wind turbine syndrome" is not an accepted medical condition. Wind Turbine Syndrome (WTS) was first proposed by Nina Pierpont, a pediatrician, in a self-published book, "Wind Turbine Syndrome – A Report on a Natural Experiment." This book appears to have been written to support her personal advocacy efforts. Pierpont describes her report as "a case series of 10 affected families" including 38 individuals living near 1.5-3 MW wind turbines with whom she has conducted a "clinical interview." According to the text, "[t]he purpose of this study is to establish a case definition for the consistent, frequently debilitating, set of symptoms experienced by people while living near wind turbine installations, and to place this symptom complex within the context of known pathophysiology." Unsurprisingly, she reported an array of symptoms among these "affected families" including many common conditions with numerous common risk factors: impaired communication, sleep disturbance, impaired cognitive functioning, headaches, dizziness, tinnitus, and annoyance. In constructing this case series (which does not constitute a valid epidemiological study), individuals with some disease (or rarely, symptoms, which are inherently subjective) of possible interest. Ultimately case reports have limited value with respect to causal inference, and at most might suggest hypotheses that can be evaluated using standard and properly rigorous epidemiological methods.

Unfortunately, interviewing individuals (or presumably family members, as the youngest participant was less than one year old) provides no valid information regarding the rate at which these conditions or symptoms occurred over a specified period of time (i.e., risk) in a group defined as "exposed," relative to the risk among a comparable non-exposed population (the relative risk is a ratio of these two risk estimates). Observations on 38 individuals – even if they were in the context of a properly designed epidemiology study – would represent too small a group for valid inferential purposes. Ultimately, the case series as presented by Pierpont may reflect a select group of individuals' perceptions, but is of no inferential value and cannot substantiate claims that wind turbines cause any specific true health effect. Had this exercise any true scientific value, it would have been published as an article in a peer-reviewed scientific journal.

Researchers at the University of Sydney (Australia) responded to the Pierpont book by publishing their own book with the parodic title, "Wind Turbine Syndrome: A Communicated Disease." This was published by Sydney University Press (a legitimate publication house) in 2017. The authors (Simon Chapman and Fiona Crichton, both highly published scientific researchers on the topic of wind turbines and health) note in the introduction to their text, "The notion [that wind turbines are the direct cause of illness in some of those exposed to them] began to attract minor attention from around 2002, when claims made in unpublished 'research' by a British doctor were covered by a few news outlets and began to be circulated among objectors. The 2009 appearance of a self-published book, Wind turbine syndrome, by a US pediatrician, Nina Pierpont, acted like petrol thrown onto a fire of latent anxiety in a small number of communities where activists were doing their utmost to spread concern and to urge people to attribute common health problems to sub-audible sound emitted by the turbines. The book put the alleged health issue on the global map, although as we shall see, concerns about windfarms and health are virtually unknown in most nations which have windfarms today" (Chapman and Crichton, 2017, p. xxviii).

A case definition for "adverse health effects in the environs of industrial wind turbines," essentially the same as WTS, was proposed in 2014, but it lacks specificity and scientific support in the peer-reviewed medical literature. Similar to the effect of preconceptions about noise from wind turbines on health, a peer-reviewed published article addressed possible psychological mechanisms for WTS concluding that such mechanisms "may be sufficient to account for the experiences reported by sufferers" (Rubin et al. 2014). I am a co-author of an analysis of the proposed case definition which found that it was overly broad and posed risks to patients by overlooking treatable conditions (McCunney et al. 2015). In short, "wind turbine syndrome" is not a supported or accepted condition in the epidemiological community.

VII. CONCLUSION – Potential Health Effects At Proposed Noise Levels

Q-40. Are the proposed noise levels associated with the facility consistent with the findings of the Health Canada Study?

A-40. Yes. As stated in my publication, I found no clear or consistent association between noise from wind turbines and any reported disease or other indicators of harm to human health. The conclusions from my publication are only further strengthened by the more recent, higher quality epidemiology studies, in particular those performed by Canadian government health professionals. As demonstrated in the Health Canada study, wind turbine noise levels up to 46 dBA are not associated with harm to human health. Wind turbine sound pressures of higher than 46 dB(A) may be statistically correlated with some (and especially self-reported) symptoms or complaints, but not with any objectively measured indicators of health.

Q-41. As an epidemiologist, can you give an opinion on whether the operation of utility-scale wind turbines causes adverse health effects?

A-41. Yes. A quality-based critical review and synthesis of the literature does not establish that exposure to wind turbines causes any disease or harms human health among nearby residents and community members. At most, the literature reports an association (or statistical correlation) between sound pressure levels and self-reported or perceived annoyance; however, these findings may well reflect attitudes toward wind turbines, or fears or perceptions of economic loss or aesthetic degradation. Due to the cross-sectional nature of several of the studies, however, strong causal explanations are not possible. Annoyance and measured sound pressure levels were not linked with health outcomes such as myocardial infarctions (i.e., heart attacks), stroke, hypertension or self-reported conditions such as headaches. Some statistical correlations between wind turbine noise and annoyance were reported, but the studies in which this and other sporadic associations were reported were cross-sectional surveys (*i.e.*, cannot establish whether the noise caused the sleep disturbance or whether sleep problems led to the perception of and annoyance with the night-time noise), relied on self-reporting of symptoms (which may be subject to volunteer and reporting biases) and were limited by small sample size. Therefore, these studies do not provide evidence on which valid causal conclusions can be drawn.

The tendency of individuals to perceive and self-report symptoms differently under different exposure and study circumstances is well known in epidemiology (and other fields relying on volunteer participants and self-reported information). For example, in medicine, the well-known placebo effect has been shown to occur where individuals given inactive substances resembling active drugs (i.e., a "sugar pill") report improvement in symptoms. Conversely, symptoms are more likely to be reported after individuals believe that they have been exposed to a hazard. In medicine, this is known as the nocebo effect (Hauser, et al., 2012). These effects or biases can be reduced or eliminated through the "blinding" of participants as to the treatment they receive, or in observational studies, to the underlying purpose and hypotheses of the study. Some studies employ "double-blinding" in which not only the participants, but also the interviewers and data extractors, are blocked from knowing the study hypotheses and objectives. The laboratory studies in which messages reinforcing positive or negative expectations prior to exposure to recorded wind turbine noise – or even sham noise – consistently demonstrate the critical role of expectation in shaping responses.

Q-42. Upon what do you base your opinion?

A-42. All of my opinions are based upon my critical review and synthesis of the totality of epidemiological evidence from the peer-reviewed published scientific literature. My opinions are grounded in my training and experience of over 30 years teaching, applying, interpreting and publishing on epidemiological methods used to determine preventable causes of human disease.

Q-43. What is your summary opinion?

A-43. Based on my review and synthesis of the relevant published, peer-reviewed scientific epidemiological evidence, attached as Exhibit KM-5, I found no causal connection between sound levels from industrial wind turbines and any human disease or other indicator of serious harm to human health. It should be noted that some degree of noise is consistently perceived by residents living near wind turbines depending on number of turbines, time of day, season, and level background noise, and to a lesser extent shadow flicker, again, depending on time of day, season, and position of the turbine blades. However, wind turbine noise at or below the level proposed for this facility – while potentially distracting or annoying to some – does not harm human health.

Q-44. Does this conclude your testimony?

A-44. Yes, it does, except that I reserve the right to update this testimony to respond to any further testimony in this case.

CERTIFICATE OF SERVICE

I hereby certify that the foregoing Direct Testimony of Kenneth Mundt was served upon the following parties of record via regular or electronic mail this 21st of 2019.

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MM-1

Kenneth A Mundt, PhD, FACE

Current Position

Senior Principal Health Scientist

Discipline Areas

> Epidemiology
> Hazard / Causation Assessment
> Risk Evaluation

Years' Experience

28

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2018

Education

> PhD, Epidemiology, University of North Carolina at Chapel Hill, 1990
> MS, Epidemiology, University of Massachusetts at Amherst, 1986
> MA, English, University of Virginia, 1982
> AB, English, Dartmouth College, 1981

Summary of Experience

Dr. Kenneth A. Mundt is an epidemiologist with professional interest and experience in applying epidemiological concepts and methods to understand human health risks from environmental, occupational and consumer product exposures. He has designed, conducted and published numerous epidemiological studies, performed critical reviews and syntheses of the published literature, and is active in the development of methods for integrating evidence across lines of evidence including epidemiology, toxicology and exposure science. Dr. Mundt's evaluations, publications and consulting have explored complex relationships between exposure to chemicals, metals, minerals, air pollutants, tobacco products, pharmaceutical agents, food contaminants, wind turbine emissions, and risk of a broad range of human health outcomes including cancers, reproductive effects, cardiovascular and respiratory diseases.

Dr. Mundt specializes in the practical application of scientific concepts, methods and evidence in evaluating disease causation, deriving health protective regulations, litigation and other decision-making.

Significant Projects

Epidemiological Studies

Managed multidisciplinary teams in designing, conducting and interpreting occupational epidemiological studies of workers involved in rubber, porcelain, chemical and steel industries, as well as military and other professionals.

Health Risks Evaluation and Communication

Generated and evaluated scientific data in responding to observed and perceived health problems related to exposure to occupational, environmental and consumer product exposures.

Teaching and Scholarship

Former university professor with several current adjunct faculty appointments. Frequently participates in scientific meetings, training courses, and litigation proceedings. Consistent record of research, publication and developing new research opportunities.

Scientific Regulatory Support

Provided scientific evaluation and support to regulatory and policy processes, oral and written testimony, statistical re-analysis of data from key studies, commentaries and technical communications, and constituted and managed expert panels.

Systematic Critical Reviews and Syntheses

Comprehensively identified, systematically critically reviewed and synthesized the epidemiological literature on human health risks associated with numerous occupational, environmental and consumer product exposures. Current focus on evidence integration.

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Professional History

Senior Principal Health Scientist (2018-Current)

Cardno ChemRisk

Provides a broad range of clients advanced consulting services in epidemiology, risk evaluation and evidence integration. Serves as a senior leader and mentor at ChemRisk.

Principal and Health Sciences Global Network Leader (2003-2018)

Ramboll US Corporation (formerly ENVIRON International Corporation)

Helped develop and lead ENVIRON's and Ramboll US's Health Sciences Global Practice and directed the Applied Epidemiology Practice Area.

President and Founder (1991-2003)

Applied Epidemiology, Inc.

Formed consultancy focused on applying epidemiological concepts and methods to diverse occupational and environmental health challenges on behalf of corporations, government agencies, international organizations, and law firms.

Associate Professor, Department of Family Medicine and Community Health (1997-2002)

University of Massachusetts Medical School, Worcester

Served as faculty member in and advisor to the Occupational Medicine Residency Program. Collaborated in conducting clinical trial on carpal tunnel release surgery. Taught epidemiology component of Masters in Public Health (MPH) Program.

Associate Professor of Epidemiology, School of Public Health and Health Sciences (1989-1999)

University of Massachusetts at Amherst

Taught at the graduate university level in epidemiological concepts and methods in the Department of Biostatistics and Epidemiology. Developed and directed the Occupational Epidemiology Unit. Mentored dozens of students at the doctoral and masters level.

Professional Honors/Awards

- Kammer Merit in Authorship Award, American College of Occupational and Environmental Medicine, 2017
- Award for Significant Contributions to the field of Public Health, University of Massachusetts School of Public Health, 2011
- Teaching Excellence Award, University of Massachusetts School of Public Health, 1995
- Delta Omega Award for Dissertation Research, University of North Carolina at Chapel Hill, 1990
- Deutscher Akademischer Austauschdienst (DAAD) Epidemiology Program Fellowship, University of North Carolina, 1989

Membership in Professional Societies

- > Fellow, American College of Epidemiology (FACE)
- > Delta Omega - Honorary Society in Public Health
- > International Commission on Occupational Health
- > International Society for Environmental Epidemiology
- > MEDICHEM
- > Sigma Xi - The Scientific Research Society
- > Society for Epidemiologic Research
- > Society for Risk Analysis

Other Professional Activities

- > Secretary General, MEDICHEM, 2015-2021
- > Secretary, ICOH Scientific Committee on Occupational Health and Safety in the Chemical Industry 2016-2019
- > Advisor, Institute for Global Health, University of Massachusetts, 2018-present
- > Member, Ethics Committee, American College of Epidemiology, 2016-present
- > Member, Dean's Advisory Board, University of Massachusetts School of Public Health and Health Sciences, 2002-present
- > Editorial Service
  - – Advisory Editor, Archives of Industrial Hygiene and Toxicology, 2013-present
  - – Member Executive/Steering Committee, International Hormesis Society, 2005-preset
  - – Advisory Editor, International Archives of Occupational and Environmental Health, 2002-present
  - – Associate Editor, Dose-Response, 2001-2012
- > Invited Observer, Proceedings of IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volumes 93, 98 and 100f, International Agency for Research on Cancer (IARC), 2006-2009
- > Scientific Consultant, Science Review Board, FIFRA Scientific Advisory Panel, United States Environmental Protection Agency (EPA), 2002-2004
- > Epidemiology Consultant and Scientific Advisor, Health Services Department, The World Bank, 1993-2004
- > Member of the Board of Directors and Haiti Program Director, Opportunities for Communities, Inc., a 501(c)(3) educational organization, 2008-present
- > Peer Reviewer in Epidemiology, Agency for the Toxic Substances and Disease Registry, 1993-2005

Peer Reviewer

- > American Journal of Epidemiology
- > American Journal of Industrial Medicine
- > Archives of Industrial Hygiene and Toxicology
- > Critical Reviews in Toxicology
- > Dose-Response
- > Drug and Chemical Toxicology

- International Archives of Occupational and Environmental Health
- Occupational and Environmental Medicine
- Regulatory Toxicology and Pharmacology

Academic Appointments

- Adjunct Professor of Epidemiology, University of South Carolina, 2018-present
- Adjunct Professor of Environmental Health, University of South Carolina, 2016-present
- Adjunct Professor of Epidemiology, University of Massachusetts, 2005-present
- Adjunct Professor of Epidemiology, University of North Carolina, 2007-2018 (renewal pending)
- Adjunct Associate Professor, Department of International Health, School of Nursing and Health Studies, Georgetown University, 2002-2007
- Consulting Faculty, United States Navy, Department of Undersea Medicine, Naval Submarine Base, New London, CT, 1999
- Visiting Professor, Abteilung für Sozialmedizin und Epidemiologie, Ruhr-Universität Germany 1991-1994
- Epidemiology Short Course Instructor: Norway, Germany, Slovakia, Thailand, Italy, Switzerland and USA

Publications

Peer-Reviewed Publications

- Sax, S.N., P.R. Gentry, C. Van Landingham, H.J. Clewell 3rd and K.A. Mundt. 2019. Extended Analysis and Evidence Integration of Chloroprene as a Human Carcinogen. Risk Analysis. (in press).
- Andersen, M.E., P.R. Gentry, J.A. Swenberg, K.A. Mundt, K.W. White, C. Thompson, J. Bus, J.H. Sherman, H. Greim, H. Bolt, G.M. Marsh, H. Checkoway, D. Coggon, and H.J. Clewell 3rd. 2019. Considerations for refining the risk assessment process for formaldehyde: Results from an interdisciplinary workshop Regulatory Toxicology and Pharmacology 2019 Aug;106:210-223.
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> Mundt KA, Dell LD, Crawford L, Sax SN, Boffetta P. Cancer Risk Associated with Exposure to Bitumen and Bitumen Fumes: An Updated Systematic Review and Meta-Analysis. Journal of Occupational and Environmental Medicine 2018 Jan;60(1):e6-e54.

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Wind Turbines and Health

A Critical Review of the Scientific Literature

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

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

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

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

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

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

Earlier reviews of wind turbines and potential health implications have been published in the peer-reviewed literature[1–6] by state and provincial governments (Massachusetts, 2012, and Australia, 2014, among others) and trade associations.[7]

This review is divided into the following five sections:

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

METHODS

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

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

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3. After identifying articles obtained via these searches, they were categorized into five main areas that are noted below (section D) and referred to the respective authors of each section for their review and analysis. Each author then conducted their own additional review, including a survey of pertinent references cited in the identified articles. Articles were selected for review and commentary if they addressed exposure and a health effect—whether epidemiological or experimental—or were primary exposure assessments.
4. Identified studies were categorized into the following areas:

    I. Sound, its components, and field measurements conducted in the vicinity of wind turbines;
    II. Epidemiology;
    III. Effects of sound components such as infrasound and low-frequency sound on health;
    IV. Psychological factors associated with responses to wind turbines;
    V. Governmental and nongovernmental reports.

5. The authors are aware of reports and commentaries that are not in the scientific or medical peer-reviewed literature that have raised concern about potential health implications for people who live near wind turbines. These reports describe relatively common symptoms with numerous causes, including headache, tinnitus, and sleep disturbance. Because of the difficulties in comprehensively identifying non–peer-reviewed reports such as these, and the inherent uncertainty in the quality of non–peer-reviewed reports, they were not included in our analysis, aside from some books and government reports that are readily identified. A similar approach of excluding non–peer-reviewed literature in scientific reviews is used by the World Health Organization (WHO)'s International Agency for Research on Cancer (IARC) in its deliberations regarding identification of human carcinogens.[8] International Agency for Research on Cancer, however, critically evaluates exposure assessments not published in the peer-reviewed literature, if conducted with appropriate quality and in accordance with international standards and guidelines. International Agency for Research on Cancer uses this policy for exposure assessments because many of these efforts, although containing valuable data in evaluating health risks associated with an exposure to a hazard, are not routinely published. The USA National Toxicology Program also limits its critical analysis of potential carcinogens to the peer-reviewed literature. In our view, because of the critical effect of scientific studies on public policy, it is imperative that peer-reviewed literature be used as the basis. Thus, in this review, only peer review studies are considered, aside from exposure-related assessments.

RESULTS

Characteristics of Wind Turbine Sound

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

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

Sound Level and Frequency

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

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

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

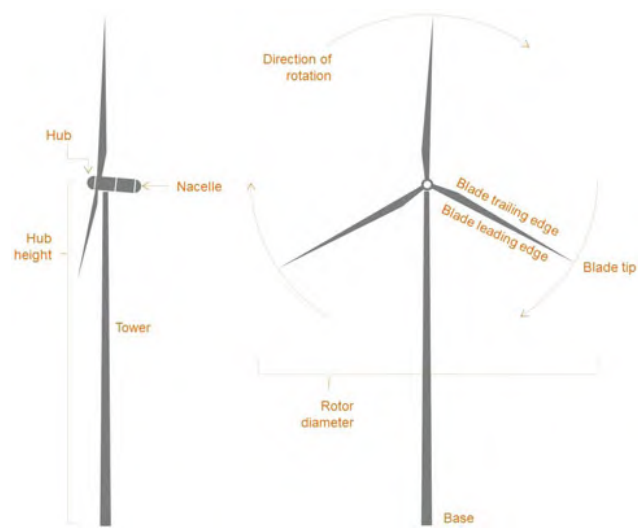

FIGURE 1 . Schematic of a modern day wind turbine.

FIGURE 2. Sample A-weighted sound pressure levels.

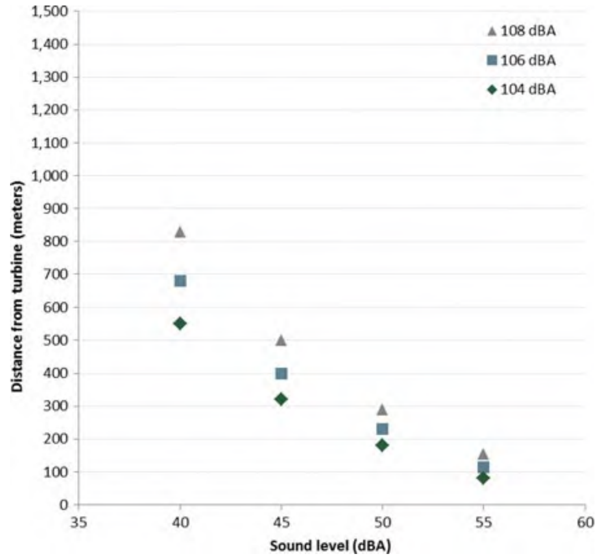

FIGURE 3. Sound levels at varying setbacks and turbine sound power levels—RSG Modeling, Using ISO 9613-2.

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

Wind Turbine Sound Power and Pressure Levels

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

Wind turbine sound is typically broadband in character with most of the sound energy at lower frequencies (less than 1000 Hz). Although wind turbines produce sound at frequencies less than the 25 Hz 1/3 octave band, sound power data are rarely published below that frequency. Most larger, utility-scale wind turbines have sound power levels between 104 and 107 dBA. Measured sound levels because of wind turbines depend on several factors, including weather conditions, the number of turbines, turbine layout, local topography, the particular turbine used, distance between the turbines and the receiver, and local fiora. Meteorological conditions alone can cause 7 to 14 dB variations in sound levels.[10] Examples of the SPLs because of a single wind turbine with three different sound powers, and at various distances, are shown in Fig. 3 as calculated with ISO 9613-2.[11] Measurement results of A-weighted, C-weighted, and G-weighted sound levels have confirmed that wind turbine sound attenuates logarithmically with respect to distance.[12]

With respect to noise standards, Hessler and Hessler[13] found an arithmetic average of 45 dBA daytime and 40 dBA nighttime for governments outside the United States, and a nighttime average of 47.7 dBA for US state noise regulation and siting standards. The metrics for those levels can vary. Common metrics are the day-evening-night level (Lden), day-night level (Ldn), equivalent average level (Leq), level exceeded 90% of the time (L90), and median (L50). The application of how these are measured and the time period over which they are measured varies, meaning that, from a practical standpoint, sound-level limits are even more varied than the explicit numerical level. The Leq is one of the more commonly used metric. It is the logarithmic average of the squared relative pressure over a period of time. This results in a higher weighting of louder sounds.

Owing to large number of variables that contribute to SPLs because of wind turbines at receivers, measured levels can vary dramatically. At a wind farm in Texas, O'Neal et al[14] measured sound levels with the nearest turbine at 305 m (1000 feet) and with four turbines within 610 m (2000 feet) at 50 to 51 dBA and 63 dBC (10-minute Leq), with the turbines producing sufficient power to emit the maximum sound power. During the same test, sound levels were 27 dBA and 47 dBC (10-minute Leq) inside a home that was located 290 m (950 feet) from the nearest turbine and within 610 m (2000 feet) of four turbines[15] (see Fig. 4).

Bullmore et al[16] measured wind turbine sound at distances from 100 to 754 m (330 to 2470 feet), where they found sound levels ranging from 40 to 55 dBA over various wind conditions. At typical receiver distances (greater than 300 m or 1000 feet), sound was attenuated to below the threshold of hearing at frequencies above the 1.25 kHz 1/3 octave band. In studies mentioned here, measurements were made with the microphone between 1 and 1.6 m (3 and 5 feet) above ground.

Wind Turbine Emission Characteristics

Low-Frequency Sound and Infrasound

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

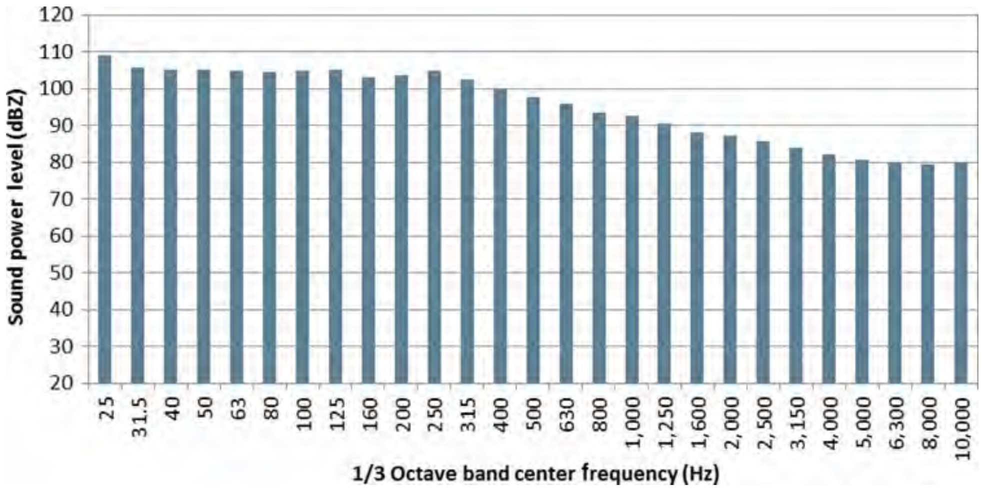

FIGURE 4. Sound power of the Siemens SWT 2.3-93 (TX) wind turbine.[15]

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

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

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

Amplitude Modulation

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

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

Tonality

Tones are specific frequencies or narrow bands of frequencies that are significantly louder than adjacent frequencies. Tonal sound is not typically generated by wind turbines but can be found in some cases.[20,26] In most cases, the tonal sound occurs at lower frequencies (less than 200 Hz) and is due to mechanical noise originating from the nacelle, but has also been found to be due to structural vibrations originating from the tower, and anomalous aerodynamic characteristics of the blades[27] (see Fig. 5).

Sound Levels at Residences where Symptoms Have Been Reported

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

Overall Noise Levels

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

Low Frequency and Infrasonic Levels

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

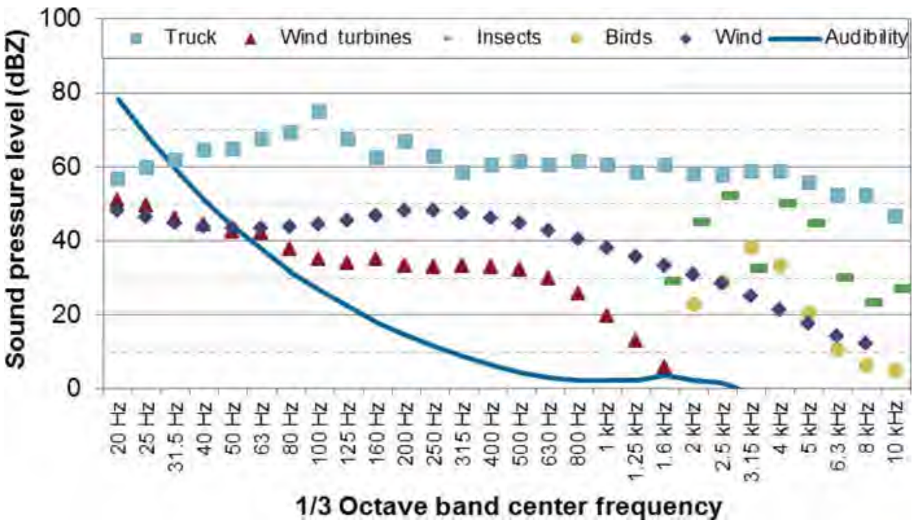

FIGURE 5. Comparison of frequency spectrum of a truck passby at 50 feet, wind turbines at 3500 feet, insects, birds, wind, and the threshold of audibility according to ISO 387-7.

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

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

Amplitude Modulation

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

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

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

Sound Measurement Methodology

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

Low-Frequency Sound and Infrasound Measurement

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

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

A common method of dealing with infrasound is using an additional wind screen to further insulate the microphone from air fiow.[18,35] In some cases, this is simply a larger windscreen that further insulates the microphone from air fiow.[35] One author used a windscreen with a subterranean pit to shelter the microphone, and another used wind resistant cloth.[35] A compromise to an underground microphone mounting is mounting the microphone close (20-cm height) to the ground, minimizing wind infiuence, or using a standard ground mounted microphone with mounting plate, as found in IEC 61400-11.[35] Low-frequency sound and infrasound differences between measurements made with dedicated specialized windscreens and/or measurement setup and standard wind screens/measurements setups can be quite large.[12,37] Nevertheless, increased measurement accuracy can come at the cost of reduced accuracy at higher frequencies using some methods.[38]

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

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

Conclusions

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

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

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

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

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

Epidemiological Studies of Wind Turbines

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

Methods

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

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

Results

Of the approximately 80 articles initially identified in the search, only 20 met the screening criteria (14 observational and six controlled human exposure studies), and these were reviewed in detail to determine the relative quality and validity of reported findings. Other documents included several reviews and commentaries[4,5,7,43–51]; case reports, case studies, and surveys[23,52–54]; and documents published in media other than peer-reviewed journals. One study published as part of a conference proceedings did not meet the peer-reviewed journal eligibility criterion but was included because it seemed to be the first epidemiological study on this topic and an impetus for subsequent studies.[55]

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

Figure 6 depicts the 14 observational epidemiological studies published in peer-reviewed health or medical journals, all of which were determined to be cross-sectional studies or surveys. As can be seen from the figure, the 14 publications were based on analyses of data from only eight different study populations, that is, six publications were based on analyses of a previously published study (eg, Pedersen et al[56] and Bakker et al[57] were based on the data from Pedersen et al[58]) or on combined data from previously published studies (eg, Pedersen and Larsman[59] and Pedersen and Waye[60] were based on the combined data from Pedersen and Waye[61,62]; and Pedersen[63] and Janssen et al[64] were based on the combined data from Pedersen et al,[58] Pedersen and Waye,[61] and Pedersen and Waye[62]). Therefore, in the short summaries of individual studies below, publications based on the same study population(s) are grouped.

Summary of Observational Epidemiological Studies

Possibly the first epidemiological study evaluating wind turbine sound and noise annoyance was published in the proceedings of the 1993 European Community Wind Energy Conference.[55] Investigators surveyed 574 individuals (159 from the Netherlands, 216 from Germany, and 199 from Denmark). Up to 70% of the people resided near wind turbines for at least 5 years. No response rates were reported, so the potential for selection or participation bias cannot be evaluated. Wind turbine sound levels were calculated in 5 dBA intervals for each respondent, on the basis of site measurements and residential distance from turbines. The authors claimed that noise-related annoyance was weakly correlated with objective sound levels but more strongly correlated with indicators of respondents' attitudes and personality.[55]

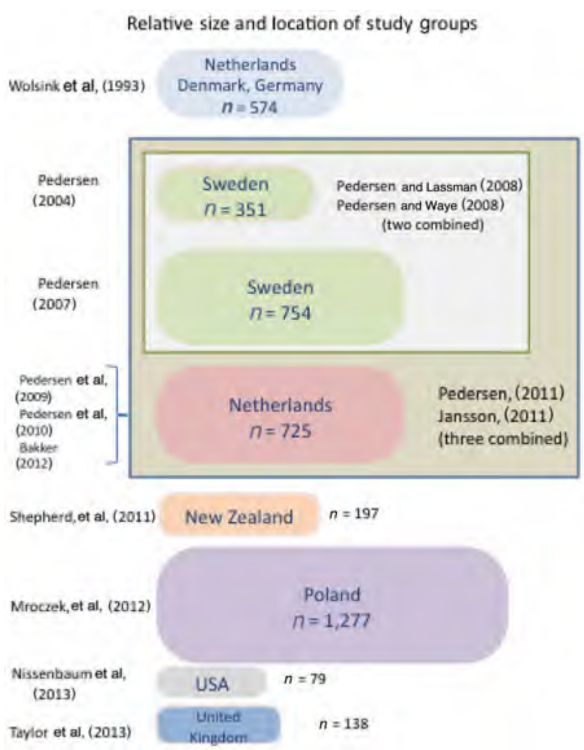

FIGURE 6. The 14 observational epidemiological studies published in peer-reviewed health or medical journals, all of which were determined to be cross-sectional studies or surveys.

In a cross-sectional study of 351 participants residing in proximity to wind turbines (power range 150 to 650 kW), Pederson (a coauthor of the Wolsink[55] study) and Persson and Waye[61] described a statistically significant association between modeled wind turbine audible noise estimates and self-reported annoyance. In this section, "statistically significant" means that the likelihood that the results were because of chance is less than 5%. No respondents among the 12 exposed to wind turbine noise less than 30 dBA reported annoyance with the sound; however, the percentage reporting annoyance increased with noise exceeding 30 dBA. No differences in health or well-being outcomes (eg, tinnitus, cardiovascular disease, headaches, and irritability) were observed. With noise exposures greater than 35 dBA, 16% of respondents reported sleep disturbance, whereas no sleep disturbance was reported among those exposed to less than 35 dBA. Although the authors observed that the risk of annoyance from wind turbine noise exposure increased statistically significantly with each increase of 2.5 dBA, they also reported a statistically significant risk of reporting noise annoyance among those self-reporting a negative attitude toward the visual effect of the wind turbines on the landscape scenery (measured on a five-point scale ranging from "very positive" to "very negative" opinion). These results suggest that attitude toward visual effect is an important contributor to annoyance associated with wind turbine noise. In addition to its reliance on self-reported outcomes, this study is limited by selection or participation bias, suggested by the difference in response rate between the highest-exposed individuals (78%) versus lowest-exposed individuals (60%).

Pederson[62] examined the association between modeled wind turbine sound pressures and self-reported annoyance, health, and well-being among 754 respondents in seven areas in Sweden with wind turbines and varying landscapes. A total of 1309 surveys were distributed, resulting in a response rate of 57.6%. Annoyance was significantly associated with SPLs from wind turbines as well as having a negative attitude toward wind turbines, living in a rural area, wind turbine visibility, and living in an area with rocky or hilly terrain. Those annoyed by wind turbine noise reported a higher prevalence of lowered sleep quality and negative emotions than those not annoyed by noise. Because of the cross-sectional design, it cannot be determined whether wind turbine noise caused these complaints or if those who experienced disrupted sleep and negative emotions were more likely to notice and report annoyance from noise. Measured SPLs were not associated with any health effects studied. In the same year, Petersen et al reported on what they called a "grounded theory study" in which 15 informants were interviewed in depth regarding the reasons they were annoyed with wind turbines and associated noise. Responses indicated that these individuals perceived the turbines to be an intrusion and associated with feelings of lack of control and infiuence.[65] Although not an epidemiological study, this exercise was intended to elucidate the reasons underlying the reported annoyance with wind turbines.

Further analyses of the combined data from Pedersen and Waye[61,62] (described above) were published in two additional papers.[59,60] The pooled data included 1095 participants exposed to wind turbine noise of at least 30 dBA. As seen in the two original studies, a significant association between noise annoyance and SPL was observed. A total of 84 participants (7.7%) reported being fairly or very annoyed by wind turbine noise. Respondents reporting wind turbines as having a negative effect on the scenery were also statistically significantly more likely to report annoyance to wind turbine noise, regardless of SPLs.[59] Self-reported stress was higher among those who were fairly or very annoyed compared with those not annoyed; however, these associations could not be attributed specifically to wind turbine noise. No differences in self-reported health effects such as hearing impairment, diabetes, or cardiovascular diseases were reported between the 84 (7.7%) respondents who were fairly or very annoyed by wind turbine noise compared with all other respondents.[60] The authors did not report the power of the study.

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

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

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

Another report based on these data (in these analyses, 1820 of the 1830 total participants) modeled the relationship between wind turbine noise exposure and annoyance indoors and outdoors.[64] The authors excluded respondents who benefited economically from wind turbines, then compared their modeled results with other modeled relationships for industrial and transportation noise; they claimed that annoyance from wind turbine noise at or higher than 45 dBA is associated with more annoyance than other noise sources.

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

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

A small survey of residents of two communities in Maine with multiple industrial wind turbines compared sleep and general health outcomes among 38 participants residing 375 to 1400 m from the nearest turbine with another group of 41 individuals residing 3.3 to 6.6 km from the nearest wind turbine.[68] Participants completed questionnaires and in-person interviews on a range of health and attitudinal topics. Prevalence of self-reported health and other complaints was compared by distance from the wind turbines, statistically controlling for age, sex, site, and household cluster in some analyses. Participants living within 1.4 km of a wind turbines reported worse sleep, were sleepier during the day, and had worse SF-36 Mental Component Scores compared with those living farther than 3.3 km away. Statistically significant correlations were reported between Pittsburgh Sleep Quality Index, Epworth Sleepiness Scale, SF-36 Mental Component Score, and log-distance to the nearest wind turbine. The authors attributed the observed differences to the wind turbines[68]; methodological problems such as selection and reporting biases were overlooked. This study has a number of methodological limitations, most notably that all of the "near" turbine groups were plaintiffs in a lawsuit against the wind turbine operators and had already been interviewed by the lead investigator prior to the study. None of the "far" group had been interviewed; they were "cold called" by an assistant. This differential treatment of the two groups introduces a bias in the integrity of the methods and corresponding results. Details of the far group, as well as participation rates, were not noted.[68]

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

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

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

Other Possibly Relevant Studies

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

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

Discussion

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

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

Conclusions

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

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

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

Notwithstanding the limitations inherent to cross-sectional studies and surveys—which alone may provide adequate explanation for some of the reported correlations—several possible explanations have been suggested for the wind turbines–associated annoyance reported in many of these studies, including attitudinal and even personality characteristics of the survey participants.[69] Pedersen and colleague,[59] who have been involved in the majority of publications on this topic, noted "The enhanced negative response [toward wind turbines] could be linked to aesthetical response, rather than to multi-modal effects of simultaneous auditory and visual stimulation, and a risk of hindrance to psycho-physiological restoration could not be excluded."[(p.389)] They also found that wind turbines might be more likely to elicit annoyance because some perceive them to be "intrusive" visually and with respect to their noise.[65] Alternative explanations on the basis of evaluation of all health complaints filed between 1993 and 2012 with wind turbine operators across Australia include the influence of anti-wind power activism and the surrounding publicity on the likelihood of health complaints, calling the complaints "communicated diseases."[52]

As noted earlier, the 14 papers meeting the selection criteria for critical review and synthesis were based on only eight independent study groups—three publications were based on the same study group from the Netherlands[58] and four additional publications were based on the combined data from the two Swedish surveys[61,62] or from the combined data from all three. The findings across studies based on analyses of the same data are not independent observations, and therefore the body of available evidence may seem to be larger and more consistent than it should. This observation does not necessarily mean that the relationships observed (or the lack of associations between calculated wind turbines sound pressures and disease or other indicators of health) are invalid, but that consistency across reports based on the same data should not be overinterpreted as independent confirmation of findings. Perhaps more important is that all eight were cross-sectional studies or surveys, and therefore inherently limited in their ability to demonstrate the presence or absence of true health effects.

Recent controlled exposure laboratory evaluations lend support to the notion that reports of annoyance and other complaints may reflect, at least in part, preconceptions about the ability of wind turbine noise to harm health[52,71,72] or even the color of the turbine[73] more than the actual noise emission.

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

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

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

Introduction

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

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

TABLE 1. Human Thresholds for Different Frequencies

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

SPL, sound pressure level.

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

Several studies[44,75,76] have shown that at distances of 300 m or more, wind turbine sounds are below human detection thresholds for frequencies less than 50 Hz. The most audible frequencies (those whose acoustic energies exceed human thresholds the most) are in 500 to 2000 Hz range. At this distance from a single wind turbine, overall levels are typically 35 to 45 dBA.[77,78] These levels can be audible in a typical residence with ambient noise of 30 dBA and windows open (a room with an ambient level of 30 dBA would be considered by most people to be quiet or very quiet). In outdoor environments, sound levels drop about 6 dB for every doubling of the distance from the source, so one would predict levels of 23 to 33 dBA, that is, below typical ambient noise levels in homes, at a distance of 1200 m. For a wind farm of 12 large turbines, Møller and Pedersen[79] predicted a level of 35 dBA at a distance of 453 m.

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

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

Low-Frequency Sound and Infrasound

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

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

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

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

1. Outer hair cells of the cochlea[82];
2. Hair cells of the normal vestibular system,[83] especially the otolith organs[84];
3. Hair cells of the vestibular system after its fluid dynamics have been disrupted by infrasound[82];
4. Visceral graviceptors acting as vibration sensors.[83]

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

How the Inner Ear Works

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

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

Responding to Airborne Sound

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

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

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

Although more numerous than the IHCs, the OHCs receive only very scanty afferent innervation, from "type II" neurons, the function of which is unknown. Salt and Hullar[82] have pointed out that OHCs generate measurable electrical responses called cochlear microphonics to very low frequencies (eg, 5 Hz) at levels that are presumably inaudible to the animals and have hypothesized that the type II afferent fibers from the OHCs might carry this information to the brain. Nevertheless, it seems that no one has ever recorded action potentials from type II cochlear neurons, nor have physiological responses other than cochlear microphonics been recorded in response to inaudible sounds.[86,87] In other words, as Salt and Hullar[82] acknowledge, "The fact that some inner ear components (such as the OHC) may respond to [airborne] infrasound at the frequencies and levels generated by wind turbines does not necessarily mean that they will be perceived or disturb function in any way."(p.19)

Responses of the Vestibular Organs

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

Many people complaining about wind turbines have reported dizziness, which can be a symptom of vestibular disorders; this has led to suggestions that wind turbine sound, especially inaudible infrasound, can stimulate the vestibular organs.[83,84] Pierpont[83] introduced a term "Wind Turbine Syndrome" based on a case series of 10 families who reported symptoms that they attributed to living near wind turbines. The author invited people to participate if they thought they had symptoms from living in the vicinity of wind turbines; this approach introduces substantial selection bias that can distort the results and their corresponding significance. Telephone interviews were conducted; no medical examination, diagnostic studies or review, and documentation of medical records were conducted as part of the case series. Noise measurements were not provided. Nonetheless, the author described a collection of nonspecific symptoms that were described as "Wind Turbine Syndrome." The case series, at the time of preparation of this review, has not been published in the peer-reviewed scientific literature. Although not medically recognized, advocates of this "disorder" suggest that wind turbines produce symptoms, such as headaches, memory loss, fatigue, dizziness, tachycardia, irritability, poor concentration, and anxiety.[88]

To support her hypotheses, Pierpont cited a report by Todd et al[89] that demonstrated human vestibular responses to bone-conducted sound at levels below those that can be heard. But as previously noted, this effect is not surprising because the vestibular system is designed to respond to head movement (including head vibration induced by direct contact with a vibrating source). The relevant issue is how the vestibular system responds to airborne sound, and here the evidence is clear. Vestibular responses to airborne sound require levels well above audible thresholds.[90,91] Indeed, clinical tests of vestibular function using airborne sound use levels in excess of 120 dB, which raise concerns of acoustic trauma.[92]

Salt and Hullar[82] acknowledge that a normal vestibular system is unlikely to respond to inaudible airborne sound—"Although the hair cells in other sensory structures such as the saccule may be tuned to infrasonic frequencies, auditory stimulus coupling to these structures is inefficient so that they are unlikely to be influenced by airborne infrasound."(p.12) They go on to hypothesize that infrasound may cause endolymphatic hydrops, a condition in which one of the inner ear fluid compartments is swollen and may disturb normal hair cell function. But here, too, they acknowledge the lack of evidence—" . . . it has never been tested whether stimuli in the infrasound range cause endolymphatic hydrops."(p.19) In previous research, Salt[93] was able to create temporary hydrops in animals using airborne sound, but only at levels (115 dB at 200 Hz) that are many orders of magnitude higher than levels that could exist at residential distances from wind turbines.

Human Vibrotactile Sensitivity to Airborne Sound

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

Pierpont[83] hypothesized that "visceral graviceptors,"[95,96] which contain somatosensory receptors, could detect airborne infrasound transmitted from the lungs to the diaphragm and then to the abdominal viscera. These receptors would seem to be well suited to detect body tilt or perhaps whole-body vibration, but there is no evidence that airborne sound could stimulate sensory receptors in the abdomen. Airborne sound is almost entirely reflected away from the body; when Takahashi et al[97] used airborne sound to produce chest or abdominal vibration that exceeded ambient body levels, levels had to exceed 100 dB at 20 to 50 Hz.

Further Studies of Note

The influence of preconception on mood and physical symptoms after exposure to LFN was examined by showing 54 university students one of two series of short videos that either promoted or dispelled the notion that sounds from wind turbines had health effects, then exposing subjects to 10 minutes of quiet period followed by infrasound (40 dB at 5 Hz) generated by computer software, and assessing mood and a series of physical symptoms.[71] In a double-blind protocol, participants first exposed to either a "high-expectancy" presentation included first-person accounts of symptoms attributed to wind turbines or a "low-expectancy" presentation showed experts stating scientific positions indicating that infrasound does not cause symptoms. Participants were then exposed to 10 minutes of infrasound and 10 minutes of sham infrasound. Physical symptoms were reported before and during each 10-minute exposure. The study showed that healthy volunteers, when given information designed to invoke either high or low expectations that exposure to infrasound causes symptom complaints, reported symptoms that were consistent with the level of expectation. These data demonstrate that the participants' expectations of the wind turbine sounds determined their patterns of self-reported symptoms, regardless of whether the exposure was to a true or sham wind turbine sound. The concept known as a "nocebo" response, essentially the opposite of a placebo response, will be discussed in more detail later in this report. A nocebo response refers to how a preconceived negative reaction can occur in anticipation of an event.[98]

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

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

Adults exposed to sounds recorded from a 1.5 MV Korean wind turbine were assessed for the degree of noise annoyance.[100] Over a 40-minute period, subjects were exposed to a series of 25 random 30-second bursts of wind turbine noise, separated by at least 10 seconds of quiet between bursts. Following a 3-minute quiet period, this pattern was repeated. Participants reported their annoyance on a scale of 1 to 11. Authors found that the amplitude modulation of wind turbine noise had a statistically significant effect on the subjects' perception of noise annoyance.

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

Epilepsy and Wind Turbines

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

Smedley et al[103] applied a complex simulation model of seizure risk to wind turbines, assuming worst-case conditions—a cloudless day, an observer looking directly toward the sun with wind turbine blades directly between the observer and the sun, but with eyes closed (which scatters the light more broadly on the retina); they concluded that there would be a risk of seizures at distances up to nine times the turbine height, but only when blade frequency exceeds 3 Hz, which would be rare for large wind turbines. Smaller turbines, typically providing power for a single structure, often rotate at higher frequencies and might pose more risk of provoking seizures. At the time of preparation of this report, there has been no published report of a photoepileptic seizure being triggered by looking at a rotating wind turbine.

Sleep and Wind Turbines

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

In contrast to the WHO position, an author in an editorial claimed that routine wind turbine operations that result in noise levels less than 45 dBA can have substantial effects on sleep, with corresponding adverse health effects.[105] Another author, however, challenged the basis of the assertion by pointing out that Hanning had ignored 17 reviews on the topic with alternative perspectives and different results.[106]

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

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

Shepherd et al[66] found a significant difference in perceived sleep quality between their wind farm and comparison groups, with the wind farm group reporting worse sleep quality. In the wind farm group, noise sensitivity was strongly correlated with sleep quality. In both the wind farm and comparison groups, sleep quality showed similar strong positive relationships with physical HRQL and psychological HRQL. Pedersen[63] found that sound-level exposure was associated with sleep interruption in two of three studies reviewed; however, the effect sizes associated with sound exposure were minimal.

Bakker et al[57] found that noise exposure was related to sleep disturbance in quiet areas ($d = 0.40$) but not for individuals in noisy areas ($d = 0.02$). Nevertheless, when extreme sound exposure groups were composed,[57] data showed that individuals living in high sound areas (greater than 45 dBA) had significantly greater sleep disruption than subjects in low sound areas (less than 30 dBA). Annoyance ratings were more strongly associated with sleep disruption.[57] Furthermore, when[57] structural equation models (SEMs) were applied, the direct association between sound level and sleep disruption was lost and annoyance seemed to mediate the effect of wind turbine sound on sleep disturbance. Across the reviewed studies it seems that sleep disruption was associated with sound-level exposure; however, the associations were weak and annoyance ratings were more strongly and consistently associated with self-reported sleep disruption.

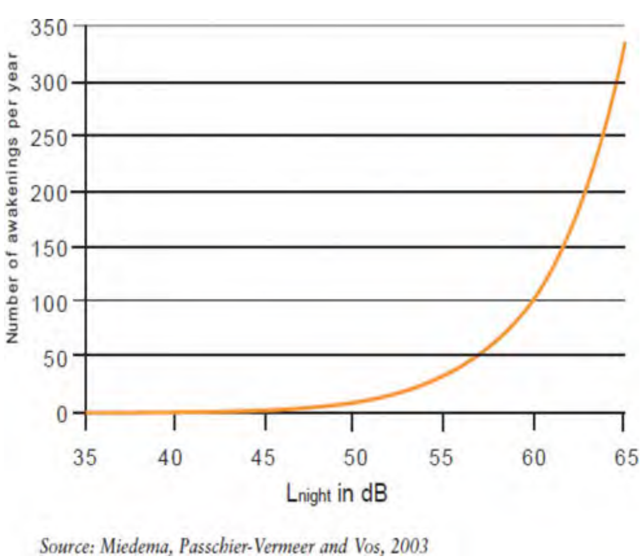

FIGURE 7. Worst-case prediction of noise-induced behavioral awakenings. Adapted from WHO[104] (Chapter 3); Miedema et al.[163]

Conclusions

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

Annoyance, Wind Turbines, and Potential Health Implications

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

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

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

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

This section reviews the literature on the effect of wind turbines, including noise-related annoyance and its corresponding effect on health, QOL, and psychological well-being. "Quality of life" is a multidimensional concept that captures subjective aspects of an individual's experience of functioning, well-being, and satisfaction across the physical, mental, and social domains of life. The WHO defines QOL as "an individual's perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns. It is a broad ranging concept affected in complex ways by the person's physical health, psychological status, personal beliefs, social relationships and their relationship to salient features of their environment".[113(p1404)] Numerous well-validated QOL measures are available, with the SF-12 and SF-36[114] and the WHO Quality of Life—Short Form (WHOQLO-BREF[115]) being among the most commonly used. Quality of life measures have been widely adopted as primary outcomes for clinical trials and cost-effectiveness research.

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

Noise Sensitivity

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

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

Noise-Related Annoyance

Noise sensitivity and noise-related annoyance are moderately correlated ($r = 0.32$[120]) but not isomorphic. The WHO[112] defines noise annoyance as a subjective experience that may include anger, disappointment, dissatisfaction, withdrawal, helplessness, depression, anxiety, distraction, agitation, or exhaustion. A survey of an international group of noise researchers indicated that noise-related annoyance is multifaceted and includes both behavioral and emotional features.[126] This finding is consistent with Job's[122] definition of noise annoyance as a state associated with a range of reactions, including frustration, anger, dysphoria, exhaustion, withdrawal, and helplessness.

Annoyance and Wind Turbine Sounds

As noted elsewhere in this review, Pedersen and colleagues[58,61,62,65] conducted the world's largest epidemiological studies of people living in the vicinity of wind turbines. These studies have been discussed in detail in the epidemiological studies section of this review. Other authors have also addressed annoyance in the context of living near wind turbines.[57,61,125,127,128] Pedersen[63] later compared findings from the three cross-sectional epidemiological studies to identify common outcomes. Across all three studies, SPLs were associated with annoyance outside (*r* between 0.05 and 0.09) and inside of the people's homes (*r* between 0.04 and 0.05). These effect sizes were all less than the small effect boundary of 0.10, meaning that sound levels played a minor role in annoyance. The percentages of people reporting annoyance with wind turbine noise ranged from 7% to 14% for indoor exposure and 18% to 33% for outside exposure.[58,61] These rates are similar to those reported for exposure to other forms of environmental noise.[129]

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

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

Nonacoustical Factors Associated With Annoyance

Although noise levels and noise sensitivity affect the risk of a person reporting annoyance, nonacoustic factors also play a role, including the visual effect of the turbines, whether a person derives economic benefit from the turbines and the type of terrain where one lives.[4] Pedersen and Waye[61] assessed the effect of visual/perceptual factors on wind turbine–related annoyance; all of the variables described above were significantly related to self-reported annoyance after controlling for SPLs. Nevertheless, when these variables were evaluated simultaneously, only attitude to the visual effect of the turbines remained significantly related to annoyance ($r = 0.41$, which can be interpreted as a large effect) beyond sound exposure. Pedersen and Waye[128] also found visual effect to be a significant factor in addition to sound exposure for self-reported annoyance to wind turbine sounds. Pedersen et al[58] explored the effect of visual attitude on wind turbine sound-related annoyance. Logistic regression showed that sound levels, noise sensitivity, attitudes toward wind turbines, and visual effect were all significant independent predictors of annoyance. Nevertheless, visual attitudes showed an effect size of $r = 0.27$ (medium effect), whereas noise sensitivity had an *r* of 0.09. Other authors have also found the visual effect of wind turbines to be related to annoyance ratings.[130] Results from multiple studies support the conclusion that visual effect contributes to wind turbine annoyance,[4] with this review finding visual effect to have an effect size in the medium to large range. Nevertheless, given that noise sensitivity and visual attitude are consistently correlated ($r = 0.19$ and $r = 0.26$, respectively),[58,61] it is possible that visual effect enhances annoyance through multisensory (visual and auditory) activation of the noise-sensitivity trait.

Economic Benefit, Wind Turbines, and Annoyance

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

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

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

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

A study a year earlier of 39 individuals in New Zealand came to different conclusions than the Polish study.[131] Survey results from 39 residents located within 2 km of a wind turbine in the South Makara Valley in New Zealand were compared with 139 geographically and socioeconomically matched individuals who resided at least 8 km from any wind farm. The response rates for both the proximal and more distant study groups were poor, that is, 34% and 32%, respectively, although efforts were made to blind respondents to the study hypotheses. No other indicator of exposure to wind turbines was included beyond the selection of individuals from within 2 km or beyond 8 km of a wind turbine, so actual or calculated wind turbine noise exposures were not available. Subjective HRQOL scales were used to describe and compare the self-reported physical, psychological, and social well-being for each group. Health-related quality of life measures are believed to provide an alternative approach to direct health assessment in that decrements in well-being are assumed to be sensitive to and reflect possible underlying health effects. The authors reported statistically significant differences between the groups in some HRQOL domain scores, with residents living within 2 km of a turbine installation reporting lower mean physical HRQOL domain score (including lower component scores for sleep quality and self-reported energy levels) and lower mean environmental QOL scores (including lower component scores for considering one's environment to be less healthy and being less satisfied with the conditions of their living space). The wind farm group scored significantly lower on physical HRQL ($r = 0.21$), environmental QOL ($r = 0.19$), and overall HRQL ($r = 0.10$) relative to the comparison group. Although the psychological QOL ratings were not significantly different ($P = 0.06$), the wind farm group also scored lower on this measure ($r = 0.16$). In the wind farm group, noise sensitivity was strongly correlated with noise annoyance ($r = 0.44$), psychological HRQL ($r = 0.40$), and social HRQOL ($r = 0.35$). These correlations approach or exceed the large effect size boundary ($r > 0.37$ suggested by Cohen).

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

Across three studies, Pedersen[63] found that outdoor annoyance with turbine sound was associated with tension and stress ($r = 0.05$ to 0.06) and irritability ($r = 0.05$ to 0.08), qualities associated with psychological distress. Bakker et al[57] also found that psychological distress was significantly related to wind turbine sound ($r = 0.16$), reported outside annoyance ($r = 0.18$) and inside annoyance ($r = 0.24$). Taylor et al[69] found that subjects living in areas with a low probability of hearing turbine noise reported significantly higher levels of positive affect than those living in moderate or high noise areas ($r = 0.24$), suggesting greater well-being for the low noise group.

Personality Factors and Wind Turbine Sound

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

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

Nocebo Response

The nocebo response refers to new or worsening symptoms produced by negative expectations.[98,136] When negatively worded pretreatment information ("could lead to a slight increase in pain") was given to a group of chronic back pain patients, they reported significantly more pain ($r = 0.38$) and had worse physical performance ($r = 0.36$).[98] These effect sizes are within the moderate to large ranges and reflect a meaningful adverse effect for the negative information contributing to the nocebo response. The effect of providing negative information regarding wind turbines prior to exposure to infrasound has been experimentally explored. Crichton et al[137] exposed college students to sham and true infrasound under high-expectancy (ie, adverse health effects from wind turbines) and low-expectancy (ie, no adverse health effects) conditions. The high-expectancy group received unfavorable information from TV and Internet accounts of symptoms associated with wind farm noise, whereas the low-expectancy group heard experts stating that wind farms would not cause symptoms. Symptoms were assessed pre- and postexposure to actual and sham infrasound. The high-expectancy group reported significantly more symptoms ($r = 0.37$) and greater symptom intensity ($r = 0.37$) following both sham and true infrasound exposure ($r = 0.65$ and 0.48, respectively). The effect sizes were similar to those found in medical research on the nocebo response. These findings demonstrate that exposing individuals to negative information can increase symptom reporting immediately following exposure. The inclusion of information from TV and the Internet suggests that similar reactions may occur in real-world settings.

A study by Deignan et al[138] analyzed newspaper coverage of wind turbines in Canada and found that media coverage might contribute to nocebo responses. Newspaper coverage contained fright factor words like "dread," "poorly understood by science," "inequitable," and "inescapable exposure"; the use of "dread" and "poorly understood by science" had increased from 2007 to 2011. These results document the use of fright factor words in the popular coverage of wind turbine debates; exposure to information containing these words may contribute to nocebo reactions in some people.

Wind turbines, similar to multiple technologies, such as power lines, cell phone towers, and WiFi signals, among others, have been associated with clusters of unexplained symptoms. Research suggests that people are increasingly worried about the effect of modern life (in particular emerging technologies) on their health (modern health worries [MHW]).[140]) Modern Health Worries are moderately correlated with negative affect ($r = 0.23$) and, like the nocebo response, are considered psychogenic in origin. The expansion of wind turbine energy has been accompanied by substantial positive and negative publicity that may contribute to MHW and nocebo responses among some people exposed to this information. Health concerns have also been raised about the potential of electromagnetic fields associated with wind turbine operations; however, a recent study indicated that magnetic fields in the vicinity of wind turbines were lower than those produced by common household items.[140]

Chapman et al[52] explored the pattern of formal complaints (health and noise) made in relation to 51 wind farms in Australia from 1993 to 2012. The authors suggest that their study is a test of the psychogenic (nocebo or MHW) hypothesis. The findings showed that very few complaints were formally lodged; only 129 individuals in Australia formally or publically complained during the time period studied, and the majority of wind farms had no complaint made against them. The authors found that complaints increased around 2009 when "wind turbine syndrome" was introduced. On the basis of these findings, the authors conclude that nocebo effects likely play an important role in wind farm health complaints. But the authors do report that the vast majority of complaints (16 out of 18) were filed by individuals living near large wind farms ($r = 0.32$). So while few individuals complain, those who do almost exclusively live near large wind farms. Nevertheless, it is important to note that filing a formal or public complaint is a complex sociopolitical action, not a health-related outcome. Furthermore, analysis of data provided in Table 2 of the Chapman[54] study shows that the strongest predictor of a formal complaint was the presence of an opposition group in the area of the wind farm. A review of Table 2 shows that opposition groups were present in 15 of the 18 sites that filled complaints, whereas there was only one opposition group in the 33 areas that did not file a complaint ($r = 0.82$). Therefore, the relevance of this study for understanding health effects of wind turbines is limited. Chapman has also addressed the multitude of reasons why some Australian home owners may have left their homes and attributed the decision to wind turbines.[54] Gross[140] provides a community justice model designed to counter the potential for nocebo or psychogenic response to wind farm development. This method was pilot tested in one community and showed the potential to increase the sense of fairness for diverse community members. No empirical data were gathered during the pilot study so the effect of method cannot be formally evaluated.

Conclusions

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

Economic benefit mitigates the effect of wind turbine sound; however, research is needed to clarify the potential confounding role of (self) selection in this finding. The most powerful multivariate model reviewed accounted for approximately 50% ($r = 0.69$) of the variance in reported annoyance, leaving 50% unexplained. Clearly other relevant factors likely remain unidentified. Nevertheless, it is not unusual for there to be a significant percentage of unexplained variance in biomedical or social science research. For example, a meta-analysis of postoperative pain (a subjective experience), covering 48 studies and 23,037 subjects, found that only 54% ($r = 0.73$) of the variance in pain ratings could be explained by the variables included in the studies.[144] Wind turbine development is subject to the same global psychogenic health worries and nocebo reactions as other modern technologies. Therefore, communities, government agency, and companies would be well advised to adopt an open, transparent, and engaging process when debating the potential effect of wind turbine sites. The vast majority of findings reviewed in this section were correlational and, therefore, do not imply causality, and that other as of yet unidentified (unmeasured) factors may be associated with or responsible for these findings.

DISCUSSION

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

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

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

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

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

There are no available cohort or longitudinal studies that can more definitively address the question about causal links between wind turbine operations and adverse health effects. Nevertheless, results from cross-sectional and experimental studies, as well as studies of other environmental noise sources, can provide valuable information in assessing risk. On the basis of the published cross-sectional epidemiological studies, "annoyance" is the main outcome measure that has been raised in the context of living in the vicinity of wind turbines. Whether annoyance is an adverse health effect, however, is disputable. "Annoyance" is not listed in the International Classification of Diseases (10th edition), although it has been suggested by some that annoyance may lead to stress and to other health consequences, such as sleep disturbance. This proposed mechanism, however, has not been demonstrated in studies using methods capable of elucidating such pathways.

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

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

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

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

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

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

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

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

Areas for Further Inquiry

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

Noise From Wind Turbines

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

Efforts directed at evaluating models used to predict noise levels from wind turbines—in contrast to actual measured noise levels—would be valuable and may be helpful in informing and reassuring residents involved in public discussions related to the development of wind energy projects. Efforts at fine tuning noise models for accuracy to real-world situations can be reassuring to public health officials charged with evaluating potential health effects of noise. The development and the use of reliable and portable noise measuring devices to address components of noise near residences and evaluating symptoms and compliance with noise guidelines would be valuable.

Epidemiology

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

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

Sound and Its Components

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

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

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

Efforts to document a potential effect of infrasound on health have been unsuccessful, including searches for responses to sound from cochlear type II afferent neurons or responses to inaudible airborne sound from the vestibular system. But in other cases, the relevant experiments (can inaudible sound cause endolymphatic hydrops?) seem not to have been conducted to date. This seemingly improbable hypothesis, however, could be tested in guinea pigs, which reliably develops endolymphatic hydrops in response to other experimental interventions.

Psychological Factors

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

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

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

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

SUMMARY

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

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LITIGATION TESTIMONY

In the previous four years, Dr. Kenneth A. Mundt has provided the following deposition, hearing and trial testimony presented by topical area:

Asbestos

Lubertha McLeod v. Nokia of America Corporation as successor-in-interest to Western Electric Company, et al. Civil District Court for the Parish of Orleans, State of Louisiana. Division J-15. Case No. 2018-5352. Deposition: October 9, 2019. *(disease: pleural mesothelioma; alleged exposure: occupational exposure to asbestos from telecommunications work)*

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George Crudge and Shara Crudge v. American International Industries, et al. Superior Court of the State of California for the County of Los Angeles. Case No. BC685901. Deposition: May 30, 2019. (*disease: pleural mesothelioma; alleged exposure: contaminated cosmetic talc)*

Candace Carmichael v. Soco West, Inc., sued individually and as successor-in-interest to, parent, alter ego and equitable trustee of Western Chemical & Manufacturing Co. and A.J. Lynch & Co., et al. Superior Court of the State of California for the County of Los Angeles. Case No. BC711670. Deposition: May 24, 2019. (*disease: peritoneal mesothelioma; alleged exposure: asbestos from father's work clothing)*

Larry Boynton, individually and on behalf of the heirs of Barbara Boynton, v. Kennecott Utah Copper LLC, et al. Third Judicial District Court in and for Salt Lake County, State of Utah. Case No. 160902693. Deposition: May 21, 2019. (*disease: pleural mesothelioma; alleged exposure: asbestos from husband's work clothing)*

Jody E. Ratcliff v. Brenntag, Inc. and Whittaker, Clark & Daniels, Inc. United States District Court for the Middle District of North Carolina. Case No. 1-17-CV-00174. Deposition: May 6, 2019. (*disease: peritoneal mesothelioma; alleged exposure: contaminated cosmetic talc)*

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Patricia Schmitz vs. Whittaker, Clark & Daniels, Inc., et al. Superior Court of the State of California for the County of Alameda. Case No. RG18923615. Deposition: April 1, 2019. (*disease: pleural mesothelioma; alleged exposure: contaminated cosmetic talc)*

LITIGATION TESTIMONY

Daniel W. Strajna vs. SoCo West, Inc., et al. Superior Court of the State of California for the County of Alameda. Case No. RG18898464. Deposition: March 15, 2019. (*disease: pleural mesothelioma; alleged exposure: occupational exposure to asbestos from emberizing fireplace materials)*

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Carolyn Weirick and Elvira Graciela Escudero Lora v. Chanel, Inc., et al. Superior Court for the State of California for the County of Los Angeles. Case No. BC 656425. JCCP No. 4674. Deposition: May 14, 2018. *(disease: pleural mesothelioma; alleged exposure: contaminated cosmetic talc)*

Susan Jenkins v. Avon Products, Inc., et al. San Diego County Superior Court, State of California. Case No. J.C.C.P. 4674/37-2016-00025572-CU-AS-CTL. Deposition: October 4, 2017. (*disease: pleural mesothelioma; alleged exposure: contaminated cosmetic talc*)

Betty Ann Breaux Defiore v. Continental Insurance Company, et al. Civil District Court, Parish of Orleans, State of Louisiana. Case No. 2016-10800, Division: "J-5." Deposition: August 3, 2017. (*disease: pleural mesothelioma; alleged exposure: asbestos from husband's work clothing*)

<u>LITIGATION TESTIMONY</u>

Michael Mandel v. American International Industries, Inc., Whitaker Clark & Daniels and Cyprus Amax, et al. Superior Court of the State of California, County of Los Angeles. JCCP Case No. 4674. Case No. BC644175. Deposition: July 6, 2017. (*disease: pleural mesothelioma; alleged exposure: contaminated cosmetic talc)*

Geraldine T. Hedges v. Continental Insurance Company, et al. Civil District Court, Parish of Orleans, State of Louisiana. Case No. 2016-8284, Division: "M", Section 13. Deposition: June 6, 2017. (*disease: pleural mesothelioma; alleged exposure: asbestos from husband's work clothing*)

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Linda E. Colpitts and Michael Colpitts v. Whittaker, Clark & Daniels, Inc., et al. Superior Court of the State of California, County of Los Angeles. Case No. BC600850. Deposition: August 11, 2016. Trial Testimony: October 14, 2016. (*disease: pleural mesothelioma; alleged exposure: contaminated cosmetic talc)*

Philip John Depoian and Julie Pastor Depoian v. Whitaker, Clark & Daniels, Inc., et al. Superior Court of the State of California, for the County of Los Angeles. Case No. BC607192. Deposition: September 8, 2016. Trial Testimony: October 3, 2016. *(disease: pleural mesothelioma; alleged exposure: contaminated cosmetic talc)*

Nolan Lamb v. Sierra Rock Products, Inc., et al. Superior Court of the State of California, County of Contra Costa. Case No. C15-00057. Deposition: September 27, 2016. *(disease: peritoneal mesothelioma; alleged exposure: environmental asbestos exposure)*

Peter J. Lamonica and Exine Lamonica v. Colgate-Palmolive Company, et al. Superior Court of the State of California, County of Los Angeles. Case No. BC604809. Deposition: June 21, 2016. Trial

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Chemicals

In the Matter of the Complaint of Maersk Tankers as, as Owner and Operator of the MIT Carla Maersk for Exoneration from or Limitation of Liability (Regarding CONTI 168. Sehifffahrts-GMBH & Co. Bulker KG MS "CONTI PERIDOT," Bremer Bereederungsgesellschaft MBH & Co. KG). United States District Court for the Southern District of Texas, Galveston Division. C.A. No. 3:15-CV-00106 (Admiralty). Deposition: June 11, 2019. (*disease: various acute and chronic effects; exposure: methyl tert-butyl ether*)

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Wind Turbines

Application of Cassadaga Wind Project for a Certificate under Article 10 of the Public Service Law. State of New York Public Service Commission. Case No. 14-F-0490. Written Rebuttal Testimony: June 9, 2017. (*disease: various health complaints; alleged exposure: wind turbine noise emissions*)

Association for the Protection of Amherst Island v. Director, Ministry of the Environment and Windlectric, Inc. Township of Loyalty, Lennox and Addington County, Ontario, Canada. Environmental Review Tribunal (ERT) Case No. 15-084. Hearing: December 9, 2015. (*disease: various health complaints; alleged exposure: wind turbine noise emissions*)

Radiation

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Philip John Depoian and Julie Pastor Depoian v. Whitaker, Clark & Daniels, Inc., et al. Superior Court of the State of California, for the County of Los Angeles. Case No. BC607192. Deposition: September 8, 2016. Trial Testimony: October 3, 2016. *(disease: pleural mesothelioma; alleged exposure: contaminated cosmetic talc)*

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Last updated: October 17, 2019

1. A comprehensive review and synthesis of the peer-reviewed, published epidemiological literature specifically addressing potential health impacts of noise emissions from industrial wind turbines has been conducted. Studies were identified using PubMed, the US National Library of Medicine's primary research tool that indexes most of the world's health and medical peer-reviewed journals since at least 1966. In addition, a similar search was conducted using Google scholar, an online search engine that searches a wide variety of sources, including academic publishers, universities, and preprint depositories. Searches of the published health and medical literature were performed using the following key words individually and in various combinations: "wind," "wind turbine," "wind farm," "windmill," "health," "low frequency noise," "infrasound," "sub-acoustic," "cardiovascular," "heart," "sleep," "noise," "health," "symptom," "condition," "disease," "cohort," "case-control," "cross-sectional" and "epidemiology." Additionally, references cited in relevant publications were checked to ensure that the universe of literature was substantially identified.

2. Articles were reviewed in detail if they reported relevant epidemiological results based on standard and appropriate research methods, included study groups exposed to wind turbine noise or low frequency noise from other sources, or conducted analyses considering amplitude and frequency of noise exposure, level, duration and/or timing of exposure. Articles were also reviewed in detail if they reported relevant controlled human exposures to sounds or sights related to wind turbines in a laboratory setting (*i.e.*, laboratory studies).

Peer-Reviewed Studies

3. Of all papers identified using the methods described above, a total of 68 peer-reviewed published reports examining groups exposed to utility-scale wind turbines were identified. Sixteen studies were laboratory studies (discussed in detail later). Forty-four were cross-sectional studies or surveys of residents living near wind turbines or wind industry workers (Abbasi et al. 2015, Abbasi et al. 2016, Barry et al. 2018, Blanes-Vidal and Schwartz 2016, Bakker et al. 2012, Botelho et al. 2017, Feder et al. 2015, Garrido et al. 2018, Hongisto et al. 2017, Jalali et al. 2016a, Jalali et al. 2016b, Jalali et al. 2016c, Janssen et al. 2011, Kageyama et al. 2016, Klaeboe and Sundfor 2016, Kuwano et al. 2014, Lane et al. 2016, Magari et al. 2014, Michaud et al. 2016a, Michaud et al. 2016b, Michaud et al. 2016c, Michaud et al. 2016d, Michaud et al. 2018a, Michaud et al. 2018b, Mroczek et al. 2015, Mroczek et al. 2012, Nissenbaum et al. 2012, Pawlaczyk-Luszczynska et al. 2014, Pawlaczyk-Łuszczyńska et al. 2018, Pedersen 2011, Pedersen and Larsman 2008, Pedersen and Persson Waye 2004, Pedersen and Persson Waye 2007, Pedersen and Persson Waye 2008, Pedersen et al. 2009,

Pedersen et al. 2010, Pohl et al. 2018, Shepherd et al. 2014, Shepherd et al. 2011, Song et al. 2016, Taylor et al. 2013, Voicescu et al. 2016, Walker et al. 2015, Wolsink et al. 1993[1]). Additionally, there were six registry-based studies (Poulsen et al. 2018a, Poulsen et al. 2018b, Poulsen et al. 2018c, Poulsen et al. 2018d, Poulsen et al. 2019a, Poulsen et al. 2019b) including one with a case crossover design (Poulsen et al. 2018c), and two prospective cohort studies of residents living near wind turbines (Bräuner et al. 2018, Bräuner et al. 2019). These reports were based on analyses of data from multiple different study populations in multiple countries (Wolsink 1993 in a group containing individuals from the Netherlands, Germany, and Denmark; Klaeboe 2016 in Norway; Pedersen 2004 and Pederson 2007 in Sweden; Pederson 2009 in the Netherlands; Blanes-Vidal 2016, Poulsen et al. 2018, Poulsen et al. 2018a, Poulsen et al. 2018b, Poulsen et al. 2018c, Poulsen et al. 2019, Poulsen et al. 2019a, Bräuner et al. 2018 and Bräuner et al. 2019 in Denmark; Pohl et al. 2018 and Garrido et al. 2018 in Germany and the German exclusive economic zone, Shepherd 2011 and Shepherd 2014 in New Zealand; Kageyama 2016 and Kuwano 2014 in Japan; Song 2016 in China; Mroczek 2012, Pawlaczyk-Luszczynska 2014, Mroczek 2015, Pawlaczyk-Łuszczyńska, et al. 2018 in Poland; Nissenbaum 2012 and Magari 2014 in the United States; Taylor 2013 in the United Kingdom; Abbasi et al. 2015 and 2016 in Iran; Barry et al. 2018, Feder 2015, Jalali et al. 2016a, Jalali et al. 2016b, Jalali et al. 2016c, Lane et al. 2016, Michaud et al. 2016a, Michaud et al. 2016b, Michaud et al. 2016c, Michaud et al. 2016d, Michaud et al. 2018a, Michaud et al. 2018b, Voicescu 2016 and Walker 2015 in Canada; Hongisto et al. 2017 in Finland; Botelho et al. 2017 in Portugal). Other studies were either based on analysis of a previously published study (Pedersen 2010 and Bakker 2012 were based a study by Pederson 2009), or based on combining data from published studies (Pedersen 2008a and Pedersen 2008b were based on the combined data from the studies by Pedersen 2004 and Pederson 2007b; while Pedersen 2011 and Janssen 2011 were based on the combined data from the published studies Pedersen 2004, Pedersen 2007b and Pedersen 2009). Thus, many of these publications are based on the same data sets and do not represent independent observations.

4. Many of the publications from these cross-sectional epidemiologic studies report on the association between exposure to noise from wind turbines and self-reported annoyance (e.g., Bakker et al. 2012, Janssen et al. 2011, Kageyama, et al. 2016, Klaeboe, et al. 2016, Pedersen 2011, Pedersen and

[1] This study did not meet the peer-reviewed journal eligibility criterion, but is included because it appears to be the first epidemiological study on this topic and an impetus for subsequent studies.

Larsman 2008, Pedersen and Persson Waye 2004, 2007, Pedersen et al. 2009, Wolsink, et al. 1993). A few studies (including one longitudinal study) also include associations between exposure to noise from wind turbines and subjective, self-reported quality of life outcomes such as stress or sleep quality (e.g., Jalali et al. 2016c, Magari et al. 2014, Nissenbaum et al. 2012, Pawlaczyk-Luszczynska, et al. 2014, Shepherd et al. 2011, Pohl et al. 2018). Several of the publications from these cross-sectional epidemiologic studies report on associations between exposure to wind turbine noise and self-reported hypertension or self-reported, subjective conditions such as headaches (e.g., Blanes-Vidal 2016, Mroczek et al. 2012, Pedersen 2011, Pedersen, Larsman 2008, Pedersen, Persson Waye 2004, 2007, Pedersen, Persson Waye 2008). Other studies utilized a polysomnography sleep study or actigraphy (Jalali et al. 2016b; Lane et al. 2016). The studies conducted in Denmark (including registry-based and prospective cohort designs) evaluated redemption of sleep medication, antidepressants, antihypertensive drugs, (Poulsen et al. 2019b) and cases of diabetes, myocardial infarction, stroke, and adverse birth outcomes (Poulsen et al. 2018a, 2018b, 2018c, 2019a, Bräuner et al. 2018 and Bräuner et al. 2019). Finally, the Community Noise and Health Study conducted by Health Canada included both objective and self-reported measures of health as well as used actigraphy on a subset of participants to study sleep (e.g., Feder et al. 2015 and Michaud et al. 2016a).

5. Possibly the first epidemiological study evaluating wind turbine sound and self-reported noise annoyance was published in the proceedings of the 1993 European Community Wind Energy Conference (Wolsink, et al. 1993). Investigators surveyed 574 individuals (159 from the Netherlands, 216 from Germany and 199 from Denmark). Seventy percent of the people resided near wind turbines for at least five years. No response rates were reported, so the potential for selection or participation bias cannot be evaluated. Wind turbine sound levels were calculated in 5 dB(A) intervals for each respondent, based on site measurements and residential distance from turbines. The authors claimed that noise related annoyance was weakly correlated with objective sound levels, but more strongly correlated with indicators of respondents' attitudes and personality (Wolsink 1993). Although this study was not published in a peer-reviewed journal, it clearly served as the impetus for several later studies. It is also noteworthy that from the beginning of this line of investigations, the role of survey respondents' attitudes and personality was recognized, and that objective indicators of sound levels were only weakly correlated. Overall, this study raises interesting and useful hypotheses regarding annoyance, some of which were pursued in subsequent studies, but no indication of any adverse health effects.

6. Pedersen and Persson Waye (2004) observed a significant relationship between wind turbine audible noise and self-reported annoyance in a cross-sectional study conducted in 351 Swedish subjects living varying distances from wind turbines (power range 150-650 kW). No respondents exposed to wind turbine noise less than 30 dB(A) reported annoyance with the sound, and the percentage reporting annoyance increased with noise exceeding 30 dB(A). Despite the association between increased sound pressure levels and greater annoyance from wind turbine noise, no differences in health or well-being outcomes (e.g., tinnitus, cardiovascular disease, headaches, irritability) were observed. Of the 128 respondents in the high night-time noise category – sources of which included road traffic, rail traffic, neighbors, and wind turbines – 20 reported being disturbed in their sleep by wind turbine noise, whereas those in the low night-time noise category reported no sleep disturbance. While the authors found that the risk of annoyance from wind turbine noise exposure increased significantly with each increase of 2.5 dB(A), they also found a significant risk of reporting noise annoyance among those with a negative attitude towards the visual impact of the wind turbines. These results suggest that attitude regarding visual impact is a confounder or possibly effect modifier of the association with wind turbine noise and reported annoyance. In addition to the cross-sectional design and reliance on self-reported outcomes, this study is limited by selection bias, which is indicated in the difference in response rate between the highest-exposed individuals (78%) versus lowest-exposed individuals (60%). Reasons for this imbalance were not provided by the authors and could have contributed to the reported difference in reported self-reported annoyance (Pedersen and Persson Waye 2004). Despite the weaknesses of the cross-sectional design with self-reported health indicators (information bias) and differential participation rates (possible selection bias), this study was still unable to demonstrate that wind turbine noise is associated with any of several self-reported health and well-being measures.

7. Pedersen and Persson Waye (2007) examined the association between wind turbine noise and self-reported annoyance, health, and well-being in 754 Swedish residents living in proximity to one of seven wind turbine sites. The authors reported that annoyance was significantly associated with sound pressure levels from wind turbines as well as having a negative attitude toward wind turbines, living in a rural area, and living in an area with rocky or hilly terrain. Those annoyed by wind turbine noise reported a higher prevalence of sleep disturbance than those not annoyed by noise. Due to the cross-sectional design, where both the exposure and health are reported concurrently, it cannot be determined whether wind turbine noise caused sleep disruption, or if those who experienced disrupted sleep were more likely to notice and/or to report annoyance.

Directly measured sound pressure levels were not associated with any health effects or well-being factors studied. In the same year, Pedersen et al., reported on what they called a “grounded theory study” in which 15 informants were interviewed in depth regarding the reasons they were annoyed with wind turbines and associated noise. Responses indicated that these individuals perceived the turbines to be an intrusion and associated with feelings of lack of control and influence (Pedersen, et al. 2007). While not a formal epidemiological study, this exercise was intended to elucidate the reasons underlying the self-reported annoyance with wind turbines. While limited methodologically due to the cross-sectional design and reliance on self-reported annoyance and health indicators, this study highlights the important role of perceptions and attitudes in a self-evaluation context, a theme that is consistently reported across studies (and elucidated in some laboratory-based experiments, described below).

8. Pedersen and Persson Waye combined the data from their 2004 and 2007 cross-sectional studies described above for a total analytic pool of 1,095 participants exposed to wind turbine noise of at least 30 dB(A) (Pedersen, Larsman 2008, Pedersen, Persson Waye 2008). A total of 84 participants (7.7%) reported being fairly or very annoyed by wind turbine noise, and a significant association between self-reported noise annoyance and sound pressure level was observed. Respondents reporting wind turbines as having a negative impact on the scenery were also significantly more likely to report annoyance to wind turbine noise, regardless of sound pressure levels (Pedersen, Larsman 2008). Self-reported stress was found to be higher among those who were fairly or very annoyed compared to those not annoyed, but again, these cannot be attributed to wind turbine noise, as those reporting stress might be more susceptible to any stimuli, especially those perceived negatively. No differences in health effects such as hearing impairment, diabetes, or cardiovascular diseases were reported (Pedersen, Persson Waye 2008). Though this combined study shares the same limitations of its predecessors, results based on the larger sample size continue to point to self-reported annoyance as a factor of perceived negative impact on the scenery, and raise the hypothesis that self-reported stress also contributes to self-reported annoyance with wind turbines.

9. A study by Pedersen et al. (2009) used geographic information systems (GIS) methods to identify 1,948 contactable residential addresses in the Netherlands living within 2.5 km of a site containing at least two wind turbines of 500 kW or greater. Completed surveys were received from 725 for a response rate of 37%. This study found similar results to others with respect to self-reported annoyance and negative attitude: annoyance increased with increasing sound level, but was also

strongly correlated with a negative attitude toward the visual impact of wind turbines on the landscape. In addition, a significantly decreased risk of self-reported annoyance from noise was observed among those who benefited economically from wind turbines, despite equal perception of noise and exposure to generally higher (>40 dB(A)) sound levels (Pedersen, et al. 2009). These study findings suggest that self-reported annoyance may be correlated both with sound levels and with negative (or positive) attitude; however, the poor response rate significantly limits the inferential value of this study.

10. The Pedersen et al. (2009) study data was later analyzed further by Pedersen et al., 2010 and Bakker et al., 2012. Although the above-mentioned 37% response rate was lower than in previous cross-sectional studies, non-response analyses indicated that similar proportions responded across all landscape types and sound pressure categories (Bakker, et al. 2012). Calculated sound levels, other sources of community noise, noise sensitivity, general attitude and visual attitude towards wind turbines were evaluated. The authors reported an exposure-response relationship between calculated A-weighted sound pressure levels (associated with wind turbines) and self-reported annoyance. Wind turbine noise was reported to be more annoying than transportation noise or industrial noise at comparable levels. Self-reported annoyance, however, was also correlated with a negative attitude toward the visual impact of wind turbines on the landscape. The further analyses of noise annoyance reported in (Pedersen, et al. 2010) indicated that road traffic noise had no effect on annoyance to wind turbine noise, and vice versa. Visibility of, and attitude towards, winds turbines and road traffic were significantly related to annoyance from their respective noise source; stress was significantly associated with both types of noise (Pedersen, et al. 2010). A statistically significantly decreased level of annoyance from wind turbine noise was observed among those who benefited economically from wind turbines, despite equal perception of noise and exposure to generally higher (>40 dB(A)) sound levels (Pedersen, et al. 2009). Self-reported annoyance was strongly correlated with self-reporting a negative attitude toward the visual impact of wind turbines on the landscape scenery (measured on a five-point scale ranging from “very positive” to “very negative” opinion). The low response rate and reliance on self-reporting of noise annoyance again limit the inferential value of these findings.

11. In their analysis of the association of exposure to wind turbine noise and annoyance, sleep, and psychological distress, Bakker (2012) proposed a structural equation approach that indicates although “exposure” to wind turbine noise was associated with reports of annoyance, sleep

disturbance, and psychological distress, wind turbine noise did not have a direct effect on sleep disturbance or psychological distress. Consistent with previous studies, the apparent effects of wind turbine noise occurred only in those who reported being annoyed (Bakker, et al. 2012). The results of this study should be interpreted cautiously, as the response rate to the survey was unacceptably low (*i.e.*, 37%), with no elucidation of the differences between participants and non-participants reported.

12. Results of analyses of the combined data from the two Swedish (Pedersen, Persson Waye 2004, 2007) and the Dutch (Pedersen, et al. 2009) cross-sectional studies have been published in two additional papers. Using the combined data from these three predecessor studies, Pedersen et al. identified 1,755 (*i.e.*, 95.9%) of the 1,830 total participants for which complete data were available to explore the relationships between Calculated A-weighted sound pressure levels and a range of indicators of health and well-being. Specifically, they considered, sleep interruption, headache, undue tiredness, feeling tense, stressed or irritable, diabetes, high blood pressure, cardiovascular disease, and tinnitus (Pedersen 2011). As in the precursor studies, self-reported noise annoyance indoors and outdoors appeared to be correlated with A-weighted sound pressure levels. Sleep interruption appeared at higher sound levels and was also related to annoyance. No other health or well-being variables were consistently related to sound pressure levels. No significant effects were seen for chronic disease, high blood pressure, cardiovascular disease, impaired hearing, headache, undue tiredness, tense and stressed, and irritable (Pedersen 2011). Although stress was not directly associated with sound pressure levels, it was associated with self-reported noise related annoyance. Again, notwithstanding the inherent limitations of the cross-sectional design and self-reporting of indicators of annoyance and indicators of health and well-being, this study indicates that sound pressure levels were still not able to predict health complaints.

13. Another report based on these combined sets of data (in these analyses, 1820 of the 1830 total participants) examined the data from two studies in Sweden and one in the Netherlands to model the relationship between wind turbine noise exposure and self-reported annoyance indoors and outdoors (Janssen, et al. 2011). The authors excluded from their analysis those respondents who benefited economically from wind turbines. The authors compared their modelled results with other modelled relationships for industrial and transportation noise claiming that annoyance from wind turbine noise is higher than annoyance from other noise sources (in the overlapping noise range, >45 dB(A)) (Janssen, et al. 2011), which indicates that factors in addition to sound pressure likely

influence the reporting of annoyance. While limited methodologically due to the cross-sectional design, this study continues to highlight the important role of other factors in evaluating self-reported annoyance.

14. Shepherd, et al. (2011) compared 39 residents located within 2 km of a wind turbine in the Makara Valley in New Zealand with 139 controls (matched geographically and socioeconomically) who resided at least 8 km from any wind farm. No indicator of exposure to wind turbine noise was considered beyond the selection of individuals based on the proximity of their residences from the nearest wind turbine. The authors reported correlation between proximity to wind turbines and several self-reported conditions (including sleep quality and self-reported energy levels, considering one's environment to be less healthy and being less satisfied with the conditions of their living space). No differences were reported for social or psychological parameters. The group residing closer to a wind turbine also reported lower amenity, but not related to traffic or neighborhood noise annoyance. However, the response rates of both the proximal and more distant study groups were unacceptably poor, 34% and 32%, respectively (Shepherd 2011) and therefore are highly susceptible to selection bias. No effort to elucidate possible selection bias was reported. Lack of actual wind turbine and other noise source measurements also significantly limits the veracity of the conclusions of this study.

15. Shepherd, et al. (2014) reported on a cross-sectional survey comparing 29 residents located within 2 km of a wind turbine in the Makara Valley in New Zealand with 41 controls (matched) who resided at least 10 km from any wind farm (Greenbelt sample) as well as surveying individuals living close to a major international airport with those located in a demographically matched area. It is unclear from the methods described whether these participants were distinct from those participating in their 2011 study. The authors reported statistically significant differences in the mean self-reported annoyance and quality of life for physical health domain between the Turbine and Greenbelt samples, but no significant differences were observed between psychological, social, environmental and amenity domains. This study, however, has the same known limitations as Shepherd et al (2011) such as small sample size, self-reported measures of health, and lack of measurements of noise. Furthermore, the survey response rate was not reported, so it is not possible to determine whether the likely problem of select participation by a small proportion of the eligible study target population resulted in biased findings.

16. In the cited literature, individuals' self-reported annoyance with wind turbines was strongly correlated with their negative perception of the visual impact of the turbines. This outcome is consistent with the statement by Berglund et al. suggesting that individuals' attitudes towards a source contribute to reported concerns (Berglund, et al. 1996). Further analyses of annoyance from both wind turbine and road traffic noise in the Pedersen et al. (2009) population revealed that road traffic noise had no effect on annoyance to wind turbine noise, and vice versa. Visibility of, and attitude towards, wind turbines and road traffic were significantly related to self-reported annoyance from their respective noise, and self-reported stress was significantly associated with self-reported annoyance from both types of noise (Pedersen, et al. 2010).

17. Nissenbaum (2012) refers to their study as a "stratified cross-sectional study." The study actually is a simple cross-sectional survey of residents of two communities in Maine, selected because each has multiple industrial wind turbines (IWTs) nearby. Participants were solicited in two groups based on the distance their residences were located from the nearest IWT: 38 participants residing 375 to 1400 m from the nearest turbine with another group of 41 individuals residing 3.3 to 6.6 km from the nearest wind turbine. Participants completed questionnaires and in-person interviews on a range of health and attitudinal topics. Prevalence of self-reported health and other complaints was compared by distance from the IWTs, statistically controlling for age, gender, site and household cluster in some analyses. Prevalence of several self-reported symptoms, including worse sleep, sleepier during the day, and some SF36 Mental Component Scores, were statistically significantly higher among residents living nearer IWTs, which the authors attributed to the IWTs.

18. Though Nissenbaum (2012) contains elements that resemble parts of an epidemiological study, it also contains numerous misstatements and misinterpretations, suggesting a poor appreciation of valid epidemiological concepts and methods. This survey is subject to all of the limitations common to cross-sectional studies – primarily that information on symptoms is solicited at one point in time after IWTs are operational – as well as those resulting from basic epidemiological study design and implementation errors. Observed differences between compared groups (*i.e.*, those living nearer to vs. more distant from IWTs) are, at most, statistical correlations. Interpretation of these correlations is not straightforward, as there may be many reasons that those living in proximity to the IWTs perceive and/or report more symptoms. These reasons may include, but are not limited to, underlying inherent differences in the populations being compared; selective participation (or non-participation) based on different individual propensities to self-report health and other complaints

(possibly related to attitude toward IWTs in the neighborhood); and inaccurate reporting of symptoms resulting from the failure to blind participants to the hypothesis. For example, Taylor, et al. (2013), in a cross-sectional study of small wind turbines, found that the relationship between perceived noise and non-specific symptoms only occurred in individuals with negative oriented personality traits. Disentangling the role, if any, of IWT "exposures" from other design, selection and reporting factors as outlined above in any observed statistical correlation is not possible, and renders the approach ineffectual for evaluating causation. The Nissenbaum study has a further serious limitation in that the "near" turbine group were plaintiffs in a law suit against the wind turbine operators and had already been interviewed by the lead investigator prior to the study.[2] None of the "far" group had been interviewed; they were "cold called" by an assistant. This differential treatment of the two groups introduces a bias in the integrity of the methods and corresponding results. Details of the far group, as well as participation rates were not noted. Combined, these methodological problems severely limit the value of the reported findings.

19. Possibly the largest cross-sectional epidemiological study of wind turbine noise on quality of life was conducted in an area of northern Poland with the most wind turbines (Mroczek, et al. 2012). Surveys were completed by a total of 1,277 adults (703 women and 574 men), aged 18-94 years, representing a 10% two-stage random sample of the selected communities. Although the response rate was not reported, participants were sequentially enrolled until a 10% sample was achieved, and the proportion of individuals invited to participate but unable or refusing to participate is estimated at 30% (personal communication with B. Mroczek). Proximity of residence was the exposure variable, with 220 (17.2%) respondents within 700 m; 279 (21.9%) between 700-1,000 m; 221 (17.3%) between 1,000-1,500 m, and 424 (33.2%) residing more than 1,500 m from the nearest wind turbine. Indicators of quality of life and health were measured using the Short Form 36

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[2] *e.g.*, see the news report on the Mars Hill Lawsuit filed in August 2009 (http://bangordailynews.com/2009/08/12/news/mars-hill-windmills-prompt-civil-lawsuit/) and a preliminary report by Nissenbaum et al. at the 10th International Congress on Noise as a Public Health Problem Poster 2011 ("A questionnaire was offered to all residents meeting inclusion criteria living within 1.5 km of an IWT and to a random sample of residents meeting inclusion criteria living 3 to 7 km from an IWT between March and July of 2010." Further, Dr. Nissenbaum provided testimony before the Ohio Power Siting Board in November 2009 in the matter of the Application of Buckeye Wind LLC (Case No. 08-666-EL-BGN) where he stated "I have studied the health effects that the wind turbines in the Mars Hill Wind Farm have had upon 15 persons residing between 1200 and 3400 feet of the turbines."

Questionnaire (SF-36). The SF-36 consists of 36 questions specifically addressing physical functioning, role functioning-physical, bodily pain, general health, vitality, social functioning, role-functioning emotional, mental health. An additional question concerning health change was included, as well as the Visual Analogue Scale (VAS) for health assessment. It is unclear whether age, gender education and occupation were controlled in the statistical analyses. The authors report that within all subscales, those living closest to wind farms reported the best quality of life (QoL), and those living farther than 1,500 m scored the worst, and that this was observed. They concluded that living in close proximity of wind farms does not result in the worsening of, and might improve, the quality of life in this region (Mroczek, et al. 2012). In a separate publication, the authors reported that "[t]he presence of wind farms near residential areas has no negative influence on the QoL of residents" (Mroczek, et al. 2015). Despite the weaknesses of the cross-sectional design with its inherent limitations, this large study with high participation rates was unable to demonstrate that wind turbine noise is associated with a worsening of the quality of life.

20. A small but more detailed study on response to the wind turbine noise also was carried out in Poland (Pawlaczyk-Luszczynska, et al. 2014). The study population consisted of 156 people, age 15-82 years, living in the vicinity of 3 wind farms located in the central and north-western parts of Poland. No exclusion criteria were applied, and each individual agreeing to participate was sent a questionnaire patterned after the one used in the Pedersen 2004 and Pedersen 2007 studies and including questions on living conditions, self-reported annoyance due to noise from wind turbines, and self-assessment of physical health and well-being (such as headaches, dizziness, fatigue, insomnia, and tinnitus). The response rate was 71%. Distance from the nearest wind turbine and modelled A-weighted sound pressure levels (SPLs) were considered as exposure indicators. One third (33.3%) of the respondents found wind turbine noise annoying outdoors, and one fifth (20.5%) found the noise annoying while indoors. Wind turbine noise was reported as being more annoying than other environmental noises, and self-reported annoyance increased with increasing A-weighted SPLs. Factors such as attitude towards wind turbines and "landscape littering" (visual impact) influenced the perceived annoyance from the wind turbine noise. This study, as with most others, is limited by the cross-sectional design and reliance on self-reported health and well-being indicators; however, analyses focused on predictors of self-reported annoyance, and found that wind turbine noise, attitude toward wind turbines, and attitude toward "landscape littering" explain most of the reported annoyance.

21. In a continuation of their pilot study published in 2014, Pawlaczyk-Łuszczyńska, et al. (2018) investigated the perception and annoyance of noise from wind turbines in a cross-sectional study. The study group consisted of 517 people, 18 to 88 years old, who lived near ten wind farms in northern, central, and south eastern Poland. Persons less than 18 years of age or who lived < 200 meters from small wind turbines or greater than 2 km were excluded. A questionnaire patterned after those used in the Pedersen 2004 and Pedersen 2007 studies that included questions regarding housing, annoyance with wind turbine noise, and self-assessment of physical health (including hearing status, chronic illnesses), well-being, and sleep was delivered to participants. Mental health status was assessed in a portion of the study group. The response rate was 78%. Calculated A-weighted sound pressure levels (SPLs) (SPLs ranged from 33.7 to 49.9 dB) and distance to the nearest wind turbine were used as exposure metrics. Noise measurements were collected to verify the calculated values. WTN was assessed outdoors as annoying by 46.4% of subjects while 33.7% reported that indoor WTN was annoying. WTN was significantly more frequently considered annoying than other environmental nuisances. The proportion of subjects annoyed with both outdoor and indoor WTN generally decreased significantly with increased distance from wind turbines whereas annoyance did not differ significantly between calculated noise categories. The authors found that noise level, distance, noise sensitivity, attitude towards wind turbines, terrain, and intensity of road-traffic noise were all associated with high annoyance due to wind turbine noise. There were no significant associations between noise level or distance from a wind turbine and health and well-being outcomes. However, the authors reported that annoyance was positively correlated with health and well-being outcomes including stress symptoms.

22. In a study of residents living in and around a 14 square mile "wind park" in Western New York State, surveys were administered to 62 individuals living in 52 homes (Magari, et al. 2014). The wind park included 84 turbines spanning approximately 19 square miles of farmland. Short-term outdoor and indoor sound level measurements were obtained at each dwelling in which a questionnaire was administered. Authors reported no association between an individual's level of self-reported annoyance and the short duration sound measurements collected at the time of the survey. However, a correlation was noted between the measure of an individual's expressed concern regarding health risks and the reported measures of the prevalence of sleep disturbance and stress among the study population. While this, too, is a cross-sectional study based on self-reported annoyance and health indicators, and therefore limited in its interpretation, one of its strengths is that it is one of the few studies that performed actual sound measurements (indoors and outdoors).

23. A study of 53 "voluntary workers" from a wind farm (171 wind turbines with capacities ranging from 300 to 660 kW) near Gilan, Iran assessed correlations between measured noise exposures in three general job categories (maintenance, security, office) and general health (Abbasi, et al. 2015). The 8 hr. equivalent noise levels ranged from 60 to 83.66 dB(A). The authors reported that annoyance and sleep disturbance in workers were related to different job groups as well as that distance from wind turbines could explain 44.5% of the variance in sleep disturbance and 34.2% of the variance in general health. The authors did not discuss the disconnect between noise exposure at work and effect on sleep.

24. Abbasi et al. (2016) reported additional information from a cross-sectional study of the workers (n=53; total staff at wind farm) of the wind farm located in Gilan province, Iran. Workers were categorized as maintenance, security, and office. The relationships between four subscales of a general health questionnaire (screening tool used for determining mental disorder probability) as well as the overall sum of the subscales and 8 hr. equivalent sound levels were analysed. Equivalent sound levels ranged from 60 to 83 dB(A) for the three groups. The general health score differed significantly between the different job groups. Equivalent sound levels were significantly correlated with the general health scores except for the depression subscale. The authors concluded that higher noise exposures led to higher scores on the general health questionnaire and increased anxiety and insomnia. The authors also stated that their study demonstrated that "with increasing distance (e.g. office staff)" who had the lowest noise equivalent level, the mean general health questionnaire score decreased.

25. A mixed method survey of two communities near wind turbines (Port Burwell and Clear Creek, Ontario) assessed mental health and quality of life issues (Walker, et al. 2015). Interviews were conducted on 26 individuals living within 1 km of a turbine and questionnaires were obtained from 152 individuals who lived within 2 km of a turbine. Notably, seven of the 26 interviews were "purposefully chosen because of their expertise (n=2) or known opposition to local wind turbines (n=5)." The final survey response rate was 33%. Overall, 80% of respondents in Port Burwell were supportive of wind turbines while 63% of respondents in Clear Creek were supportive. The authors explored various psychosocial issues differing between the two communities finding differences in perceived impacts on daily life and community conflict.

26. Klæboe and Sundfør (2016) reported on a survey of residents at 179 dwellings within 2 km of a wind turbine farm in Norway where complaints resulted in the undertaking of the study. Only 90

residents responded and the response rate was reported as 38%. The authors reported high annoyance with increasing wind turbine noise. The authors further noted that "annoyance depends strongly on separate non-acoustic factors" such as attitudes toward wind turbines, visual factors and aesthetic factors (Klaeboe, Sundfor 2016).

27. Three publications report on different aspects of a "prospective cohort" survey of residents pre-turbine operation (but after the turbines were erected) and post-turbine operation during 2014 in a rural setting in Ontario Canada. One publication addressed quality of life and perceptions of general health. 195 potential respondents were identified within 2 kilometers of five 1.8 MW wind turbines. 43 questionnaires were returned in the first phase and 31 in the in the second phase (16% response rate). The authors reported that the mental component score worsened post-operation for those with negative attitudes toward wind turbines (Jalali, et al. 2016a). Another component of the study evaluated sleep effects. This component had a response rate of around 30% (50 questionnaires for pre-operation and 37 questionnaires returned for post-operation). The authors noted increased reports of poor sleep quality, daytime sleepiness, and rates of insomnia (significantly greater means for PSQI, ESS and ISI scores). They also noted that changes of PSQI and ISI values were "strongly associated" with negative attitudes about wind turbines as well as concerns about property values. Interestingly, the authors also reported that average A-weighted noises measured both before and after operation at three receptors were not significantly different (mean of 31.52 dBA in time 1 and 31.23 dBA in time 2) (Jalali, et al. 2016c). A polysomnography sleep study on 16 participants was also conducted. The authors found that polysomnography sleep parameters were not altered after operation of the wind turbines, but some reported sleep qualities were worse after operation of the wind turbines. The authors further noted that average noise levels did not change after operation of the wind turbines. The authors concluded that "the result of this study based on advanced sleep recording methodology together with extensive noise measurements in an ecologically valid setting cautiously suggests that there are no major changes in the sleep of participants who host new industrial WTs in their community" (Jalali, et al. 2016b). Although these sleep findings were challenged (Palmer 2017), additional analyses continue to support these findings (Jalali, et al. 2017).

28. Blanes-Vidal and Schwartz (2016) evaluated exposure to wind turbines at 454 residences using the distance to the closest wind turbine and number of wind turbines. They considered five "idiopathic" symptoms (dizziness, difficulty concentrating, headache, unnatural fatigue and nausea) as well as six "irritation/respiratory" symptoms ("itching, dryness or irritation of eyes", "itching, dryness or

irritation of the nose", "runny nose", "cough", "chest wheezing or whistling" and "difficulty breathing"). The minimum distance to a wind turbine was 167 meters and the maximum was 8,983 meters. Noise annoyance was associated with wind turbine exposure, but wind turbine noise annoyance was not associated with symptoms. The authors also noted that distance to wind turbines was associated with "unnatural fatigue" and "difficulty concentrating" when controlling for socio-demographic characteristics. The number of wind turbines was associated "unnatural fatigue" and "headache" when controlling for socio-demographic characteristics. Adding additional covariates for "personal reactions to noise from sources different from wind turbines and agricultural odor exposure" made the findings insignificant and the parameter estimates were diminished. The authors concluded that "wind turbines health associations can be confounded by personal reactions to other environmental co-exposures."

29. An interview survey conducted in Japan during 2010-2012 of 747 adults in 34 wind turbine areas and 332 adults in 16 control areas reported on the prevalence of self-reported symptoms of sleep and health problems. Outdoor wind turbine noise was estimated from actual measurement at some locations in each wind turbine area. Noise levels were usually 36-40 dB in the wind turbine areas and 35 or less dB in the control areas. Using multiple logistic analysis for noise levels and insomnia or poor health, the authors found insomnia was significantly higher when the noise exposure level exceeded 40 dB. The prevalence of insomniacs in the wind turbine areas was 1.5% compared with 0.6% in the control areas. The authors also noted that self-reported sensitivity to noise and visual annoyance with wind turbines were independently related to insomnia (Kageyama, et al. 2016). An earlier publication on the same survey (Kuwano, et al. 2014) reported on annoyance, sleep disturbance and health status. Annoyance with wind turbine noise was reported and with increasing annoyance at higher decibel levels. Wind turbine noise was reportedly more annoying than road traffic noise which the authors thought was related to (1) visual disturbance of wind turbines, (2) low background noise levels, and (3) temporal characteristics of wind turbine noise (Kuwano, et al. 2014).

30. Song, et al. (2016) conducted a face-to-face survey of 326 residences in China living within 79-1155 meters to a wind farm with 25 2MW wind turbines. 251 questionnaires were returned although some had missing information; 227 questionnaires contained complete information. Noise levels of the houses within 70-339 meters of the wind farm were reported to range from 44.1-56.7 dBA. 175 of the 227 respondents (77%) lived within 700 meters of wind turbines. 51.5% of the respondents

were highly annoyed by wind turbine noise. Noise sensitivity, noise annoyance and noise intensity were related to reported sleep disturbance, but not other reported health effects (Song, et al. 2016).

31. One of the largest and well-designed cross-sectional studies on wind turbines has been conducted by Health Canada and is referred to as the Community Noise and Health Study (Feder, et al. 2015). This study has some notable improvements in methodology over previous studies. These improvements primarily include obtaining some objective measurements (in contrast to self-reporting) pertaining to health, including hair cortisol concentrations, blood pressure measurements, resting heart rate and measured sleep indicators. Also, the Health Canada Study researchers indicated that they relied on "more than 4000 hours of WTN measurements conducted by Health Canada to support the calculation of WTN levels at residences captured in the study scope." The following summarize findings published to date from this study:

- Feder, et al. (2015) report on quality of life measures obtained from 1,238 randomly selected participants living within 0.25 to 11.22 km from wind turbines. The response rate was 78.9%. In their main statistical analyses, the authors reported that wind turbine noise levels were not related to physical, psychological, social or environmental domains as well as rated quality of life and satisfaction with health. That said, the authors do report that some variables related to wind turbines were related to quality of life irrespective of sound levels from the wind turbines. For example, lower scores in the physical and environmental domains "were observed among participants reporting high visual annoyance toward wind turbines." The authors concluded overall that these "results do not support an association between exposure to WTN up to 46 dBA and QOL assessed using the WHOQOL-BREF questionnaire."
- Michaud et al. (2016a) evaluated self-reported sleep quality over the past 30 days using the Pittsburgh Sleep Quality Index as well as objective measures for aspects of sleep in a subset of 654 participants using actigraphy. The authors found that "self-reported and objectively measured sleep outcomes consistently revealed no apparent pattern or statistically significant relationship to WTN levels. However, sleep was significantly influenced by other factors, including, but not limited to, the use of sleep medication, other health conditions (including sleep disorders), caffeine consumption, and annoyance with blinking lights on wind turbines."
- Michaud et al. (2016b) used multiple regression modeling to evaluate perceived stress scale (PSS) scores, hair cortisol concentrations, resting blood pressure, and heart rate finding that wind turbine noise exposure did not have an effect on any of these endpoints.

- Michaud et al. (2016c) evaluated associations between reported visual and auditory perception of wind turbines with wind turbine noise levels finding that increasing perception was related to increasing noise levels. High annoyance also increased with increasing perceptions due to noise, blinking lights, shadow flicker, visual impacts and vibrations. The authors continued to state that, other than annoyance, health-related endpoints were not related to wind turbine noise up to 46 dBA.
- Michaud et al. (2016d) further evaluated factors associated with wind turbine noise annoyance finding that other wind turbine-related annoyances, personal benefit, noise sensitivity, physical safety concerns, property ownership, province, noise levels, and sensitivity to noise were related to annoyance. Although not related to wind turbine noise levels, a number of health indicators (migraines, dizziness, tinnitus, chronic pain, and restless leg syndrome) were related to annoyance.
- Voicescu et al. (2016) investigated the relationship between high annoyance to wind turbine shadow flicker and several variables considered to be related to wind turbine noise exposures. The authors reported that annoyance to other wind turbine-related features (such as visual perception), concern for physical safety, and noise sensitivity were associated with high annoyance to wind turbine shadow flicker.

- Michaud et al. (2018a) performed principle components analysis on data collected during the study to develop a single construct for overall annoyance related to wind turbines, incorporating responses to noise, blinking lights, shadow flicker, visual impacts, and vibrations. Depending on the components included, the construct tested in the PCA explained 58 to 69% of the variability in total annoyance. Significantly increased aggregate annoyance scores were observed with decreased distance to turbines. Of the 1238 participants, 110 reported personally benefiting from wind turbines in the area. While the proportion of variance in total annoyance explained by the PCA did not differ when the personally benefiting persons were excluded, there were differences in the pattern of differences between distance categories in one of the provinces examined indicating that conclusions drawn from the differences in aggregate annoyance scores between distance categories should be made with caution.

- Michaud et al. (2018b) evaluated whether there was an association between aggregate annoyance to wind turbines and health effects and noise complaints. The health effects assessed included those claimed to be due to wind turbine noise (e.g. dizziness, tinnitus, migraines, sleep disturbance, depression) or potentially altered due to a stress response (e.g. both self-reported and objectively measured indicators of stress such as perceived stress and hair cortisol). The statistical analyses performed adjusted for age, sex, distance to the nearest turbine or A-weighted WTN levels, and provinces. Average aggregate annoyance was significantly increased among those with various self-reported health effects as well as among those who had submitted complaints regarding wind turbine noise and those who did not report receiving personal benefits from wind turbines in the area. Diastolic blood pressure, perceived stress, and sleep quality index scores were also significantly, positively associated with increased aggregate annoyance while several quality of life domain scores were significantly, negatively associated with increased aggregate annoyance scores. Hair cortisol concentrations and systolic blood pressure were not related to aggregate annoyance. It is important to note the cross-sectional nature of the study and that this study is useful for generating hypothesis, but not drawing firm conclusions regarding the observed associations. The authors themselves stated that the observed associations between aggregate annoyance and health outcomes "should not be mistakenly interpreted to mean that annoyance causes adverse health effects (or vice versa)" (Michaud et al. 2018b: p. 258). They further stated that their findings were "statistical observations made from data collected at one point in time with no documented historical records for any of the evaluated outcomes or control for other factors that may impact annoyance or health" (Michaud et al. 2018b: p. 258).

32. Barry et al. (2018) evaluated the use of distance to wind turbines as an alternative exposure measurement to sound pressure levels in investigating health and annoyance effects of wind turbine noise (WTN). Previously collected data from the Health Canada Community Noise and Health was used. Using various models, distance to wind turbines was found to be significantly associated with the quality of life score domains and increased annoyance. Specifically, closer proximity to wind turbines was associated with decreased quality of life and increased annoyance or likelihood of annoyance. The cross-sectional design of this study limits the ability to draw conclusions based on the results of the study. The authors themselves noted that the study could not "distinguish between effects caused by and those simply correlated with distance to the turbines" (Barry et al. 2018: p. 3281). The potential for volunteer bias, "survivor bias" (in that those who were most affected by WTN may have already moved out of the area), and the lack of base line environmental quality scores were other potential limitations of the study noted by the authors.

33. Michaud et al. (2018c) published a commentary which discussed Health Canada's Community Noise and Health Study in response to limitations identified by some critics. Michaud et al. (2018c) discussed that the control group (wind turbine noise [WTN] exposure < 25 dBA) had similar demographics to participants in other categories and that none of the demographic differences "were strong enough to exert an influence on the overall results" (Michaud et al. 2018c: p. 100). The authors noted the following strengths of the study: large randomly selected sample, high response rate with no variation by proximity to wind turbines, a broad questionnaire, use of objective measurements of stress, blood pressure, heart rate, and sleep, field validated calculated WTN levels, and an exposure response analysis with greater than 21 dB range of exposure. The authors noted that while the limitations of the individual objective measurements had been raised, consistent relationships between the measurements and the corresponding self-reported measures had been found. The authors stated that with the strengths and limitations of the study in mind, the findings of the study did support "the general conclusion that beyond an increase in the prevalence of long-term high annoyance toward several wind turbine features … there was no evidence to support an association between WTN levels up to 46 dBA and any other self-reported or objectively measured health outcomes" (Michaud et al. 2018c: p. 101).

34. In a separate study in Canada, Lane et al. (2016) utilized actigraphy and sleep diaries in a study comparing sleep quality of individuals residing in a rural Ontario community in the vicinity of industrial wind turbines (IWTs) (exposed group, n=12) to individuals in a rural Ontario community without wind power installations (unexposed group, n=10). Random samples of 50 and 56 residences from the exposed and unexposed groups, respectively, were selected for door-to-door recruitment. Out of 29 persons contacted from the exposed group and 25 from the unexposed group, 15 from the exposed group and 12 from the unexposed group agreed to participate yielding response rates of 52% and 48%, respectively. After excluding several participants, the overall participation rate was 43%. Sound levels were reportedly measured in a bedroom of one participant from each group for five consecutive nights. No statistically significant differences were observed in actigraphy derived sleep variables between the exposed and unexposed groups when adjusted for age differences. The authors' concluded that the study did not demonstrate a statistically significant relationship between IWTs and poor sleep. The small sample size of the study and the lack of information on other sleep-related factors are limitations of the study.

35. Pohl et al. (2018) conducted a longitudinal survey to investigate effects of WTN among 212 participants aged 19 to 88 years old who resided near a wind farm in Lower Saxony, Germany. The researchers noted that 635 total persons were contacted and that both randomly selected persons and persons whom had contacted the researchers were included in the study. A non-response analysis indicated that those who felt more negatively impacted by the wind farm were more likely to participate. Participants, who resided in areas with predicted sound pressure levels of 25 to 30 dB(A) or 30 to 35 dB(A), responded to questionnaires about stress indicators and moderators in 2012 (n=212) and 2014 (n=133). Of all participants, 34.9% were annoyed with the WTN. For those that perceived WTN, it was as annoying as several other local noise sources. Only 9.9% of participants reported psychological or physical symptoms attributed to WTN that occurred at least once a month which decreased to 6.8% in 2014. Symptoms experienced were related to “general performance,” emotion, mood, and sleep with sleep disturbance decreasing and no symptoms of impaired performance in 2014. On average, both WTN and traffic noise were both “somewhat” annoying, with more participants experiencing symptoms attributed to traffic noise than WTN (Pohl et al. 2018). Only “small correlations” between health indicators and WT noise annoyance were found.

36. In a cross-sectional survey, Garrido et al. (2018) assessed relationships between sleep quality and job characteristics, characteristics of sleeping accommodations, wind farm phase, and exposure to environmental factors including noise, vibrations, and air quality among offshore wind industry workers in the German exclusive economic zone. Male workers who were regularly deployed offshore or whom had a total of 28 days offshore in the past year were included in the analysis (n=268). An estimated total of 5000 to 7600 persons were directly or indirectly employed in these offshore wind installation at the time of the survey. Sound levels were not reported in the study. The authors found that 47.9% of workers reported their quality of sleep to be worse when offshore than onshore while 44.1% reported no differences. Workers who were currently offshore (42.9%) or had been offshore < 1 month prior to answering the survey (27.6%) were significantly different than others with these workers reporting poorer sleep quality both in regards to the four weeks prior and generally during offshore commitments. The authors generally concluded that environmental factors including noise, vibrations, air quality, and shared accommodations were associated with sleep disturbances and poorer sleep quality during offshore deployments. It was noted that noise could result from multiple sources in the offshore environment including work being performed by other workers, operation of ventilation, power generation, and the wind turbines themselves. As the

overall offshore wind energy workforce is not well characterized, it is unknown whether the study participants were representative of the overall population and as participants were self-selected, it is possible that they may differ from those who did not participate which may bias the results.

37. Hongisto et al. (2017) evaluated the exposure-response relationship between outdoor sound level and distance to the nearest wind turbine and noise annoyance. The cross-sectional study was conducted among households within 2 km of wind turbines in three different wind power areas believed to collectively represent Finnish wind power areas. The response rate ranged from 48.1% to 65.4% with an overall rate of 57% (n=429 households). Different data collection methods (interview versus mail-in) were used in two of the wind power areas versus the third. The sound level, defined as the A-weighted sound pressure level outdoors during maximum sound emission of the wind power area at each household participant location, was modeled. Additionally, sound level measurements were collected to verify predicted values. Only 17.3% of the total respondents indicated indoor noise annoyance. Indoor noise annoyance and sound level as well as indoor noise annoyance and distance to the nearest wind turbine were statistically significantly correlated. Indoor noise annoyance increased as sound level increased or distance to turbines decreased. However, coefficients of determination indicated that sound level explained only 8% of the variance in indoor noise annoyance and distance from a wind turbine explained only 4%. The authors noted that ten participants in the study benefited economically from wind turbines, but reported that though the benefiters and non-benefiters differed significantly in their responses the effect on the exposure-response relationship was negligible.

38. Botelho et al. (2017) investigated annoyance and noise abatement decisions in relation to measurements of A frequency equivalent continuous sound pressure levels (LA_{eq}) in four Portuguese villages in the immediate vicinity of a wind farm. Questionnaires were administered to all inhabitants in the village at the time of the study who were available to respond and willing to participate. Response rates were not determined. A total of 80 respondents participated with 51 indicating that they had not spent nor considered spending resources to retrofit their homes to address noise and 29 indicated that they had spent or considered spending resources on doing so. The authors found that increasing sound pressure level increased the probability of being annoyed indoors by wind turbine (WT) noise. Individuals who were annoyed indoors by WT noise were more likely to spend resources on retrofitting their homes than those who were not annoyed at the same sound pressure level. Overall, the effect of a unit of sound pressure level increase in the likelihood of

an individual spending resources on retrofitting was 23.2 percentage points with 9.3 percentage points directly resulting from the increase in sound pressure level and the other 13.9 percentage points the indirect effect due to the probability of being annoyed due to increase in the SPL. The analysis results for outdoor annoyance were similar in sign and statistical significance to those for indoor annoyance except that the sound pressure level did not have a statistically significant impact on outdoor annoyance.

39. Poulsen and colleagues conducted a series of prospective registry-based studies in Denmark investigating long-term residential exposure (in one study short-term residential exposure) to night time outdoor and night time low-frequency indoor WTN and various health related outcomes. All residences within a radius of 20 wind turbine heights from the nearest turbine and 25% of residences (randomly selected) within a radius of 20 to 40 wind turbine heights were identified (residences within 100 m of a town center were excluded). The study population generally consisted of adults who were 25 to 84 or 85 years of age and resided in these residences for at least one year (exceptions noted below). Various exclusion criteria were applied to the potential total study population for each of the individual prospective studies. Both night time outdoor A-weighted sound pressure levels and night time low-frequency indoor A-weighted sound pressure levels due from WTN were modelled for each residence. The associations between various duration running mean sound pressure levels for both indoor and outdoor WTN (determined using each subject's residential history) and health outcomes were investigated in the individual studies. The consistently low numbers of outcomes in the highest exposure groups was a limitation of the individual studies.

- Poulsen, et al. (2018a) investigated whether night time WTN exposure (1 and 5 year running means) was associated with an increased risk of diabetes during a study period of 1996 to 2012. After excluding persons whom had emigrated, disappeared, with unknown addresses, who lived in hospitals or institutions, or who had diabetes before the start of follow-up, a final study population of 614,731 people was identified of which 25,148 developed diabetes. There was no association or positive exposure-response relationship between long term exposure to night time WTN and risk of diabetes.

- Poulsen, et al. (2018b) investigated whether night-time WTN exposure during pregnancy (mean night time WTN during pregnancy and by trimester) was associated with higher odds of three adverse birth outcomes: preterm birth, term small for gestational age, and term low birth weight. The study population consisted of women who gave birth between 1983 and 2013, with a complete address history during pregnancy, and resided in the previously identified residences at "any time during pregnancy" while the WT was operation. Various exclusions were applied to the deliveries. Of the final study population of 135,795 births, 13,003 were preterm births. Of the term births, 12,220 were small for gestational age and 1,127 were low birth weight. There were no associations between mean WTN exposure during pregnancy and any of the three adverse birth outcomes.

- Poulsen, et al. (2018c) also examined the short-term effects of WTN (mean night-time WTN over the 1-4 days prior to event) on the occurrence of myocardial infarction (MI) and stroke using a time-stratified, case-crossover design. For this specific study, the study population was persons 18 years or older who lived in a residence that experienced at least one hour of outdoor WTN above 30 dB(A) on two separate days between 1982 and 2013. Cases excluded were outpatients, found dead, had lived less than 18 months at their present address, or for which the closest WT had changed within the previous 18 months. With the exclusions applied, 15,092 MI events were identified out of 13,343 people, and 14,623 stroke events were identified out of 13,026 people. Exposure to outdoor WTN at the highest level ($\geq$ 42 dB(A)) was negatively associated with risk for MI (OR: 0.54, 95% CI: 0.30-0.95) whereas it was positively associated with risk for stroke (but not significantly). The authors believed negative association was likely a chance finding. For indoor low frequency WTN, non-significant increases of MI and stroke were observed at measured 10 to >15 dB(A) and higher for a mean lag of 1-4 days. When evaluating the lag by a specific day, the ORs for the individual exposure groups (10-15 dB(A) and > 15 db(A)) were not significantly elevated or decreased except for stroke with 10-15dB(A) and a two-day lag. The authors concluded that their study did not provide "conclusive evidence of an association between WTN and MI or stroke" though it "suggest[ed] that indoor LF WTN at night may trigger cardiovascular events." They further concluded that MI and stroke "seemed largely unaffected by night time outdoor WTN."

- Poulsen, et al. (2018d) researched whether night time WTN (running 1- and 5-year means) increased the risk for hypertension (measured as the redemption of prescriptions for antihypertensive (AHT) drugs) over the study period of 1996 to 2013. After excluding persons who emigrated, disappeared, with unknown addresses, who lived in hospitals or institutions, who had redeemed AHT prescriptions, been diagnosed with diabetes, or had been admitted to a hospital with a cardiovascular diagnosis prior to follow-up, a study population of 535,675 persons was achieved. Over the study period, 83,729 people redeemed AHT. Overall, there was no associations between long-term exposure to WTN and the redemption of AHT prescriptions. There were some estimates for specific exposure groups/mean durations which were significantly above or below unity, but dose-response relationships were not seen. "[I]ndications of an effect-modification by age" were observed as risk for AHT redemption increased at high indoor LF WTN and outdoor WTN with "borderline" statistical significance for outdoor WTN. The authors concluded "the present study does not support an association between WTN and redemption of antihypertensive medication."

- Poulsen, et al. (2019a) also investigated whether long-term night-time WTN (1-year and 5-year running means) exposure was associated with an increased the risk of MI or stroke from 1982 to 2013. Persons who had emigrated, disappeared, with unknown addresses, who lived in institutions, or were diagnosed with MI or stroke (for each analysis respectively) prior to start of follow-up were excluded. During the study period, 19,145 out of 711,249 people developed MI, and 18,064 out of 712, 401 people developed stroke. Exposure to outdoor WTN was marginally positively associated with MI at 24-36 dB(A), but not significantly above 36 dB(A). For the five-year exposure time, IRRs were only marginally significantly positively associated with MI in the 24-30 dB(A) exposure group. There were no consistent patterns in IRRs for stroke with WTN exposure though some point estimates for outdoor WTN were significantly elevated at lower exposure and nonsignificantly reduced for higher exposure groups. The authors concluded that their results did not provide "convincing evidence of associations between WTN and MI or stroke."

- Poulsen, et al. (2019b) investigated whether night-time WTN was associated with the redemption of sleep medication and antidepressants during the study period of 1996 to 2013. Persons who emigrated, disappeared, with unknown address, who lived in hospitals or institutions, or had redeemed both sleep medication and antidepressants prior to the start of follow up were excluded. Over the study period, 68,696 out of 583,968 persons redeemed sleep medication, and 82,373 out of 584,891 persons redeemed antidepressants. A five-year mean exposure to outdoor night-time (≥42 dB) WTN was non-significantly slightly elevated for sleep medication prescription redemption (adjusted HR=1.14; 95% CI:

0.98-1.33) and significantly but slightly elevated for antidepressant prescription redemption (adjusted HR=1.17; 95% CI: 1.01-1.35). One-year mean exposures to night time outdoor WTN and antidepressant redemption or sleep medication were not significantly elevated at any exposure. Associations were not found with indoor low-frequency wind turbine noise. Age-stratified analysis indicated a positive exposure-response relationship in those who were over the age of 65 between 5-year night-time outdoor WTN and sleep medication and antidepressant redemption. Significant relationships were lacking for people over the age of 65 who were exposed to low frequency night-time WTN and sleep medication and antidepressant prescription redemption. The authors concluded that there were no consistent associations between exposures to low frequency indoor night-time WTN and the investigated outcomes. This study suggests a small increase in sleep and antidepressant medication use in people over age 65, but is not conclusive due to lack of detailed information on other lifestyle factors and uncertainty in noise exposure from traffic as well as wind.

40. Bräuner et al. (2018) examined the association between long-term WTN exposure and the incidence of MI, using the Danish Nurse Cohort in a prospective cohort study. From the total recruited population of 28,731, 23,994 nurses were included in the final analysis after exclusions were made based on previous history of a MI, death or emigration, or missing information. The outdoor WTN (as the annual mean of a weighted 24-hour average) for each home for each nurse from wind turbines located within a 6000 m radius between 1982 and 2013 was calculated. Those with at least one turbine within 6000 m of a residence were considered exposed. During the study period, 686 nurses developed MI. There were no associations between MI incidence and either eleven -, five -, or one-year mean residential WTN prior to diagnosis, and there was no evidence of an exposure-response relationship. However, there were only a “few” cases in the highest exposure groups (>29.9 dB). It was concluded that there was “little evidence to support a causal relationship” between long-term exposure to WTN and MI incidence.

41. Bräuner et al. (2019) examined the association between long-term exposure to WTN and stroke risk in another prospective study of the Danish Nurse Cohort. In this analysis, 23,912 subjects were included after exclusion due to death, missing information, or prior history of stroke. Residential WTN exposure was estimated as described in Bräuner et al. (2018). During the study period, 1097 nurses registered with a hospital discharge for stroke. The authors found no associations between

WTN (examined as the 11-, 5-, and 1—year mean prior to diagnosis/censure) and stroke incidence. A significant effect modification of the association between WTN and stroke was observed only for urbanacity. The authors stated that nonstroke death did not potentially mask the association of interest. The authors concluded that they found “no evidence to support a causal relationship between long-term exposure to WTN and stroke incidence, within the exposure windows considered (11-, 5-, and 1-year)” (Bräuner et al. 2019: p. 7). They stated that the few hazard ratios observed above one were believed to be chance findings or due to residual confounding and not true effects which was supported by the lack of linear dose-response relationships.

Laboratory studies

42. Sixteen studies were laboratory studies of volunteers exposed to recordings of wind turbine noise, synthesized wind turbine noise, or noises with similar characteristics as wind turbine noise (Agegborg et al. 2018, Crichton, et al. 2014a, Crichton, et al. 2014b, Crichton, et al. 2015, Crichton, Petrie 2015, Hafke-Dys et al. 2016, Ioannidou, et al. 2016, Lee, et al. 2011, Maffei, et al. 2013, Persson Waye, Ohrstrom 2002, Ruotolo, et al. 2012, Schaffer, et al. 2016, Schaffer et al. 2018, Szychowska et al. 2018, Tonin et al. 2016, Van Renterghem, et al. 2013). Taken together, these controlled exposure laboratory evaluations strengthen the notion that reports of annoyance and other complaints may reflect, at least in part, preconceptions about the ability of wind turbine noise to harm health, and can be significantly influenced by factors as insignificant as the color of the turbine.

43. Persson Waye (2002) exposed Swedish university students to sound recorded from 100 m from a series of wind turbines for periods of 10 minutes duration at a level of 40 dB-Aeq (the “eq” refers to the average level over the 10-minute exposure), and then exposed the students to an additional 3 minutes of noise while filling out questionnaires assessing annoyance. Ratings of annoyance, relative annoyance, and awareness of noise were different among the different wind turbine recordings played at equivalent noise levels. Various psycho-acoustic parameters (sharpness, loudness, roughness, fluctuation strength, modulation) were assessed, and then grouped into profiles. Authors found significant differences in levels of annoyance from different wind turbine model noise. Characteristics considered most annoying included “swishing,” “lapping” and “whistling,” while “grinding” and “low frequency” were considered the least annoying (Persson Waye, Ohrstrom 2002). Because of the study design used, none of these studies can individually or collectively

provide sufficiently strong evidence to validly inform a conclusion that industrial wind turbines cause serious harm to human health.

44. Crichton (2014b) exposed 54 university students to one of two presentations labelled as “high-” or “low-expectancy.” The “high-expectancy” presentation included first-person accounts of symptoms attributed to wind turbines from TV and internet accounts of symptoms associated with wind farm noise, while the “low-expectancy” presentation showed experts stating scientific positions indicating that infrasound does not cause symptoms. Participants were then exposed to 10 minutes of infrasound and 10 minutes of sham-infrasound. Physical symptoms were reported before and during each 10-minute exposure. The high-expectancy group had more reports of symptoms, and symptom-intensity scores increased during exposure. The low-expectancy participants did not report any significant changes from pre-exposure or during exposure in either number of symptoms or intensity. However, elevated symptom reporting was reported by the high-expectancy group during both the infrasound and sham infrasound exposure. These data demonstrate that the participants’ expectations of the wind turbine sounds determined their patterns of self-reporting symptoms, regardless of whether the exposure was to a true or sham wind turbine sound.

45. Crichton (2014a) also examined whether positive or negative health information about infrasound generated by wind turbines affected participants’ symptoms and health perceptions in response to wind farm sound. A group of 60 university students were shown positive expectancy or negative expectancy short videos intended to promote or dispel the notion that wind turbines sounds impacted health. In this study, the negative expectancy group was shown a set of videos indicating that exposure to wind turbine sound, particularly infrasound, poses a health risk; the positive expectancy group was presented with information that compared wind turbine sound to sub-audible sound created by natural phenomena such as ocean waves and the wind, emphasizing their positive effects on health. Students were then continuously exposed during two 7-minute listening sessions to both infrasound (50.4dB, 9Hz) and audible wind farm sound (43dB) recorded 1 km from a wind farm, and assessed for changes in mood and several physical symptoms. Both positive expectancy and negative expectancy groups were made aware they were listening to the sound of a wind farm, were being exposed to sound containing both audible and sub-audible components and that the sound was at the same level during both sessions. Participants exposed to wind farm sound demonstrated a placebo response (i.e., reported positive health effects) elicited by positive pre-exposure expectations that infrasound produced health benefits reporting. In contrast, participants

in the negative expectancy group reported negative health effects. They concluded reports of symptoms or negative effects could be nullified if expectations could be framed positively. Another publication on the same subjects examined the role of noise sensitivity. They reported that noise sensitivity was related to annoyance only in the negative expectation group (Crichton, et al. 2015). Additionally, Crichton and Petrie (2015) assigned 64 volunteers to watch either positive or negative information about the health effects of infrasound before subjecting them to both audible sound and infrasound from wind turbines reporting that positive information may help moderate the effect of negative expectations (Crichton, Petrie 2015).

46. Lee (2011) exposed adults for 40 minute periods to 25 random 30-second bursts of wind turbine noise, as recorded from a 1.5 MV Korean wind turbine, separated by at least 10 seconds of quiet between bursts. Following a 3 minute quiet period, this pattern was repeated. Participants then reported their annoyance on a scale of 1-11. Authors found that the amplitude modulation of wind turbine noise had a statistically significant effect on the subjects' perception of noise annoyance.

47. Ruotolo (2012) randomly assigned 93 university students in Italy to three experimental exposure conditions: audio, video, and audio plus video. The audio conditions consisted of sounds of a wind farm recorded from 20m, 100m, 250m, and 600m away from the turbines. The video showed a landscape with a wind farm. Participants were asked to describe their reaction to the video and/or audio scenarios. Researchers concluded that "the results about subjective annoyance confirm a reciprocal influence between auditory and visual stimuli by showing a mitigating effect of the visual context on noise annoyance and a disturbing effect of the auditory context on visual annoyance. Furthermore, noise sensitivity correlated with both noise and visual annoyance" (Ruotolo, et al. 2012).

48. Maffei (2013) exposed Italian adults from rural and urban areas to sounds of wind turbines, recorded from different distances (150m, 250m, 500m) from the turbines, while showing them pictures of wind turbines that differed in color, number of wind turbines, and distance from wind turbines. These individuals were asked to describe their reaction to the pictures. Researchers found that pictures had a weak effect on individual reactions to the number of wind turbines; the color of the wind turbines influenced both visual and auditory individual reactions, although in different ways.

49. Van Renterghem (2013) explored how masking noise from wind turbines with other sounds might impact perception of the noise. Highway and local road noise was combined with wind turbine noise to simulate the resulting noise of wind turbines and traffic in an indoor environment. Wind turbine sounds were recorded close to a 1.8-MW wind turbine operating at 22 rpm, and mixed with traffic noise 50m away from a highway or 15m away from a local road. Wind turbine and highway noise were assumed to be at 250m from the building, and the local road was assumed to be 15m away. The 50 participants ranging in age from 19 to 71 years old were told that the research involved "quality of the living environment." Two conditions were simulated: (1) combined exposure to low levels of wind turbine and road traffic noise indoors during a quiet leisure activity with different photographs of windows facing a garden projected onto a screen; and (2) deliberate listening for the presence of wind turbine noise in audio samples in a paired comparison test to determine the limit of wind turbine noise submersed in road traffic noise, while a photograph of multiple wind turbines was projected. The measured outcomes included perceived annoyance, and recognition and detection of noise from a single wind turbine. When unaware of the purpose of the experiment, participants gave very similar annoyance ratings to wind turbine noise and unmixed highway noise at the same sound-equivalent level, and greater annoyance from local road traffic noise.

50. A laboratory study of 60 participants in Switzerland investigated and compared short-term noise annoyance from wind turbine sounds and road traffic sounds in a variety of acoustic scenarios. The authors reported that wind turbine noise was more annoying than road traffic noise. The same annoyance reactions were achieved with wind turbine noise at levels 4-5 dB lower than road traffic noise (Schaffer, et al. 2016).

51. A listening experiment on 19 participants ages 23-28 in Denmark investigated the effects of amplitude modulation of wind turbine noise on annoyance. The authors found that mean depth of amplitude modulation was a significant predictor of annoyance while frequency of amplitude modulation had a limited effect on noise (Ioannidou, et al. 2016).

52. Schäffer et al. (2018) conducted a laboratory experiment in which fifty-two participants listened to "realistic outdoor [wind turbine] broadband sounds" as well as artificial, generic broadband sounds and rated their annoyance (Schäffer et al. 2018: p. 2). None of the participants lived near a wind farm, though 65% had heard wind turbine (WT) noise before. The acoustical stimuli were varied according to spectral shape, depth of periodic amplitude modulation (AM), and occurrence or absence of AM. All stimuli were produced at L_{Aeq} of 40 dBA which the authors stated was a typical

wind turbine (WT) noise exposure for residents in close to wind farms and associated with annoyance with WT also reproduced at 37 and 43 dBA. Annoyance with WT noise was found to increase with increasing $L_{Aeq.}$ Increased depth of periodic AM and random AM increased annoyance. The authors noted that their findings of annoyance related to acoustical characteristics other than sound pressure level would be produced by an equivalent sound pressure level change of more than 8 dB. The participants in the study rated annoyance to WT and other sounds and also completed a questionnaire regarding attitudes towards windfarms. This may have resulted in some bias in the participants' ratings of annoyance though the stimuli were played in random order. Indeed, the authors noted that in a mixed-effects model of annoyance, participants' attitudes towards windfarms made a significant predictive contribution. They also reported that ratings of annoyance with WT noise were lower among those with a more positive attitude towards wind farms.

53. Ageborg, et al. (2018) investigated the effects of WTN on sleep in a controlled laboratory setting. The authors conducted two pilot laboratory studies that examined the effects of WTN on sleep by exposing participants (6 per study) to WTN during three nights and comparing outcomes to a baseline night (a habituation night was also included). Polysomnography measured physiological effects of WTN on sleep. Questionnaires assessed subjective sleep quality and noise-specific effects on sleep. During the three eight-hour night time exposures for Study A, noise levels were varied to correspond to different outdoor sound pressure levels, and different indoor-outdoor filters were used to simulate the bedroom window being "slightly" open or closed. During Study B, noise level, outdoor-indoor filtering, and the frequency of the amplitude modulation were varied between nights, and within nights there were variations in AM strength, rotational frequency, and the presence or absence of beats. The results of Study A showed significant effects of WTN on the frequency of awakenings, especially when the window was slightly open, on perceived sleep disturbance, and on tiredness in the morning. The results of Study B showed that night time exposure to WTN had significant effects on time spent in certain sleep stages, on the time of first awakening, tiredness in the morning, tension in the morning, difficulties falling asleep, perceived sleep disturbance, poor sleep, awakenings (self-reported), and difficulty falling asleep after awakening. Additionally, perceived WTN-related disturbance was greater in night one than in night two, and tension and WTN-induced tiredness were greater in night three than in night two. These findings of the pilot studies indicate that WTN led to objective sleep disruption, and increased self-reported sleep disturbance. However, there was "a high degree of heterogeneity between the two

studies presented, precluding firm conclusions regarding effects of WTN on sleep," likely the result of the small number of participants. The authors noted plans to conduct larger studies.

54. A laboratory study was conducted to evaluate the impact of modulation rate and depth (sound level fluctuation) on noise annoyance using artificially created noises "resembling the main characteristics of temporal wind turbine noise" (Hafke-Dys et la. 2016: p. 221). Twenty-one volunteers aged 19 to 24 years were exposed to broadband noise and narrowband noises at various modulation frequencies and depths as well as noise generated by moving cars to have the same characteristics (also a broadband noise). Analysis included results of 19 of the participants. The broadband noise was selected as it "resemble[ed] the frequency characteristics of general wind turbine noise" whereas the narrowband noises were used to evaluate the impact the frequency band where amplitude modulation occurred on annoyance. The moving car noise was described as more similar to wind turbine noise than the narrowband noises. For the broadband and moving car noises, annoyance generally increased when modulation rate and depth increased. For a modulation rate of 1 Hz (typical for wind turbine noise), the moving car noise was considered more annoying than the broadband noise, supporting the conclusion that the low frequency components of broadband noise were "not a real problem" (Hafke-Dys et al.: p. 229). For all the sound types, annoyance did not significantly increase for a given modulation rate with sound level fluctuations. For narrowband noises, annoyance did not change significantly with the rate of modulation. The authors also concluded that the same modulation rate and sound level fluctuations were not sufficient to have a similar annoyance perception as wind turbine noise, but that the sound needed similar broadband spectral characteristics.

55. Szychowska et al. (2018) evaluated the impact of audio and visual information on the assessment of wind turbine annoyance in a laboratory study involving 44 students (average age: 22.5 years). The authors concluded that the results of an auditory only experiment showed that wind turbine noise was not more annoying than other sources of sound at the same level. Participants who recognized wind turbines as the source of the small wind turbine sounds rated the sounds as significantly more annoying than those who did not recognize the source. However, these participants also had higher annoyance ratings for the transportation sounds. For an audio-visual experiment with matching samples, inclusion of wind turbine visual information increased the annoyance at lower sound levels (below 65 dBA). Sound level was indicated as the most important factor in explaining variance followed by the type of visual sample and then the audio sample. The authors concluded that the

presence of wind turbines in either the audio or visual samples increased the annoyance ratings of the combined audio-visual samples. Self-rated noise sensitivity significantly increased annoyance and participants who had previous exposure to wind turbines or had a wind turbine build nearby had increased annoyance ratings. For the latter two, it was unclear whether only annoyance to wind turbine sounds or all sounds was increased.

56. Tonin et al. (2016) conducted a double-blind study on the reported pathological symptoms of simulated infrasound produced by wind turbines. Infrasound generated by wind turbines at the Shirley Wind Farm in Wisconsin, USA was recorded at three residences where occupants reported health problems attributed to the wind turbine noise. The closest wind turbine was reportedly 390 meters from the nearest residence, and the recurring fundamental frequency was reported to range from 0.7 to 0.9 Hz. Seventy-two volunteers (27 female, 45 male), ranging from 17 to 82 years in age, were exposed either to wind turbine infrasound noise or to non-wind turbine infrasound noise (sham noise), after watching one of two videos: one video to “heighten expectations,” which showed an interview with a couple who were affected by a wind farm, and one to “lower expectations,” which showed an academic explaining why infrasound is not a problem. Participants subsequently watched a documentary that had no connection to wind farms, while an examiner played either the wind turbine infrasound, or the sham noise for the duration of the documentary. Three primary results were reported: 1) in the high expectation groups, infrasound exposure was associated with a reduced number of reported typical symptoms; 2) baseline concern was significantly correlated with both the mean number and the mean intensity of reported typical symptoms; and 3) age was significantly correlated with the number of reported typical symptoms, with the older participants reporting fewer symptoms. Other observations included 1) an increase in overall concern in the high expectation groups; 2) an increase in the difference in concern that participants expressed after listening to the infrasound; and 3) an increase in atypical symptoms in females when compared to males. Based on these results, it was concluded that “simulated infrasound ha[d] no statistically significant effect on the symptoms reported by volunteers, but the prior concern that volunteers had about the effect of infrasound ha[d] a statistically significant influence on the symptoms reported.”

Synthesis

57. The peer-reviewed literature on wind turbine noise and human health mainly consists of cross-sectional surveys (*i.e.*, few cohort or case-control studies) and controlled experiments in which

volunteers are exposed to recorded wind turbine sounds after various forms of positive and negative preconditioning. In the last several years, numerous higher quality studies have been published such as the Health Canada study and the Danish registry-based studies. Critical review and synthesis of this literature – as well as the entirety of the scientific evidence – does not establish that residential exposure to wind turbines causes any disease or any harm to human health, let alone serious harm. The literature consistently reports associations (or statistical correlation) between residential proximity to wind turbines – or in a few studies, sound pressure levels – and self-reported or perceived annoyance. However, as demonstrated in more than a dozen laboratory studies, these findings likely reflect preconceptions or attitudes toward wind turbines, including fears or perceptions of economic loss or aesthetic degradation. Due to the cross-sectional nature of several of the studies, however, definitive causal conclusions are not possible.

58. Diseases such as myocardial infarctions, stroke, hypertension and self-reported conditions such as headaches generally were not associated with annoyance or measured sound pressure levels. One study suggested a small association between proximity to wind turbines and the redemption of prescriptions for sleep and antidepressant medication, although this was seen only in people over age 65. Some associations between sleep disturbance and annoyance from wind turbine noise were observed, but the studies in which these associations were reported were cross-sectional and cannot establish whether the noise caused the sleep disturbance or whether sleep problems led to the perception of and annoyance with the night-time noise. While some individuals may experience annoyance from wind turbine noise, there is no clear relationship between annoyance from wind turbine noise and any adverse health effects.

59. Complaints such as sleep disturbance have been associated with A-weighted wind turbine sound pressures of higher than 40 to 45 dB but not any measure of health (e.g., see the review by Onakpoya (2015), one of several recently published reviews on wind turbines). Self-reported stress was associated with annoyance but not with calculated sound pressures. Studies of health-related quality of life (QOL) including physical and mental health scales and residential proximity to wind turbines report conflicting findings – one study (with only 38 participants living within 2.0 km of the nearest wind turbine) reported lower QOL among those living closer to wind turbines than respondents living farther away, whereas one of the largest studies (with 853 living within 1500 m of the nearest wind turbine) found that those living closer to wind turbines reported higher QOL and health than those living farther away.

60. My published perspective on the epidemiology of wind turbines reached similar conclusions (McCunney, et al. 2014) and was largely based on my review of some of the same literature discussed above although a number of additional studies have been published. My publication offered the following conclusions pertaining to the hypothesis that wind turbine noise harms human health, including the following:

- No clear or consistent association is seen between noise from wind turbines and any reported disease or other indicator of harm to human health.
- In most surveyed populations, some individuals (generally a small proportion) report some degree of annoyance with wind turbines; however, further evaluation has demonstrated:
    - Certain characteristics of wind turbine sound such as its intermittence or rhythmicity may enhance reported perceptibility and annoyance;
    - The context in which wind turbine noise is emitted also influences perceptibility and annoyance, including urban versus rural setting, topography, and landscape features, as well as visibility of the wind turbines;
    - Factors such as attitude toward visual effect of wind turbines on the scenery, attitude toward wind turbines in general, personality characteristics, whether individuals benefit financially from the presence of wind turbines, and duration of time wind turbines have been in operation all have been correlated with self-reported annoyance; and
    - Annoyance does not correlate well or at all with objective sound measurements or calculated sound pressures.

61. My updated critical review and synthesis of the entirety of the relevant peer-reviewed published epidemiological literature – including numerous newer studies with methodological improvements – reinforce these conclusions.