BRIAN MINISH

Chapter 4

Findings

Based on the detailed review of the scientific literature and other available reports and consideration of the strength of scientific evidence, the Panel presents findings relative to three factors associated with the operation of wind turbines: noise and vibration, shadow flicker, and ice throw. The findings that follow address specifics in each of these three areas.

4.1 Noise

4.1.a Production of Noise and Vibration by Wind Turbines

1. Wind turbines can produce unwanted sound (referred to as noise) during operation. The nature of the sound depends on the design of the wind turbine. Propagation of the sound is primarily a function of distance, but it can also be affected by the placement of the turbine, surrounding terrain, and atmospheric conditions.
    a. Upwind and downwind turbines have different sound characteristics, primarily due to the interaction of the blades with the zone of reduced wind speed behind the tower in the case of downwind turbines.
    b. Stall regulated and pitch controlled turbines exhibit differences in their dependence of noise generation on the wind speed
    c. Propagation of sound is affected by refraction of sound due to temperature gradients, reflection from hillsides, and atmospheric absorption. Propagation effects have been shown to lead to different experiences of noise by neighbors.
    d. The audible, amplitude-modulated noise from wind turbines ("whooshing") is perceived to increase in intensity at night (and sometimes becomes more of a "thumping") due to multiple effects: i) a stable atmosphere will have larger wind gradients, ii) a stable atmosphere may refract the sound downwards instead of upwards, iii) the ambient noise near the ground is lower both because of the stable atmosphere and because human generated noise is often lower at night.
2. The sound power level of a typical modern utility scale wind turbine is on the order of 103 dB(A), but can be somewhat higher or lower depending on the details of the design and the rated power of the turbine. The perceived sound decreases rapidly with the distance from the wind turbines. Typically, at distances larger than 400 m, sound

pressure levels for modern wind turbines are less than 40 dB(A), which is below the level associated with annoyance in the epidemiological studies reviewed.

3. Infrasound refers to vibrations with frequencies below 20 Hz. Infrasound at amplitudes over 100–110 dB can be heard and felt. Research has shown that vibrations below these amplitudes are not felt. The highest infrasound levels that have been measured near turbines and reported in the literature near turbines are under 90 dB at 5 Hz and lower at higher frequencies for locations as close as 100 m.
4. Infrasound from wind turbines is not related to nor does it cause a "continuous whooshing."
5. Pressure waves at any frequency (audible or infrasonic) can cause vibration in another structure or substance. In order for vibration to occur, the amplitude (height) of the wave has to be high enough, and only structures or substances that have the ability to receive the wave (resonant frequency) will vibrate.

4.1.b Health Impacts of Noise and Vibration

1. Most epidemiologic literature on human response to wind turbines relates to self-reported "annoyance," and this response appears to be a function of some combination of the sound itself, the sight of the turbine, and attitude towards the wind turbine project.
    a. There is limited epidemiologic evidence suggesting an association between exposure to wind turbines and annoyance.
    b. There is insufficient epidemiologic evidence to determine whether there is an association between noise from wind turbines and annoyance independent from the effects of seeing a wind turbine and vice versa.
2. There is limited evidence from epidemiologic studies suggesting an association between noise from wind turbines and sleep disruption. In other words, it is possible that noise from some wind turbines can cause sleep disruption.
3. A very loud wind turbine could cause disrupted sleep, particularly in vulnerable populations, at a certain distance, while a very quiet wind turbine would not likely disrupt even the lightest of sleepers at that same distance. But there is not enough evidence to

provide particular sound-pressure thresholds at which wind turbines cause sleep disruption. Further study would provide these levels.

4. Whether annoyance from wind turbines leads to sleep issues or stress has not been sufficiently quantified. While not based on evidence of wind turbines, there is evidence that sleep disruption can adversely affect mood, cognitive functioning, and overall sense of health and well-being.
5. There is insufficient evidence that the noise from wind turbines is *directly (i.e., independent from an effect on annoyance or sleep)* causing health problems or disease.
6. Claims that infrasound from wind turbines directly impacts the vestibular system have not been demonstrated scientifically. Available evidence shows that the infrasound levels near wind turbines cannot impact the vestibular system.
    a. The measured levels of infrasound produced by modern upwind wind turbines at distances as close as 68 m are well below that required for non-auditory perception (feeling of vibration in parts of the body, pressure in the chest, etc.).
    b. If infrasound couples into structures, then people inside the structure could feel a vibration. Such structural vibrations have been shown in other applications to lead to feelings of uneasiness and general annoyance. The measurements have shown no evidence of such coupling from modern upwind turbines.
    c. Seismic (ground-carried) measurements recorded near wind turbines and wind turbine farms are unlikely to couple into structures.
    d. A possible coupling mechanism between infrasound and the vestibular system (via the Outer Hair Cells (OHC) in the inner ear) has been proposed but is not yet fully understood or sufficiently explained. Levels of infrasound near wind turbines have been shown to be high enough to be sensed by the OHC. However, evidence does not exist to demonstrate the influence of wind turbine-generated infrasound on vestibular-mediated effects in the brain.
    e. Limited evidence from rodent (rat) laboratory studies identifies short-lived biochemical alterations in cardiac and brain cells in response to short exposures to emissions at 16 Hz and 130 dB. These levels exceed measured infrasound levels from modern turbines by over 35 dB.

7. There is no evidence for a set of health effects, from exposure to wind turbines, that could be characterized as a "Wind Turbine Syndrome."
8. The strongest epidemiological study suggests that there is not an association between noise from wind turbines and measures of psychological distress or mental health problems. There were two smaller, weaker, studies: one did note an association, one did not. Therefore, we conclude the weight of the evidence suggests no association between noise from wind turbines and measures of psychological distress or mental health problems.
9. None of the limited epidemiological evidence reviewed suggests an association between noise from wind turbines and pain and stiffness, diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and headache/migraine.

4.2 Shadow Flicker

4.2.a Production of Shadow Flicker

Shadow flicker results from the passage of the blades of a rotating wind turbine between the sun and the observer.

1. The occurrence of shadow flicker depends on the location of the observer relative to the turbine and the time of day and year.
2. Frequencies of shadow flicker elicited from turbines is proportional to the rotational speed of the rotor times the number of blades and is generally between 0.5 and 1.1 Hz for typical larger turbines.
3. Shadow flicker is only present at distances of less than 1400 m from the turbine.

4.2.b Health Impacts of Shadow Flicker

1. Scientific evidence suggests that shadow flicker does not pose a risk for eliciting seizures as a result of photic stimulation.
2. 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.

4.3 Ice Throw

4.3.a Production of Ice Throw

Ice can fall or be thrown from a wind turbine during or after an event when ice forms or accumulates on the blades.

1. The distance that a piece of ice may travel from the turbine is a function of the wind speed, the operating conditions, and the shape of the ice.
2. In most cases, ice falls within a distance from the turbine equal to the tower height, and in any case, very seldom does the distance exceed twice the total height of the turbine (tower height plus blade length).

4.3.b Health Impacts of Ice Throw

1. There is sufficient evidence that falling ice is physically harmful and measures should be taken to ensure that the public is not likely to encounter such ice.

4.4 Other Considerations

In addition to the specific findings stated above for noise and vibration, shadow flicker and ice throw, the Panel concludes the following:

1. Effective public participation in and direct benefits from wind energy projects (such as receiving electricity from the neighboring wind turbines) have been shown to result in less annoyance in general and better public acceptance overall.

Brian McIntosh

Wind Turbine Health Impact Study:

Report of Independent Expert Panel

January 2012

Prepared for:

Massachusetts Department of Environmental Protection

Massachusetts Department of Public Health

DUE TO THIS REPORTS LENGTH, THIS HANDOUT DOES NOT CONTAIN APPENDIXES, REFERENCES AND BIBLIOGRAPHY.

FOR A COPY OF THE FULL REPORT PLEASE DOWNLOAD THE REPORT FROM THE WEB LINK BELOW.

http://www.mass.gov/eea/docs/dep/energy/wind/turbine-impact-study.pdf

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The Panel Charge

The Expert Panel was given the following charge by the Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH):

1. Identify and characterize attributes of concern (e.g., noise, infrasound, vibration, and light flicker) and identify any scientifically documented or potential connection between health impacts associated with wind energy turbines located on land or coastal tidelands that can impact land-based human receptors.
2. Evaluate and discuss information from peer-reviewed scientific studies, other reports, popular media, and public comments received by the MassDEP and/or in response to the *Environmental Monitor Notice* and/or by the MDPH on the nature and type of health complaints commonly reported by individuals who reside near existing wind farms.
3. Assess the magnitude and frequency of any potential impacts and risks to human health associated with the design and operation of wind energy turbines based on existing data.
4. For the attributes of concern, identify documented best practices that could reduce potential human health impacts. Include examples of such best practices (design, operation, maintenance, and management from published articles). The best practices could be used to inform public policy decisions by state, local, or regional governments concerning the siting of turbines.
5. Issue a report within 3 months of the evaluation, summarizing its findings.

   To meet its charge, the Panel conducted a literature review and met as a group a total of three times. In addition, calls were also held with Panel members to further clarify points of discussion.

Executive Summary

The Massachusetts Department of Environmental Protection (MassDEP) in collaboration with the Massachusetts Department of Public Health (MDPH) convened a panel of independent experts to identify any documented or potential health impacts of risks that may be associated with exposure to wind turbines, and, specifically, to facilitate discussion of wind turbines and public health based on scientific findings.

While the Commonwealth of Massachusetts has goals for increasing the use of wind energy from the current 40 MW to 2000 MW by the year 2020, MassDEP recognizes there are questions and concerns arising from harnessing wind energy. The scope of the Panel's effort was focused on health impacts of wind turbines *per se*. The panel was *not* charged with considering any possible benefits of avoiding adverse effects of other energy sources such as coal, oil, and natural gas as a result of switching to energy from wind turbines.

Currently, "regulation" of wind turbines is done at the local level through local boards of health and zoning boards. Some members of the public have raised concerns that wind turbines may have health impacts related to noise, infrasound, vibrations, or shadow flickering generated by the turbines. The goal of the Panel's evaluation and report is to provide a review of the science that explores these concerns and provides useful information to MassDEP and MDPH and to local agencies that are often asked to respond to such concerns. The Panel consists of seven individuals with backgrounds in public health, epidemiology, toxicology, neurology and sleep medicine, neuroscience, and mechanical engineering. All of the Panel members are considered independent experts from academic institutions.

In conducting their evaluation, the Panel conducted an extensive literature review of the scientific literature as well as other reports, popular media, and the public comments received by the MassDEP.

ES 1. Panel Charge

1. Identify and characterize attributes of concern (e.g., noise, infrasound, vibration, and light flicker) and identify any scientifically documented or potential connection between health impacts associated with wind turbines located on land or coastal tidelands that can impact land-based human receptors.
2. Evaluate and discuss information from peer reviewed scientific studies, other reports, popular media, and public comments received by the MassDEP and/or in response to the *Environmental Monitor Notice* and/or by the MDPH on the nature and type of health complaints commonly reported by individuals who reside near existing wind farms.
3. Assess the magnitude and frequency of any potential impacts and risks to human health associated with the design and operation of wind energy turbines based on existing data.
4. For the attributes of concern, identify documented best practices that could reduce potential human health impacts. Include examples of such best practices (design, operation, maintenance, and management from published articles). The best practices could be used to inform public policy decisions by state, local, or regional governments concerning the siting of turbines.
5. Issue a report within 3 months of the evaluation, summarizing its findings.

ES 2. Process

To meet its charge, the Panel conducted an extensive literature review and met as a group a total of three times. In addition, calls were also held with Panel members to further clarify points of discussion. An independent facilitator supported the Panel's deliberations. Each Panel member provided written text based on the literature reviews and analyses. Draft versions of the report were reviewed by each Panel member and the Panel reached consensus for the final text and its findings.

ES 3. Report Introduction and Description

Many countries have turned to wind power as a clean energy source because it relies on the wind, which is indefinitely renewable; it is generated "locally," thereby providing a measure of energy independence; and it produces no carbon dioxide emissions when operating. There is interest in pursuing wind energy both on-land and offshore. For this report, however, the focus is on land-based installations and all comments are focused on this technology. Land-based wind turbines currently range from 100 kW to 3 MW (3000 kW). In Massachusetts, the largest turbine is currently 1.8 MW.

The development of modern wind turbines has been an evolutionary design process, applying optimization at many levels. An overview of the characteristics of wind turbines, noise, and vibration is presented in Chapter 2 of the report. Acoustic and seismic measurements of noise and vibration from wind turbines provide a context for comparing measurements from epidemiological studies and for claims purported to be due to emissions from wind turbines. Appendices provide detailed descriptions and equations that allow a more in-depth understanding of wind energy, the structure of the turbines, wind turbine aerodynamics, installation, energy production, shadow flicker, ice throws, wind turbine noise, noise propagation, infrasound, and stall vs. pitch controlled turbines.

Extensive literature searches and reviews were conducted to identify studies that specifically evaluate human population responses to turbines, as well as population and individual responses to the three primary characteristics or attributes of wind turbine operation: noise, vibration, and flicker. An emphasis of the Panel's efforts was to examine the biological plausibility or basis for health effects of turbines (noise, vibration, and flicker). Beyond traditional forms of scientific publications, the Panel also took great care to review other non-peer reviewed materials regarding the potential for health effects including information related to "Wind Turbine Syndrome" and provides a rigorous analysis as to whether there is scientific basis for it. Since the most commonly reported complaint by people living near turbines is sleep disruption, the Panel provides a robust review of the relationship between noise, vibration, and annoyance as well as sleep disturbance from noises and the potential impacts of the resulting sleep deprivation.

In assessing the state of the evidence for health effects of wind turbines, the Panel followed accepted scientific principles and relied on several different types of studies. It considered human studies of the most important or primary value. These were either human epidemiological studies specifically relating to exposure to wind turbines or, where specific exposures resulting from wind turbines could be defined, the panel also considered human experimental data. Animal studies are critical to exploring biological plausibility and understanding potential biological mechanisms of different exposures, and for providing information about possible health effects when experimental research in humans is not ethically or practically possible. As such, this literature was also reviewed with respect to wind turbine exposures. The non-peer reviewed material was considered part of the weight of evidence. In all cases, data quality was considered; at times, some studies were rejected because of lack of rigor or the interpretations were inconsistent with the scientific evidence.

ES 4. Findings

The findings in Chapter 4 are repeated here.

Based on the detailed review of the scientific literature and other available reports and consideration of the strength of scientific evidence, the Panel presents findings relative to three factors associated with the operation of wind turbines: noise and vibration, shadow flicker, and ice throw. The findings that follow address specifics in each of these three areas.

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    a. Upwind and downwind turbines have different sound characteristics, primarily due to the interaction of the blades with the zone of reduced wind speed behind the tower in the case of downwind turbines.
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4. Infrasound from wind turbines is not related to nor does it cause a "continuous whooshing."
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4. Whether annoyance from wind turbines leads to sleep issues or stress has not been sufficiently quantified. While not based on evidence of wind turbines, there is evidence that sleep disruption can adversely affect mood, cognitive functioning, and overall sense of health and well-being.
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    a. The measured levels of infrasound produced by modern upwind wind turbines at distances as close as 68 m are well below that required for non-auditory perception (feeling of vibration in parts of the body, pressure in the chest, etc.).
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    c. Seismic (ground-carried) measurements recorded near wind turbines and wind turbine farms are unlikely to couple into structures.
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exist to demonstrate the influence of wind turbine-generated infrasound on vestibular-mediated effects in the brain.

e. Limited evidence from rodent (rat) laboratory studies identifies short-lived biochemical alterations in cardiac and brain cells in response to short exposures to emissions at 16 Hz and 130 dB. These levels exceed measured infrasound levels from modern turbines by over 35 dB.

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ES 4.2 Shadow Flicker

ES 4.2.a Production of Shadow Flicker

Shadow flicker results from the passage of the blades of a rotating wind turbine between the sun and the observer.

1. The occurrence of shadow flicker depends on the location of the observer relative to the turbine and the time of day and year.
2. Frequencies of shadow flicker elicited from turbines is proportional to the rotational speed of the rotor times the number of blades and is generally between 0.5 and 1.1 Hz for typical larger turbines.
3. Shadow flicker is only present at distances of less than 1400 m from the turbine.

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1. Scientific evidence suggests that shadow flicker does not pose a risk for eliciting seizures as a result of photic stimulation.

2. 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.

ES 4.3 Ice Throw

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Ice can fall or be thrown from a wind turbine during or after an event when ice forms or accumulates on the blades.

1. The distance that a piece of ice may travel from the turbine is a function of the wind speed, the operating conditions, and the shape of the ice.
2. In most cases, ice falls within a distance from the turbine equal to the tower height, and in any case, very seldom does the distance exceed twice the total height of the turbine (tower height plus blade length).

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1. There is sufficient evidence that falling ice is physically harmful and measures should be taken to ensure that the public is not likely to encounter such ice.

ES 4.4 Other Considerations

In addition to the specific findings stated above for noise and vibration, shadow flicker and ice throw, the Panel concludes the following:

1. Effective public participation in and direct benefits from wind energy projects (such as receiving electricity from the neighboring wind turbines) have been shown to result in less annoyance in general and better public acceptance overall.

ES 5. Best Practices Regarding Human Health Effects of Wind Turbines

The best practices presented in Chapter 5 are repeated here.

Broadly speaking, the term "best practice" refers to policies, guidelines, or recommendations that have been developed for a specific situation. Implicit in the term is that the practice is based on the best information available at the time of its institution. A best practice may be refined as more information and studies become available. The panel recognizes that in countries which are dependent on wind energy and are protective of public health, best practices have been developed and adopted.

In some cases, the weight of evidence for a specific practice is stronger than it is in other cases. Accordingly, best practice* may be categorized in terms of the evidence available, as follows:

Descriptions of Three Best Practice Categories

Category	Name	Description
1	Research Validated Best Practice	A program, activity, or strategy that has the highest degree of proven effectiveness supported by objective and comprehensive research and evaluation.
2	Field Tested Best Practice	A program, activity, or strategy that has been shown to work effectively and produce successful outcomes and is supported to some degree by subjective and objective data sources.
3	Promising Practice	A program, activity, or strategy that has worked within one organization and shows promise during its early stages for becoming a best practice with long-term sustainable impact. A promising practice must have some objective basis for claiming effectiveness and must have the potential for replication among other organizations.

**These categories are based on those suggested in "Identifying and Promoting Promising Practices." Federal Register, Vol. 68. No 131. 131. July 2003.*
www.acf.hhs.gov/programs/ccf/about_ccf/gbk_pdf/pp_gbk.pdf

ES 5.1 Noise

Evidence regarding wind turbine noise and human health is limited. There is limited evidence of an association between wind turbine noise and both annoyance and sleep disruption, depending on the sound pressure level at the location of concern. However, there are no research-based sound pressure levels that correspond to human responses to noise. A number of countries that have more experience with wind energy and are protective of public health have developed guidelines to minimize the possible adverse effects of noise. These guidelines consider time of day, land use, and ambient wind speed. The table below summarizes the guidelines of Germany (in the categories of industrial, commercial and villages) and Denmark (in the categories of sparsely populated and residential). The sound levels shown in the table are for nighttime and are assumed to be taken immediately outside of the residence or building of concern. In addition, the World Health Organization recommends a maximum nighttime sound pressure level of 40 dB(A) in residential areas. Recommended setbacks corresponding to these values may be calculated by software such as WindPro or similar software. Such calculations are normally to be done as part of feasibility studies. The Panel considers the guidelines shown below to be Promising Practices (Category 3) but to embody some aspects of Field Tested Best Practices (Category 2) as well.

Promising Practices for Nighttime Sound Pressure Levels by Land Use Type

Land Use	**Sound Pressure Level, dB(A) Nighttime Limits**
Industrial	70
Commercial	50
Villages, mixed usage	45
Sparsely populated areas, 8 m/s wind*	44
Sparsely populated areas, 6 m/s wind*	42
Residential areas, 8 m/s wind*	39
Residential areas, 6 m/s wind*	37

**measured at 10 m above ground, outside of residence or location of concern*

The time period over which these noise limits are measured or calculated also makes a difference. For instance, the often-cited World Health Organization recommended nighttime noise cap of 40 dB(A) is averaged over one year (and does not refer specifically to wind turbine noise). Denmark's noise limits in the table above are calculated over a 10-minute period. These limits are in line with the noise levels that the epidemiological studies connect with insignificant reports of annoyance.

The Panel recommends that noise limits such as those presented in the table above be included as part of a statewide policy regarding new wind turbine installations. In addition, suitable ranges and procedures for cases when the noise levels may be greater than those values should also be considered. The considerations should take into account trade-offs between environmental and health impacts of different energy sources, national and state goals for energy independence, potential extent of impacts, etc.

The Panel also recommends that those involved in a wind turbine purchase become familiar with the noise specifications for the turbine and factors that affect noise production and noise control. Stall and pitch regulated turbines have different noise characteristics, especially in high winds. For certain turbines, it is possible to decrease noise at night through suitable control measures (e.g., reducing the rotational speed of the rotor). If noise control measures are to be considered, the wind turbine manufacturer must be able to demonstrate that such control is possible.

The Panel recommends an ongoing program of monitoring and evaluating the sound produced by wind turbines that are installed in the Commonwealth. IEC 61400-11 provides the standard for making noise measurements of wind turbines (International Electrotechnical Commission, 2002). In general, more comprehensive assessment of wind turbine noise in populated areas is recommended. These assessments should be done with reference to the broader ongoing research in wind turbine noise production and its effects, which is taking place internationally. Such assessments would be useful for refining siting guidelines and for developing best practices of a higher category. Closer investigation near homes where outdoor measurements show A and C weighting differences of greater than 15 dB is recommended.

ES 5.2 Shadow Flicker

Based on the scientific evidence and field experience related to shadow flicker, Germany has adopted guidelines that specify the following:

1. Shadow flicker should be calculated based on the astronomical maximum values (i.e., not considering the effect of cloud cover, etc.).
2. Commercial software such as WindPro or similar software may be used for these calculations. Such calculations should be done as part of feasibility studies for new wind turbines.
3. Shadow flicker should not occur more than 30 minutes per day and not more than 30 hours per year at the point of concern (e.g., residences).
4. Shadow flicker can be kept to acceptable levels either by setback or by control of the wind turbine. In the latter case, the wind turbine manufacturer must be able to demonstrate that such control is possible.

The guidelines summarized above may be considered to be a Field Tested Best Practice (Category 2). Additional studies could be performed, specifically regarding the number of hours per year that shadow flicker should be allowed, that would allow them to be placed in Research Validated (Category 1) Best Practices.

ES 5.3 Ice Throw

Ice falling from a wind turbine could pose a danger to human health. It is also clear that the danger is limited to those times when icing occurs and is limited to relatively close proximity to the wind turbine. Accordingly, the following should be considered Category 1 Best Practices.

1. In areas where icing events are possible, warnings should be posted so that no one passes underneath a wind turbine during an icing event and until the ice has been shed.
2. Activities in the vicinity of a wind turbine should be restricted during and immediately after icing events in consideration of the following two limits (in meters).

For a turbine that may not have ice control measures, it may be assumed that ice could fall within the following limit:

$$x_{\max, throw} = 1.5\left(2R + H\right)$$

Where: R = rotor radius (m), H = hub height (m)

For ice falling from a stationary turbine, the following limit should be used:

$$x_{\max, fall} = U\left(R + H\right)/15$$

Where: U = maximum likely wind speed (m/s)

The choice of maximum likely wind speed should be the expected one-year return maximum, found in accordance to the International Electrotechnical Commission's design standard for wind turbines, IEC 61400-1.

Danger from falling ice may also be limited by ice control measures. If ice control measures are to be considered, the wind turbine manufacturer must be able to demonstrate that such control is possible.

ES 5.4 Public Participation/Annoyance

There is some evidence of an association between participation, economic or otherwise, in a wind turbine project and the annoyance (or lack thereof) that affected individuals may express. Accordingly, measures taken to directly involve residents who live in close proximity to a wind turbine project may also serve to reduce the level of annoyance. Such measures may be considered to be a Promising Practice (Category 3).

ES 5.5 Regulations/Incentives/Public Education

The evidence indicates that in those parts of the world where there are a significant number of wind turbines in relatively close proximity to where people live, there is a close coupling between the development of guidelines, provision of incentives, and educating the public. The Panel suggests that the public be engaged through such strategies as education, incentives for community-owned wind developments, compensations to those experiencing documented loss of property values, comprehensive setback guidelines, and public education related to renewable energy. These multi-faceted approaches may be considered to be a Promising Practice (Category 3).

Chapter 1

Introduction to the Study

The Massachusetts Department of Environmental Protection (MassDEP), in collaboration with the Massachusetts Department of Public Health (MDPH), convened a panel of independent experts to identify any documented or potential health impacts or risks that may be associated with exposure to wind turbines, and, specifically, to facilitate discussion of wind turbines and public health based on sound science. While the Commonwealth of Massachusetts has goals for increasing the use of wind energy from the current 40 MW to 2000 MW by the year 2020, MassDEP recognizes there are questions and concerns arising from harnessing wind energy. Although fossil fuel non-renewable sources have negative environmental and health impacts, it should be noted that the scope of the Panel's effort was focused on wind turbines and is not meant to be a comparative analysis of the relative merits of wind energy vs. nonrenewable fossil fuel sources such as coal, oil, and natural gas. Currently, "regulation" of wind turbines is done at the local level through local boards of health and zoning boards. Some members of the public have raised concerns that wind turbines may have health impacts related to noise, infrasound, vibrations, or shadow flickering generated by the turbines. The goal of the Panel's evaluation and report is to provide a review of the science that explores these concerns and provides useful information to MassDEP and MDPH and to local agencies who are often asked to respond to such concerns.

The overall context for this study is that the use of wind turbines results in positive effects on public health and environmental health. For example, wind turbines operating in Massachusetts produce electricity in the amount of approximately 2,100–2,900 MWh annually per rated MW, depending on the design of the turbine and the average wind speed at the installation site. Furthermore, the use of wind turbines for electricity production in the New England electrical grid will result in a significant decrease in the consumption of conventional fuels and a corresponding decrease in the production of CO_2 and oxides of nitrogen and sulfur (see Appendix A for details). Reductions in the production of these pollutants will have demonstrable and positive benefits on human and environmental health. However, local impacts of wind turbines, whether anticipated or demonstrated, have resulted in fewer turbines being installed than might otherwise have been expected. To the extent that these impacts can be ameliorated, it should be possible to take advantage of the indigenous wind energy resource more effectively.

The Panel consists of seven individuals with backgrounds in public health, epidemiology, toxicology, neurology and sleep medicine, neuroscience, and mechanical engineering. With the exception of two individuals (Drs. Manwell and Mills), Panel members did not have any direct experience with wind turbines. The Panel did an extensive literature review of the scientific literature (see bibliography) as well as other reports, popular media, and the public comments received by the MassDEP.

Chapter 2

Introduction to Wind Turbines

This chapter provides an introduction to wind turbines so as to provide a context for the discussion that follows. More information on wind turbines may be found in the appendices, particularly in Appendix A.

2.1 Wind Turbine Anatomy and Operation

Wind turbines utilize the wind, which originates from sunlight due to the differential heating of various parts of the earth. This differential heating produces zones of high and low pressure, resulting in air movement. The motion of the air is also affected by the earth's rotation. Many countries have turned to wind power as a clean energy source because it relies on the wind, which is indefinitely renewable; it is generated "locally," thereby providing a measure of energy independence; and it produces no carbon dioxide emissions when operating. There is interest in pursuing wind energy both on-land and offshore. For this report, however, the focus is on land-based installations, and all comments will focus on this technology.

The development of modern wind turbines has been an evolutionary design process, applying optimization at many levels. This section gives a brief overview of the characteristics of wind turbines with some mention of the optimization parameters of interest. Appendix A provides a detailed explanation of wind energy.

The main features of modern wind turbines one notices are the very tall towers, which are no longer a lattice structure but a single cylindrical-like structure and the three upwind, very long, highly contoured turbine blades. The tower design has evolved partly because of biological impact factors as well as for other practical reasons. The early lattice towers were attractive nesting sites for birds. This led to an unnecessary impact of wind turbines on bird populations. The lattice structures also had to be climbed externally by turbine technicians. The tubular towers, which are now more common, are climbed internally. This reduces the health risks for maintenance crews.

The power in the wind available to a wind turbine is related to the cube of the wind speed and the square of the radius of the rotor. Not all the available power in the wind can be captured by a wind turbine, however. Betz (van Kuik, 2007) showed that the maximum power that can be extracted is 16/27 times the available power (see Appendix A). In an attempt to extract the maximum power from the wind, modern turbines have very large rotors and the towers are quite high. In this way the dependence on the radius is "optimized," and the dependence on the wind speed is "optimized." The wind speed is higher away from the ground due to boundary layer effects, and as such, the towers are made higher in order to capture the higher speed winds (more information about the wind profiles and variability is found in Appendix A). It is noted here that the rotor radius may increase again in the future, but currently the largest rotors used on land are around 100 m in diameter. This upper limit is currently a function of the radius of curvature of the roads on which the trucks that deliver the turbine blades must drive to the installation sites. Clearance under bridges is also a factor.

The efficiency with which the wind's power is captured by a particular wind turbine (i.e., how close it comes to the Betz limit) is a function of the blade design, the gearbox, the electrical generator, and the control system. The aerodynamic forces on the rotor blade play a major role. The best design maximizes lift and minimizes drag at every blade section from hub to tip. The twisted and tapered shapes of modern blades attempt to meet this optimal condition. Other factors also must be taken into consideration such as structural strength, ease of manufacturing and transport, type of materials, cost, etc.

Beyond these visual features, the number of blades and speed of the tips play a role in the optimization of the performance through what is called solidity. When setting tip speeds based on number of blades, however, trade-offs exist because of the influence of these parameters on weight, cost, and noise. For instance, higher tip speeds often results in more noise.

The dominance of the 3-bladed upwind systems is both historic and evolutionary. The European manufacturers moved to 3-bladed systems and installed numerous turbines, both in Europe and abroad. Upwind systems are preferable to downwind systems for on-land installations because they are quieter. The downwind configuration has certain useful features but it suffers from the interaction noise created when the blades pass through the wake that forms behind the tower.

The conversion of the kinetic energy of the wind into electrical energy is handled by the rotor nacelle assembly (RNA), which consists of the rotor, the drive train, and various ancillary components. The rotor grouping includes the blades, the hub, and the pitch control components. The drive train includes the shafts, bearings, gearbox (not necessary for direct drive generators), couplings, mechanical brake, and generator. A schematic of the RNA, together with more detail concerning the operation of the various parts, is in Appendix A.

The rotors are controlled so as to generate electricity most effectively and as such must withstand continuously fluctuating forces during normal operation and extreme loads during storms. Accordingly, in general a wind turbine rotor does not operate at its own maximum power coefficient at all wind speeds. Because of this, the power output of a wind turbine is generally described by a relationship, known as a power curve. A typical power curve is shown in the appendix. Below the cut-in speed no power is produced. Between cut-in and rated wind speed the power increases significantly with wind speed. Above the rated speed, the power produced is constant, regardless of the wind speed, and above the cut-out speed the turbine is shut down often with use of the mechanical brake.

Two main types of rotor control systems exist: pitch and stall. Stall controlled turbines have fixed blades and operate at a fixed speed. The aerodynamic design of the blades is such that the power is self-limiting, as long as the generator is connected to the electrical grid. Pitch regulated turbines have blades that can be rotated about their long axis. Such an arrangement allows more precise control. Pitch controlled turbines are also generally quieter than stall controlled turbines, especially at higher wind speeds. Until recently, many turbines used stall control. At present, most large turbines use pitch control. Appendices A and F provide more details on pitch and stall.

The energy production of a wind turbine is usually considered annually. Estimates are usually obtained by calculating the expected energy that will be produced every hour of a representative year (by considering the turbine's power curve and the estimated wind resource) and then summing the energy from all the hours. Sometimes a normalized term known as the capacity factor (CF) is used to characterize the performance. This is the actual energy produced (or estimated to be produced) divided by the amount of energy that would be produced if the turbine were running at its rated output for the entire year. Appendix A gives more detail on these computations.

2.2 Noise from Turbines

Because of the concerns about the noise generated from wind turbines, a short summary of the sources of noise is provided here. A thorough description of the various noise sources from a wind turbine is given in the text by Wagner et al. (1996).

A turbine produces noise mechanically and aerodynamically. Mechanical noise sources include the gearbox, generator, yaw drives, cooling fans, and auxiliary equipment such as hydraulics. Because the emitted sound is associated with the rotation of mechanical and electrical equipment, it is often tonal. For instance, it was found that noise associated with a 1500 kW turbine with a generator running at speeds between 1100 and 1800 rpm contained a tone between 20 and 30 Hz (Betke et al., 2004). The yaw system on the other hand might produce more of a grinding type of noise but only when the yaw mechanism is engaged. The transmission of mechanical noise can be either airborne or structure-borne as the associated vibrations can be transmitted into the hub and tower and then radiated into the surrounding space.

Advances in gearboxes and yaw systems have decreased these noise sources over the years. Direct drive systems will improve this even more. In addition, utility scale wind turbines are usually insulated to prevent mechanical noise from proliferating outside the nacelle or tower (Alberts, 2006)

Aerodynamic sound is generated due to complex fluid-structure interactions occurring on the blades. Wagner et al. (1996) break down the sources of aerodynamic sound as follows in Table 1.

Table 1

Sources of Aerodynamic Sound from a Wind Turbine (Wagner et al., 1996).

Noise Type	Mechanism	Characteristic
Trailing-edge noise	Interaction of boundary layer turbulence with blade trailing edge	Broadband, main source of high frequency noise (770 Hz < f < 2 kHz)
Tip noise	Interaction of tip turbulence with blade tip surface	Broadband
Stall, separation noise	Interaction of turbulence with blade surface	Broadband
Laminar boundary layer noise	Non-linear boundary layer instabilities interacting with the blade surface	Tonal
Blunt trailing edge noise	Vortex shedding at blunt trailing edge	Tonal
Noise from flow over holes, slits, and intrusions	Unsteady shear flows over holes and slits, vortex shedding from intrusions	Tonal
Inflow turbulence noise	Interaction of blade with atmospheric turbulence	Broadband
Steady thickness noise, steady loading noise	Rotation of blades or rotation of lifting surface	Low frequency related to blade passing frequency (outside of audible range)
Unsteady loading noise	Passage of blades through varying velocities, due to pitch change or blade altitude change as it rotates* For downwind turbines passage through tower shadow	Whooshing or beating, amplitude modulation of audible broadband noise. For downwind turbines, impulsive noise at blade passing frequency

**van den Berg 2004.*

Of these mechanisms, the most persistent and often strongest source of aerodynamic sound from modern wind turbines is the trailing edge noise. It is also the amplitude modulation of this noise source due to the presence of atmospheric effects and directional propagation effects that result in the whooshing or beating sound often reported (van den Berg, 2004). As a turbine blade rotates through a changing wind stream, the aerodynamics change, leading to differences in the boundary layer and thus to differences in the trailing edge noise (Oerlemans, 2009). Also, the direction in which the blade is pointing changes as it rotates, leading to differences in the directivity of the noise from the trailing edge. This noise source leads to what some people call the "whooshing" sound.

Most modern turbines use pitch control for a variety of reasons. One of the reasons is that at higher wind speeds, when the control system has the greatest impact, the pitch controlled turbine is quieter than a comparable stall regulated turbine would be. Appendix E shows the difference in the noise from two such systems.

When discussing noise from turbines, it is important to also consider propagation effects and multiple turbine effects. One propagation effect of interest is due to the dependence of the speed of sound on temperature. When there is a large temperature gradient (which may occur during the day due to surface warming or due to topography such as hills and valleys) the path a sound wave travels will be refracted. Normally this means that during a typical day sound is "turned" away from the earth's surface. However, at night the sound propagates at a constant height or even be "turned" down toward the earth's surface, making it more noticeable than it otherwise might be.

The absorption of sound by vegetation and reflection of sound from hillsides are other propagation effects of interest. Several of these effects were shown to be influencing the sound field near a few homes in North Carolina that were impacted by a wind turbine installation (Kelley et al., 1985). A downwind 2-bladed, 2 MW turbine was installed on a mountaintop in North Carolina. It created high amplitude impulsive noise due to the interaction of the blades and the tower wakes. Some homes (10 in 1000) were adversely affected by this high amplitude impulsive noise. It is shown in the report by Kelley et al. (1985) that echoes and focusing due to refraction occurred at the location of the affected homes.

In flat terrain, noise in the audible range will propagate along a flat terrain in a manner such that its amplitude will decay exactly as distance from the source (1/distance). Appendix E provides formulae for approximating the overall sound level at a given distance from a source. In the inaudible range, it has been noted that often the sound behaves as if the propagation was governed by a $1/(\text{distance})^{1/2}$ (Shepherd & Hubbard, 1991).

When one considers the noise from a wind farm in which multiple turbines are located close to each other, an estimate for the overall noise from the farm can be obtained. Appendix E describes the method for obtaining the estimate. All these estimates rely on information regarding the sound power generated by the turbine at the hub height. The power level for several modern turbines is given in Appendix D.

2.2.a Measurement and Reporting of Noise

Turbines produce multiple types of sound as indicated previously, and the sound is characterized in several ways: tonal or broadband, constant amplitude or amplitude modulated, and audible or infrasonic. The first two characterization pairs have been mentioned previously. Audible refers to sound with frequencies from 20 Hz to 20 kHz. The waves in the infrasonic range, less than 20 Hz, may actually be audible if the amplitude of the sound is high enough. Appendix D provides a brief primer on acoustics and the hearing threshold associated with the entire frequency spectrum.

Sound is simply pressure fluctuations and as such, this is what a microphone measures. However, the amplitude of the fluctuations is reported not in units of pressure (such as Pascals) but on a decibel scale. The sound pressure level (SPL) is defined by

$$\mathrm{SPL} = 10 \log_{10} [p^2/p^2_{ref}] = 20 \log_{10}(p/p_{ref})$$

the resulting number having the units of decibels (dB). The reference pressure p_{ref} for airborne sound is 20×10^{-6} Pa (i.e., 20 µPa or 20 micro Pascals). Some implications of the decibel scale are noted in Appendix D.

When sound is broadband (contains multiple frequencies), it is useful to use averages that measure approximately the amplitude of the sound and its frequency content. Standard averaging methods such as octave and 1/3-octave band are described in Appendix D. In essence, the entire frequency range is broken into chunks, and the amplitude of the sound at frequencies in each chunk is averaged. An overall sound pressure value can be obtained by averaging all of the bands.

When presenting the sound pressure it is common to also use a filter or weighting. The A-weighting is commonly used in wind turbine measurements. This filter takes into account the threshold of human hearing and gives the same decibel reading at different frequencies that would equate to equal loudness. This means that at low frequencies (where amplitudes have to be incredibly high for the sound to be heard by people) a large negative weight would be applied. C-weighting only filters the levels at frequencies below about 30 Hz and above 4 kHz and filters them only slightly between 0 and 30 Hz. The weight values for both the A and C weightings filters are shown in Appendix D, and an example with actual wind turbine data is presented.

There are many other weighting methods. For instance, the day-night level filter penalizes nighttime noise between the hours of 10 p.m. and 7 a.m. by adding an additional 10 dB to sound produced during these hours.

When analyzing wind turbine and other anthropogenic sound there is a question as to what averaging period should be used. The World Health Organization uses a yearly average. Others argue though that especially for wind turbines, which respond to seasonal variations as well as diurnal variations, much shorter averages should be considered.

2.2.b Infrasound and Low-frequency Noise (IFLN)

The term *infrasound* refers to pressure waves with frequencies less than 20 Hz. In the infrasonic range, the amplitude of the sound must be very high for it to be audible to humans. For instance, the hearing threshold below 20 Hz requires that the amplitude be above 80 dB for it to be heard and at 5 Hz it has to be above 103 dB (O'Neal, 2011; Watanabe & Moeller, 1990). This gives little room between the audible and the pain values for the infrasound range: 165 dB at 2 Hz and 145 dB at 20 Hz cause pain (Leventhal, 2006).

The *low frequency* range is usually characterized as 20–200 Hz (Leventhal, 2006; O'Neal, 2011). This is within the audible range but again the threshold of hearing indicates that fairly high amplitude is required in this frequency range as well. The A-weighting of sound is based upon the threshold of human hearing such that it reports the measured values adjusted by -50 dB at 20 Hz, -10 dB at 200 Hz, and + 1 dB at 1000 Hz. The A-weighting curve is shown in Appendix D.

It is known that low frequency waves propagate with less attenuation than high-frequency waves. Measurements have shown that the amplitude for the airborne infrasonic waves can be cylindrical in nature, decaying at a rate inversely proportional to the square root of the distance from the source. Normally the decay of the amplitude of an acoustic wave is inversely proportional to the distance (Shepherd & Hubbard, 1991).

It is difficult to find reliable and comparable infrasound and low frequency noise (ILFN) measurement data in the peer-reviewed literature. Table 2 provides some examples of such measurements from wind turbines. For each case, the reliability of the infrasonic data is not known (the infrasonic measurement technique is not described in each report), although it is assumed that the low frequency noise was captured accurately. The method for obtaining the sound pressure level is not described for each reported data set, and some may come from averages over many day/time/wind conditions while others may be just from a single day's measurement campaign.

Table 2
Literature-based Measurements of Wind Turbines; dB alone refers to unweighted values

Turbine Rating (kW)	**Distance (m)**	**Frequency**	**Sound Pressure Level**	**Reference**
500	200	5	55 dB(G)[2]	Jakobsen, 2005[3]
		20	35 dB(G)[2]	
3200	68	4	72 dB(G)[2]	Jakobsen, 2005[3]
		20	50 dB(G)[2]	
1500	65	5	>70 dB(A)	Leventhal, 2006
		20	60 dB(A)	
		100	35 dB(A)	
2000 (2)	100	5	95 dB	van den Berg, 2004[3]
		20	65 dB	
		200	55 dB	
1500	98	1	90 dB	Jung, 2008[3]
		10	70 dB	
		20	68 dB	
		100	68 dB	
		200	60 dB	
-	450	10	75 dB	Palmer, 2010
		100	55 dB	
		200	40 dB	
2300	305	5	73 dB(A)	O'Neal, 2011[3]
		20	55 dB(A) - 95	
		100	50 dB(A) - 70	

[1]dB alone refers to un-weighted values.
[2]G weighting reflects human response to infrasound. The curve is defined to have a gain of zero dB at 10 Hz. Between 1 Hz and 20 Hz the slope is approximately 12 dB per octave. The cut-off below 1 Hz has a slope of 24 dB per octave, and above 20 Hz the slope is -24 dB per octave. Humans can hear 95 dB(G).
[3]Indicates peer-reviewed article.

When these recorded levels are taken at face value, one might conclude that the infrasonic regime levels are well below the audible threshold. In contrast, the low frequency regime becomes audible around 30 Hz. Such data have led many researchers to conclude that the infrasound and low frequency noise from wind turbines is not an issue (Leventhal, 2009; O'Neal, 2011; Bowdler, 2009). Others who have sought explanations for complaints from those living near wind turbines have pointed to ILFN as a problem (Pierpont, 2009; Branco & Alves-

Pereira, 2004). Some have declared the low frequency range to be of greatest concern (Kamperman et al., 2008; Jung, 2008).

It is important to make the clear distinction between amplitude-modulated noise from wind turbines and the ILFN from turbines. Amplitude modulation in wind turbines noise has been discussed at length by Oerlemans (2009) and van den Berg (2004). Amplitude modulation is what causes the whooshing sound referred to as swish-swish by van den Berg (that sometimes becomes a thumping sound). The whooshing noise created by modern wind turbines occurs because of variations in the trailing edge noise produced by a rotor blade as it sweeps through its path and the directionality of the noise because of the perceived pitch of the blade at different locations along its 360° rotation. The sound is produced in the audible range, and it is modulated so that it is quiet and then loud and then quiet again at a rate related to the blade passing frequency (rate blades pass the tower) which is often around 1 Hz. Van den Berg (2004) noted that the level of amplitude modulation is often greater at night because the difference between the wind speed at the top and bottom of the rotor disc can be much larger at night when there is a stable atmosphere than during the day when the wind profile is less severe. It is further argued that in a stable atmosphere there is little wind near the ground so wind noise does not mask the turbine noise for a listener near the ground. Finally, atmospheric effects can change the propagation of the sound refracting the noise towards the ground rather than away from the ground. The whooshing that is heard is NOT infrasound and much of its content is not at low frequency. Most of the sound is at higher frequency and as such it will be subject to higher atmospheric attenuation than the low frequency sound. An anecdotal finding that the whooshing sound carries farther when the atmosphere is stable does not imply that it is infrasound or heavy in low frequency content, it simply implies that the refraction of the sound is also different when the atmosphere is stable. It is important to note then that when a complaint is tied to the thumping or whooshing that is being heard, the complaint may not be about ILFN at all even if the complaint mentions low frequency noise. Kamperman et al. (2008) state that, "It is not clear to us whether the complaints about "low frequency" noise are about the audible low frequency part of the "swoosh-boom" sound, the once-per-second amplitude modulation … of the "swoosh-boom" sound, or some combination of the two."

Chapter 3

Health Effects

3.1 Introduction

Chapter 3 reviews the evidence for human health effects of wind turbines. Extensive literature searches and reviews were conducted to identify studies that specifically evaluate population responses to turbines, as well as population and individual responses to noise, vibration, and flicker. The biological plausibility or basis for health effects of turbines (noise, vibration, and flicker) was examined. Beyond traditional forms of scientific publications, the Panel also reviewed other non-peer reviewed materials including information related to "Wind Turbine Syndrome" and provides a rigorous analysis of its scientific basis. Since the most commonly reported complaint by people living near turbines is sleep disruption, the Panel provides a robust review of the relationship between noise, vibration, annoyance as well as sleep disturbance from noises and the potential impacts of the resulting sleep deprivation.

In assessing the state of the evidence for health effects of wind turbines, the Panel relied on several different types of studies. It considered human studies of primary value. These were either human epidemiological studies specifically relating to exposure to wind turbines or, where specific exposures resulting from wind turbines could be defined, the Panel also considered human experimental data. Animal studies are critical to exploring biological plausibility and understanding potential biological mechanisms of different exposures, and for providing information about possible health effects when experimental research in humans is not ethically or practically possible (National Research Council (NRC), 1991). As such, this literature was also reviewed with respect to wind turbine exposures. In all cases, data quality is considered. At times some studies were rejected because of lack of rigor or the interpretations were inconsistent with the scientific evidence. These are identified in the discussion below.

In the specific case of the possibility of ice being thrown from wind turbine blades, the Panel discusses the physics of such ice throw in order to provide the basis of the extent of the potential for injury from thrown ice (see Chapter 2).

3.2 Human Exposures to Wind Turbines

Epidemiologic study designs differ in their ability to provide evidence of an association (Ellwood, 1998). Typical study designs include randomized trials, cohort studies, and case-control studies and can include elements of prospective follow-up, retrospective assessments, or cross-sectional analysis where exposure and outcome data are essentially concurrent. Each of these designs has strengths and weaknesses and thus can provide varying levels of strength of evidence for causal associations between exposures and outcomes, which can also be affected by analytic choices. Thus, this literature needs to be examined in detail, regardless of study type, to determine strength of evidence for causality.

Review of this literature began with a PubMed search for "wind turbine" or "wind turbines" to identify peer-reviewed literature pertaining to health effects of wind turbines. Titles and abstracts of identified papers were then read to make a first pass determination of whether the paper was a study on health effects of exposure to wind turbines or might possibly contain relevant references to such studies. Because the peer-reviewed literature so identified was relatively limited, we also examined several non-peer reviewed papers, reports, and books that discussed health effects of wind turbines. All of this literature was examined for additional relevant references, but for the purposes of determining strength of evidence, we only considered such publications if they described studies of some sort in sufficient detail to assess the validity of the findings. This process identified four studies that generated peer-reviewed papers on health effects of wind turbines. A few other non-peer reviewed documents described data of sufficient relevance to merit consideration and are discussed below as well.

3.3 Epidemiological Studies of Exposure to Wind Turbines

The four studies that generated peer-reviewed papers on health effects of wind turbines included two from Sweden (E. Pedersen et al., 2007; E. Pedersen & Waye, 2004), one from the Netherlands (E. Pedersen et al., 2009), and one from New Zealand (Shepherd at al., 2011). The primary outcome assessed in the first three of these studies is annoyance. Annoyance *per se* is not a biological disease, but has been defined in different ways. For example, as "a feeling of resentment, displeasure, discomfort, dissatisfaction, or offence which occurs when noise interferes with someone's thoughts, feelings or daily activities" (Passchier-Vermeer, 1993); or "a mental state characterized by distress and aversion, which if maintained, can lead to a deterioration of health and well-being" (Shepherd et al., 2010). Annoyance is usually assessed with questionnaires, and this is the case for the three studies mentioned above. There is consistent evidence for annoyance in populations exposed for more than one year to sound levels of 37 dB(A), and severe annoyance at about 42 dB(A) (Concha-Barrientos et al., 2004). In each of those studies annoyance was assessed by questionnaire, and the respondent was asked to indicate annoyance to a number of items (including wind turbines) on a five-point scale (do not notice, notice but not annoyed, slightly annoyed, rather annoyed, very annoyed). While annoyance as such is certainly not to be dismissed, in assessing global burden of disease the World Health Organization (WHO) has taken the approach of excluding annoyance as an outcome because it is not a formally defined health outcome *per se* (Concha-Barrientos et al., 2004). Rather, to the extent annoyance may cause other health outcomes, those other outcomes could be considered directly. Nonetheless, because of a paucity of literature on the association between wind turbines and other health outcomes, we consider here the literature on wind turbines and annoyance.

3.3.a Swedish Studies

Both Swedish studies were cross sectional and involved mailed questionnaires to potential participants. For the first Swedish study, 627 households were identified in one of five areas of Sweden chosen to have enough dwellings at varying distances from wind turbines and of comparable geographical, cultural, and topographical structure (E. Pedersen & Waye, 2004). There were 16 wind turbines in the study area and of these, 14 had a power of 600–650 kW, and the other 2 turbines had 500 kW and 150 kW. The towers were between 47 and 50 m in height. Of the turbines, 13 were WindWorld machines, 2 were Enercon, and 1 was a Vestas turbine. Questionnaires were to be filled out by one person per household who was between the ages of 18 and 75. If there was more than one such person, the one whose birthday was closest to May 20th was chosen. It is not clear how the specific 627 households were chosen, and of the 627, only 513 potential participants were identified, although it is not clear why the other households did not have potential participants. Of the 513 potential participants, 351 (68.4%) responded.

The purpose of the questionnaire was masked by querying the participant about living conditions in general, some questions on which were related to wind turbines. However, a later section of the questionnaire focused more specifically on wind turbines, and so the degree to which the respondent was unaware about the focus on wind turbines is unclear. A-weighted sound levels were determined at each respondent's dwelling, and these levels were grouped into

6 categories (in dB(A): <30, 30–32.5, 32.5–35, 35–37.5, 37.5–40, and >40). Ninety-three percent of respondents could see a wind turbine from their dwelling.

The main results of this study were that there was a significant association between noise level and annoyance. This association was attenuated when adjusted for the respondent's attitude towards the visual impact of the turbines, which itself was a strong predictor of annoyance levels, but the association with noise still persisted. Further adjustment for noise sensitivity and attitude towards wind turbines in general did not change the results. The authors indicated that the reporting of sleep disturbances went up with higher noise categories, but did not report on the significance of this association. Nor did the authors report on associations with other health-related questions that were apparently on the questionnaire (such as headache, undue tiredness, pain and stiffness in the back, neck or shoulders, or feeling tensed/stressed, or irritable).

The 68% response rate in this study is reasonably good, but it is somewhat disconcerting that the response rate appeared to be higher in the two highest noise level categories (76% and 78% vs. 60–69%). It is not implausible that those who were annoyed by the turbines were more inclined to return the questionnaire. In the lowest two sound categories (<32.5 dB(A)) nobody reported being more than slightly annoyed, whereas in the highest two categories 28% (37.5–40 dB(A)) and 44% (>40 dB(A)) reported being more than slightly annoyed (unadjusted percentages). Assuming annoyance would drive returning the questionnaires, this would suggest that the percentages in the highest categories may be somewhat inflated. The limited description of the selection process in this study is a limitation as well, as is the cross sectional nature of the study. Cross-sectional studies lack the ability to determine the temporality of cause and effect; in the case of these kinds of studies, we cannot know whether the annoyance level was present before the wind turbines were operational from a cross sectional study design. Furthermore, despite efforts to blind the respondent to the emphasis on wind turbines, it is not clear to what degree this was successful.

The second Swedish study (E. Pedersen & Persson Waye, 2007) took a similar approach to the first, but in this study the selection procedures were explained in more detail and were clearly rigorous. Specific details on the wind turbines in the area were not provided, but it was noted that areas were sought with wind turbines that had a nominal power of more than 500 kW, although some of the areas also contained turbines with lower power. A later publication by these authors (Pedersen et al., 2009) indicates that the turbines in this study were up to 1.5 MW and up to 65 m high. In the areas chosen, either all households were recruited or a random sample was used. In this study 1,309 questionnaires were sent out and 754 (57.6%) were returned. The response rate by noise category level, however, was not reported. There was a clear association between noise level and hearing turbine noise, with the percentage of those hearing turbine noise steadily increasing across the noise level categories. However, despite a significant unadjusted association between noise levels and annoyance (dichotomized as more than slightly annoyed or not), and after adjusting for attitude towards wind turbines or visual aspects of the turbines (e.g., visual angle on the horizon, an indicator of how prominent the turbines are in the field of view), each of which was strongly associated with annoyance, the association with noise level category was lost. The model from which this conclusion was drawn, however, imposed a linear relation on the association between noise level category and annoyance. But in the crude percentages of people annoyed across noise level categories, it appeared that the relation might not be linear, but rather most prevalent in the highest noise. The percentage of those in the highest noise level category (>40 dB(A)) reporting annoyance (~15%) appeared to be higher than among people in the lower noise categories (<5%).

Given the more rigorous description of the selection process in this study, it has to be considered stronger than the first Swedish study. While 58% is pretty good for a questionnaire response rate, the non-response levels still leave room for bias. The authors do not report the response rate by noise level categories, but if the pattern is similar to the first Swedish study, it could suggest that the percentage annoyed in the highest noise category could be inflated. The cross sectional nature of the study is also a limitation and complicates interpretation of the effects on the noise-annoyance association of adjustment for the other factors. Regarding the loss of the association after adjustment for attitude, if one assumes that the noise levels caused a negative attitude towards wind turbines, then the loss of association between noise and annoyance after adjusting for attitude does not argue against annoyance being caused by increasing turbine noise, but rather that that is the path by which noise causes annoyance (louder noise→negative attitude→annoyance). If, on the other hand, the attitude towards turbines was not caused by the noise, then the results would suggest that noise levels did not cause the annoyance. Visual angle, however, clearly does not cause the noise level; thus, the lack of association between noise and annoyance in analyses adjusted for visual angle more strongly suggest that the turbine noise level is not causing the annoyance, but perhaps the visual intrusion instead. This is similar to the conclusion of an earlier Danish report (T. H. Pedersen & Nielsen, 1994). Either way, however, the data still suggest that there may be an association between turbine noise and annoyance when the noise levels are >40 dB(A).

A more intricate statistical model of the association between turbine noise levels and annoyance that used the data from both Swedish studies was reported separately (Pedersen & Larsman, 2008). The authors used structural equation models (SEMs) to simultaneously account for several aspects of visual attitude towards the turbines and general attitude towards the turbines. These analyses suggested a significant association between noise levels and annoyance even after considering other factors.

3.3.b Dutch Study

The Dutch study aimed to recruit households that reflected general wind turbine exposure conditions over a range of background sound levels. All areas within the Netherlands that were characterized by one of three clearly defined land-use types—built-up area, rural area with a main road, and rural area without a main road—and that had at least two wind turbines of at least 500 kW within 500 meters of each other were selected for the study. Sites dominated by industry or business were excluded. All addresses within these areas were obtained and classified into one of five wind turbine noise categories (<30, 30–35, 35–40, 40–45, and >45 dB(A)) based on characteristics of nearby wind turbines, measurements of sound from those turbines, and the International Standards Organization (ISO) standard model of wind turbine noise propagation. Individual households were randomly selected for recruitment within noise/land type categories, except for the highest noise level for which all households were selected because of the small number exposed at the wind turbine noise levels of the highest category.

As with the Swedish studies, the Dutch study was cross sectional and involved a mailed questionnaire modeled on the one used in the Swedish studies. Of 1,948 mailed surveys, 725 (37%) were returned. There was only minor variation in response rate by turbine noise category, although unlike the Swedish studies, the response rate was slightly lower in the higher noise categories. A random sample of 200 non-responders was sent an abbreviated questionnaire asking only two questions about annoyance from wind turbine noise. There was no difference in the distribution of answers to these questions among these non-responders and those who responded to the full questionnaire.

One of the more dramatic findings of this study was that among people who benefited economically from the turbines (n=100; 14%)—who were much more commonly in the higher noise categories—there was virtually no annoyance (3%) despite the same pattern of noticing the noise as those who did not benefit economically. It is possible that this is because attitude towards turbines drives annoyance, but it was also suggested that those who benefit economically are able to turn off the turbines when they become annoying. However, it is not clear how many of those who benefited economically actually had that level of control over the turbines.

Similarly, there was very little annoyance among people who could not see a wind turbine from their residence even when those people were in higher noise categories (although none were in the highest category). In models that adjusted for visibility of wind turbines and economic benefit, sound level was still a significant predictor of annoyance. However, because of the way in which sound and visibility were modeled in this analysis, the association between higher noise levels and higher annoyance could have been driven entirely by those who could see a wind turbine, while there could still have been no association between wind turbine noise level and annoyance among those who could not see a wind turbine. Thus, this study has to be considered inconclusive with respect to an association between wind turbine sound level and annoyance *independent of* the effect of seeing a wind turbine (and vice versa).

The Dutch study has the limitation of being cross sectional as were the Swedish studies, and the non-response in the Dutch study was much larger than in the Swedish studies. The results of the limited assessment of a subset of non-responders mitigate somewhat against the concerns raised by the low response rate, but not completely.

3.3.c New Zealand Study

The New Zealand study recruited participants from what the authors refer to as two demographically matched neighborhoods (an exposed group living near wind turbines and a control group living far from turbines), although supporting data for this are not presented. The area with the turbines is described as being characterized by hilly terrain, with long ridges running 250–450 m above sea level, on which 66 125 m high wind turbines are positioned. The power of the turbines is not provided. For the exposed group, participants were drawn from those 18 years and older living in 56 houses located within 2 km of a wind turbine, and for the control group participants were drawn from those 18 years and older living in 250 houses located at least 8 km from the wind turbines. It is unclear how many participants per household were recruited, but the final study sample included 39 people in the exposed group and 158 in the control group. Response rates of 34% for the exposed group and 32% for the control group are given. The outcome assessed was response to the abbreviated version of the WHO's quality of life (QOL)-BREF (WHOQOL-BREF)—a health-related QOL questionnaire. These questions were embedded within a larger questionnaire with various facets designed to mask the focus on wind turbines. Although there were no statistically significant demographic differences between the two groups, 43.6% of those in the exposed group had a university education while only 34.2% in the control group did.

The exposed group was found to have significantly worse physical QOL (in particular the sleep and energy level items of this scale) and worse environmental QOL (in particular ratings of how healthy the environment is and satisfaction with the conditions of their living space). The groups did not differ in scores on the social or psychological scales. The mean ratings for an overall QOL item was significantly lower in the exposed group. All of these analyses were adjusted for length of residence, but for no other variables.

As with the other studies discussed, this study has the limitation of being cross sectional. As with the Dutch study, the response rate in the present study is rather low, and unfortunately, there are no data in the New Zealand study on non-participants. This raises concern that self-selection into the study could differ by important factors in some way between the two groups. The difference seen in education level between the groups exacerbates this concern. It is also unclear whether appropriate statistical analysis methods were used given that there may have been multiple respondents from the same household, which is not stated but would have needed to have been accounted for in the analysis. The lack of control for other variables that may be related to reporting of QOL is also a limitation. In this regard it is important to note that a lack of a statistically significant difference in factors between groups does not rule out the possibility of those factors potentially accounting for some of the difference in outcome scores between groups, particularly when the sample size is small like in this study. Whether participants could see wind turbines was not assessed, but it is likely that most if not all in the exposed group could and most if not all in the control group could not, given their locations. Given the findings in the

Swedish and Dutch studies, this means that even if the difference in QOL scores seen are due to wind turbines, it is possible that it is driven by seeing the turbines rather than sound from the turbines. Overall, the level of evidence from this study for a causal association between wind turbines and reported QOL is limited.

3.3.d Additional Non-Peer Reviewed Documents

Papers that appear in the peer-reviewed literature have by definition undergone a level of review external to the study team by not only the editors of the journal, but also two to three (usually) scientists familiar with the field of the study and the methodology used. These hurdles provide an opportunity to identify problems with the paper—from methodology to interpretation of the results—and either provide the opportunity to address problems or reject the paper if the problems are considered fatal to the interpretation of the results. Non-peer reviewed literature is not subject to this external review scrutiny. This does not mean that all peer-reviewed literature is of high quality nor that non-peered reviewed literature is necessarily inferior to peer-reviewed literature, but it does mean that non-peered reviewed literature does not need to undergo any review process to appear. Indeed, at times studies appear in non-peer reviewed outlets precisely because they did not meet the bar of quality necessary to appear in the peer-reviewed literature. Thus, non-peer reviewed literature needs to be scrutinized with this in mind. Four such non-peer-reviewed reports are described below. In addition to those four, a few early reports of annoyance from wind turbines generally found a weak relationship between annoyance and the equivalent A-weighted SPL, although those studies were mainly based on studies of smaller turbines of less than 500 kW (T. H. Pedersen & Nielsen, 1994; Rand & Clarke, 1990; Wolsink et al., 1993).

Project WINDFARMperception: Visual and acoustic impact of wind turbine farms on residents (van den Berg et al., 2008). This report describes the study upon which the Dutch paper summarized above (E. Pedersen et al., 2009) is based. The characteristics of the wind turbines are thus as described above. In addition to the data that appeared in the peer-reviewed literature, this report describes analyses of additional data that was collected. These additional data relate to health effects and turbine noise exposure. The questionnaire assessed stress levels with the General Health Questionnaire (GHQ), a validated scale that has been widely used in such studies and which assesses symptoms felt over the past several weeks. In models adjusted for age, economic benefit from the turbines, and sex, there was no association between sound levels and stress. In contrast, there was a significant association between sound levels and interrupted sleep (at least once a month), even when further adjusting for background noise levels. This was most obvious at turbine noise levels >45 dB(A), but there appeared to be an increasing trend in occurrence of interrupted sleep with increasing noise categories even across the lower noise categories. This study also asked participants about chronic health conditions including diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and migraine. Although no associations were seen between wind turbine noise and these outcomes in adjusted analyses, the chronic nature of these outcomes and the lack of data on timing of onset with respect to when the wind turbines were introduced make interpreting these negative findings difficult.

Report to the commission related to Moturimu wind farm, New Zealand (Phipps, 2007). This report to a commission in New Zealand related to the Moturimu wind farm describes a survey conducted by Robyn Phipps to investigate the visual and acoustical effects experienced by residents living at least 2 km from existing wind farms in the Manawatu and Tararua regions of New Zealand. Most respondents were within 3 km, although a few lived further away, as far as 15 km. The characteristics and number of wind turbines was not provided. Although this work does not appear to have come out in the peer-reviewed literature, reasonable details about the methodology are provided.

Roughly 1,100 surveys were delivered to postal addresses and 614 (56%) were returned. Participants were asked to rate on a scale of 1–5 their agreement with different statements related to their perceptions of the wind turbines. When these questions dealt with visual issues, they were framed both positively and negatively (e.g., "I think the turbines spoil the view," and "I think the turbines are quite attractive"). This apparently was not the case with other questions (e.g., "Watching the turbines can create an unpleasant physical sensation in my body").

Overall, 9% of respondents endorsed being "affected" by the flicker of the wind turbines; 15% were sufficiently bothered by the visual and noise effects of the turbines to consider complaining, and 10% actually had complained. While 56% is a relatively good response rate for a mailed survey, the reasons for non-response of nearly half of potential participants must be considered. It is possible that non-respondents did not care enough about the effects of the wind turbines to bother responding, which presumably would lower the overall percentages that were "affected" by the turbines. On the other hand, it is not clear how long the turbines were in operation prior to the survey, and it is conceivable that some more affected people may have moved out of the area before the time of the survey.

A further drawback to the reported survey was that there was not a determination of how the percentage of "affected" respondents related to distance from the turbines, the ability to see the turbines, or noise levels experienced from the turbines. The report cites a lot of literature on noise and health effects, and while such effects have been reported in the literature, they are almost uniformly at sound levels above what is usually found for people living near turbines (and most certainly higher than those usually reported for people living more than 2 km from a turbine). A WHO report provides a good review of this literature (WHO, 2009). The lowest threshold levels for seeing any effect are about 35 dB(A) (maximum per event or L_{Amax}) for some physiological sleep responses (e.g., EEG, or duration of sleep stages), but these thresholds are for levels inside the house near the sleeper, which will be much lower than what is experienced outside the house. The lowest threshold level for complaints of well-being were estimated at 35 dB(A) as a yearly average outside the house at night ($L_{night,\ outside}$). But for health outcomes the thresholds for any effect are much higher, for example 50 dB(A) ($L_{night,\ outside}$) for hypertension or myocardial infarction.

"Wind Turbine Syndrome" (Pierpont, 2009): This book describes several people who suffer health symptoms that they attribute to wind turbines. Such descriptions can be informative in describing phenomena and raising suggestions for possible follow-up with more rigorous study designs, but generally are not considered evidence for causality. In this particular case, though, there are elements that go beyond the most basic symptom descriptions and so warrant consideration as a study. But limitations to the design employed make it impossible for this work to contribute any evidence to the question of whether there is a causal association between wind turbine exposure and health effects. Given this, the very term "Wind Turbine Syndrome" is misleading as it implies a causal role for wind turbines in the described health symptoms.

The book describes health symptoms experienced among 38 people from 10 different families who lived near wind turbines and subsequently either moved away from the turbines or spent significant periods of time away. The participants ranged in age from less than 1 to 75 years old, with 13 (34%) younger than 16 years and 17 (45%) younger than 22. The participants were queried about their health symptoms before exposure to turbines (presumably before the turbines were operational), during exposure to turbines, and after moving away. There is an impressive detailed description of the extent and severity of health symptoms experienced by this group, with a core group of symptoms centered around vibratory responses and termed Visceral Vibratory Vestibular Disturbance (VVVD) by Pierpont. While these symptoms for the most part are attributed to exposure to the wind turbines by the participants—either because they appeared once the turbines were operational or because they seemed to diminish after going away from the turbines—the way in which these participants were recruited makes it impossible to draw any conclusions about attributing causality to the turbines.

The most critical problem with respect to inferring causality from Pierpont's findings lies in how the families were identified for participation. To be included in the study, among other criteria, at least one family member had to have severe symptoms *and* reside near a recently erected wind turbine. In epidemiological terms this is selecting participants based on both exposure and outcome, which guarantees a biased (non-causal) association between wind turbines and symptoms. While it could be argued that other family members may not have had severe symptoms—and so would not be selected based on outcome—it is hard to consider other family members as truly independent observations, as their reporting of symptoms, or indeed their experiencing of symptoms, could be influenced by the more severely affected family member. This is particularly so when the symptoms are in the realm of anxiety, sleep disturbance, memory, and concentration; and the severely affected family members are reporting increased irritability, anger, and shouting.

Although not always, several of the participants reported an improvement of symptoms after moving away from the wind turbines. While this is suggestive and should not be discounted as something to explore further, the highly selective nature of the interviewed group as a whole makes the evidence for causality from these data *per se* weak. There are also many factors that change when moving, making it difficult to attribute changes to any specific difference with certainty. Additional factors that contribute to the inability to infer causality from these data include the small sample size, lack of detail on the larger population that could have been considered for inclusion in the study, and lack of detail on precisely how the actual participants were recruited. In addition, while the clinical history was extensive, the symptom data were all self-reported. Another complication is that there are no precise data on distance to turbines, and noise levels or infrasound vibration levels at the participants' homes.

"Adverse health effects of industrial wind turbines: a preliminary report" (Nissenbaum et al., 2011): This report describes a study involving questionnaire assessment of mental and physical health (SF-36), sleep disturbance (Pittsburgh Sleep Quality Index), and sleepiness (Epworth Sleepiness Scale) among residents near one of two wind farms in Maine (Vinalhaven & Mars Hill). The Mars Hill site is a linear arrangement of 28 General Electric 1.5 MW turbines, sited on a ridgeline. The Vinalhaven site is a cluster of three similar turbines, sited on a flat, tree-covered island. All residents within 1.5 km of one of the turbines were identified, and all those older than 18 years and non-demented were considered eligible for the study. A set of households from an area of similar socioeconomic makeup but 3–7 km from wind turbines were also recruited. The recruitment process involved house-to-house visits up to three times to recruit participants. Among those within at most 1.5 km from the nearest turbine, 65 adults were identified and 38 (58%; 22 male, 16 female) participated from 23 unique households. Among those 3-7 km from the nearest turbine, houses were visited until a similar number of participants were recruited. This process successfully recruited 41 adults (18 male, 23 female) from 33 unique households. No information was given on the number of homes or people approached so the participation rate cannot be determined.

Analyses adjusted for age, sex, and site (the two different wind farms) found that those living within 1.5 km of a wind turbine had worse sleep quality and mental health scores and higher ratings of sleepiness than those living 3–7 km from a turbine. Physical health scores did not differ between the groups. Similar associations were found when distance to the nearest turbine was analyzed as a continuous variable.

This study is somewhat limited by its size—much smaller than the Swedish or Dutch studies described above—but nonetheless suggests relevant potential health impacts of living near wind turbines. There are, however, critical details left out of the report that make it difficult to fully assess the strength of this evidence. In particular, critical details of the group living 3–7 km from wind turbines is left out. It is stated that the area is of similar socioeconomic makeup, and while this may be the case, no data to back this up are presented—either on an area level or on an individual participant level. In addition, while the selection process for these participants is described as random, the process of recruiting these participants by going home to home until a certain number of participants are reached is not random. Given this, details of how homes were identified, how many homes/people were approached, and differences between those who did and did not participate are important to know. Without this, attributing any of the observed associations to the wind turbines (either noise from them or the sight of them) is premature.

3.3.e Summary of Epidemiological Data

There is only a limited literature of epidemiological studies on health effects of wind turbines. Furthermore, existing studies are limited by their cross sectional design, self-reported symptoms, limited ability to control for other factors, and to varying degrees of non-response rates. The study that accounted most extensively for other factors that could affect reported symptoms had a very low response rate (E. Pedersen et al., 2009; van den Berg, et al., 2008).

All four peer-reviewed papers discussed above suggested an association between increasing sound levels from wind turbines and increasing annoyance. Such an association was also suggested by two of the non-peer reviewed reports that met at least basic criteria to be considered studies. The only two papers to consider the influence of seeing a wind turbine (each one of the peer-reviewed papers) both found a strong association between seeing a turbine and annoyance. Furthermore, in the studies with available data, the influence of either sound from a turbine or seeing a turbine was reduced—if not eliminated, as was the case for sound in one study—when both of these factors were considered together. However, this precise relation cannot be disentangled from the existing literature because the published analyses do not properly account for both seeing and hearing wind turbines given the relation between these two that the data seem to suggest. Specifically, the possibility that there may be an association between either of those factors and annoyance, but possibly only for those who both see and hear sound from a turbine, and not for those who either do not hear sound from or do not see a turbine. Furthermore, in the one study to consider whether individuals benefit economically from the turbines in question, there appeared to be virtually no annoyance regardless of whether those people could see or hear a turbine. Even if one considers the data just for those who could see a wind turbine and did not benefit economically from the turbines, defining at what noise levels the percentage of those annoyed becomes more dramatic is difficult. Higher percentages of annoyance did appear to be more consistent above 40 dB(A). Roughly 27% were annoyed (at least 4 on a 1–5 point scale of annoyance; 5 being the worst), while roughly 18% were very annoyed (5 on a 1–5 scale). The equivalent levels of annoyed and very annoyed for 35–40 dB(A) were roughly 15% and 6%, respectively. These percentages, however, should be considered upper bounds for a specific relation with noise levels because, with respect to estimating direct effects of noise, they are likely inflated as a result of both selective participation in the studies and the fact that the percentages do not take into account the effect of seeing a turbine.

Thus, in considering simply exposure to wind turbines in general, while all seem to suggest an association with annoyance, because even the peer-reviewed papers have weaknesses, including the cross sectional designs and sometimes quite low response rates, **the Panel concludes that there is limited evidence suggesting an association between exposure to wind turbines and annoyance.** However, only two of the studies considered both seeing and hearing wind turbines, and even in these the possible contributions of seeing and hearing a wind turbine were not properly disentangled. Therefore, **the Panel concludes that there is insufficient evidence to determine whether there is an association between noise from wind turbines and annoyance independent from the effects of seeing a wind turbine and vice versa.** Even these conclusions must be considered in light of the possibility suggested from one of the peer-reviewed studies that there is extremely low annoyance—regardless of seeing or hearing sound from a wind turbine—among people who benefit economically from the turbines.

There was also the suggestion that poorer sleep was related to wind turbine noise levels. While it intuitively makes sense that more noise would lead to more sleep disruption, there is limited data to inform whether this is occurring at the noise levels produced from wind turbines. An association was indicated in the New Zealand study, suggested without presenting details in one of the Swedish studies, and found in two non-peer-reviewed studies. Therefore, **the Panel concludes that there is limited evidence suggesting an association between noise from wind turbines and sleep disruption and that further study would quantify precise sound levels from wind turbines that disrupt sleep.**

The strongest epidemiological study to examine the association between noise and psychological health suggests there is not an association between noise from wind turbines and measures of psychological distress or mental health problems. There were two smaller, weaker, studies: one did note an association, one did not. Therefore, **the Panel concludes the weight of the evidence suggests no association between noise from wind turbines and measures of psychological distress or mental health problems.**

One Swedish study apparently collected data on headache, undue tiredness, pain and stiffness in the back, neck, or shoulders, or feeling tensed/stressed and irritable, but did not report on analyses of these data. The Dutch study found no association between noise from wind turbines and diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and migraine, although this was not reported in the peer-reviewed literature. Therefore, **the Panel concludes that none of the limited epidemiological evidence reviewed suggests an association between noise from wind turbines and pain and stiffness, diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and headache/migraine.**

These conclusions align with those presented in the peer-reviewed article by Knopper and Ollson (2011). They write "Conclusions of the peer reviewed literature differ in some ways from those in the popular literature. In peer reviewed studies, wind turbine annoyance has been statistically associated with wind turbine noise, but found to be more strongly related to visual impact, attitude to wind turbines and sensitivity to noise. ... it is acknowledged that noise from wind turbines can be annoying to some and associated with some reported health effects (e.g., sleep disturbance), especially when found at sound pressure levels greater than 40 db(A)."

3.4 Exposures from Wind Turbines: Noise, Vibration, Shadow Flicker, and Ice Throw

In addition to the human epidemiologic study literature on exposure to wind turbines and health effects described in the section above, the Panel assessed literature that could shed light on specific exposures resulting from wind turbines and possible health effects. The exposures covered here include noise and vibration, shadow flicker, and ice throw. Each of these exposures is addressed separately in light of their documented and potential health effects. When health effects are described in the popular media, these claims are discussed.

3.4.a Potential Health Effects Associated with Noise and Vibration

The epidemiologic studies discussed above point to noise from wind turbines as a source of annoyance. The studies also noted that some respondents note sleep disruption due to the turbine noise. In this section, the characteristics of audible and inaudible noise from turbines are discussed in light of our understanding of their impacts on human health.

It is clear that when sound levels get too high, the sound can cause hearing loss (Concha-Barrientos et al., 2004). These sound levels, however, are outside the range of what one would experience from a wind turbine. There is evidence that levels of audible noise below levels that cause hearing loss can have a variety of health effects or indicators. Detail about the evidence for such health effects have been well summarized in a WHO report that came to several relevant conclusions (WHO, 2009). First, there is sufficient evidence for biological effects of noise during sleep: increase in heart rate, arousals, sleep stage changes and awakening; second, there is limited evidence that noise at night causes hormone level changes and clinical conditions such as cardiovascular illness, depression, and other mental illness. What the WHO report also details is observable noise threshold levels for these potential effects. For such health effects, where data are sufficient to estimate a threshold level, that level is never below 40 dB(A)—as a yearly average—for noise outside (ambient noise) at night—and these estimates take into account sleeping with windows slightly open.

One difficulty with the WHO threshold estimate is that a yearly average can mask the particular quality of turbine noise that leads survey respondents to note annoyance or sleep disruption. For instance, the pulsatile nature of wind turbine noise has been shown to lead to respondents claiming annoyance at a lower averaged sound level than for road noise (E. Pederson, 2004). Yearly averaging of sound eliminates (or smooths) the fluctuations in the sound and ignores differences between day and night levels. Regulations may or may not take this into account.

Health conditions caused by intense vibration are documented in the literature. These are the types of exposures that result from jackhammers, vibrating hand tools, pneumatic tools, etc. In these cases, the vibration is called arm-body or whole-body vibration. Vibration can cause changes in tendons, muscles, bones and joints, and can affect the nervous system. Collectively, these effects are known as Hand-Arm Vibration Syndrome (HAVS). Guidelines and interventions are intended to protect workers from these vibration-induced effects (reviewed by European Agency for Safety and Health at Work, 2008; (NIOSH 1989). OSHA does not have standards concerning vibration exposure. The American Conference of Governmental Industrial Hygienists (ACGIH) has developed Threshold Limit Values (TLVs) for vibration exposure to hand-held tools. The exposure limits are given as frequency-weighted acceleration (NIOSH, 1989).

3.4.a.i Impact of Noise from Wind Turbines on Sleep

The epidemiological studies indicate that noise and/or vibration from wind turbines has been noted as causing sleep disruption. In this section sleep and sleep disruption are discussed. In addition, suggestions are provided for more definitively evaluating the impact of wind turbines on sleep.

All sounds have the potential to disrupt sleep. Since wind turbines produce sounds, they might cause sleep disruption. A very loud wind turbine at close distance would likely disrupt sleep, particularly in vulnerable populations (such as those with insomnia or mood disorders, aging populations, or "light sleepers"), while a relatively quiet wind turbine would not be expected to disrupt even the lightest of sleepers, particularly if it were placed at considerable distance.

There is insufficient evidence to provide very specific information about how likely particular sound-pressure thresholds of wind turbines are at disrupting sleep. Physiologic studies of noises from wind turbines introduced to sleeping people would provide these specific levels. Borrowing existing data (e.g., Basner, 2011) and guidelines (e.g., WHO) about noises at night, beyond wind turbines, might help provide reasonable judgment about noise limits at night. But it would be optimal to have specific data about the particular influence that wind turbines have on sleep.

In this section we introduce broad concepts about sleep, the interaction of sleep and noises, and the potential for wind turbines to cause that disruption.

Sleep

Sleep is a naturally occurring state of altered consciousness and reduced physical activity that interacts with all aspects of our physiology and contributes daily to our health and well-being.

Measurements of sleep in people are typically performed with recordings that include electroencephalography (EEG). This can be performed in a laboratory or home, and for clinical or experimental purposes. Other physiological parameters are also commonly measured, including muscle movements, lung, and heart function.

While the precise amount of sleep that a person requires is not known, and likely varies across different people and different ages, there are numerous consequences of reduced sleep (i.e., sleep deprivation).

Deficiencies of sleep can take numerous forms, including the inability to initiate sleep; the inability to maintain sleep; abnormal composition of sleep itself, such as too little deep sleep (sometimes called slow-wave sleep, or stage N3); or frequent brief disruptions of sleep, called arousals. Sources of sleep deprivation can be voluntary (desirable or undesirable) or involuntary. Voluntary sources include staying awake late at night or awakening early. These can be for work or school, or while engaging in some personal activities during normal sleep times. Sleep deprivation can also be caused by myriad involuntary and undesired problems (including those internal to the body such as pain, anxiety, mood disorders) and frequent need to urinate, or by numerous sleep disorders (including insomnia, sleep apnea, circadian disorders, parasomnias, sleep-related movement disorders, etc), or simply by the lightening of sleep depth in normal aging. Finally, sleep deprivation can be caused by numerous external factors, such as noises or other sensory information in the sleeper's environment.

Sleep is conventionally categorized into rapid eye movement (REM) and non-REM sleep. Within the non-REM sleep are several stages of sleep ranging from light sleep to deep sleep. Beyond these traditional sleep categories, the EEG signal can be analyzed in a more detailed and sophisticated way, including looking at the frequency composition of the signals. This is important in sleep, as we now know that certain signatures in the brain waves (i.e., EEG) disclose information about who is vulnerable to noise-induced sleep disruption, and what moments within sleep are most vulnerable (Dang-Vu et al., 2010; McKinney et al., 2011).

Insomnia can be characterized by a person having difficulty falling asleep or staying asleep that is not better explained by another condition (such as pain or another sleep disorder) (see ICSD, 2nd Edition for details of the diagnostic criteria for insomnia). Approximately 25% of the general population experience occasional sleep deprivation or insomnia. Sleep deprivation is defined by reduced quantity or quality of sleep, and it can result in excessive daytime sleepiness as well as problems including those associated with mood and cognitive function (Roth et al., 2001; Rogers, 2007; Walker, 2008). As might be expected, the severity of the sleep deprivation has an impact on the level of cognitive functioning, and real-life consequences can include driving accidents, impulsive behaviors, errors in attention, and mood problems (Rogers, 2007; Killgore, 2010). Loss of sleep appears to be cumulative, meaning it adds up night after night. This can result in subtle impairments in reaction times, decision-making ability, attentional vigilance, and integration of information that is sometimes only apparent to the sleep-deprived individual after an accident or error occurs, and sometimes not perceived by the sleep-deprived person at all (Rogers, 2007; van Dongen 2003).

Sleep and Wind Turbines

Given the effects of sleep deprivation on health and well-being, including problems with mood and cognition, it is possible that cognitive and mood complaints and other medical or psychological issues associated with sleep loss can stem from living in immediate proximity to wind turbines, if the turbines disrupt sleep. Existing data, however, on the relationship between wind turbines and sleep are inadequate. Numerous factors determine whether a sound disrupts sleep. Broadly speaking, they are derived from factors about the sleeper and factors about the sound.

Case reports of subjective complaints about sleep, particularly those not critically and objectively appraised in the normal scientific manner, are the lowest level of evidence, not simply because they lack any objective measurements, but also because they lack the level of scrutiny considered satisfactory for making even crude claims about cause and effect. For instance, consider the case of a person who sleeps poorly at home (near a wind turbine), and sleeps better when on vacation (away from a wind turbine). One might conclude from this case that wind turbines cause sleep disruption for this person, and even generalize that information to other people. But there are numerous factors that might make it more likely that a person can sleep well on vacation, having nothing to do with the wind turbine. Furthermore, given the enormous prevalence of sleep disorders, such as insomnia, and the potentially larger prevalence of disorders that impinge on sleep, such as depression, it is crucial that these factors be taken into consideration when weighing the evidence pointing to a causal effect of wind turbines on sleep disruption for the general population. It is also important to obtain objective measurements of sleep, in addition to subjective complaints.

Subjective reports of sleeping well or sleeping poorly can be misleading or even inaccurate. People can underestimate or overestimate the quality of their sleep. Future studies should examine the acoustic properties of wind turbines when assessing the elements that might disrupt sleep. There are unique properties of the noises wind turbines make, and there are some acoustic properties in common with other noises (such as trucks or trains or airplanes). It is important to make these distinctions when assessing the effects of wind turbines on noise, by using data from other noises. Without this physiologic, objective information, the effects of wind turbines on sleep might be over- or underestimated.

It should be noted that not all sounds impair the ability to fall asleep or maintain sleep. To the contrary, people commonly use sound-masking techniques by introducing sounds in the environment that hinder the perception of undesirable noises. Colloquially, this is sometimes called "white noise," and there are certain key acoustic properties to these kinds of sounds that make them more effective than other sounds. Different noises can affect people differently. The emotional valence that is ascribed by an individual to a particular sound can have a major influence on the ability to initiate or maintain sleep. Certain aspects of sounds are particularly alerting and therefore would be more likely to disrupt sleep at lower sound pressure levels. But among those that are not, there is a wide range of responses to these sounds, depending partly on the emotional valence ascribed to them. A noise, for instance, that is associated with a distressing object, is more likely to impede sleep onset.

Finally, characteristics of sleep physiology change across a given night of sleep—and across the life cycle of a person—and are different for different people, including the effects of noise on sleep (e.g., Dang-Vu et al., 2010; McKinney et al., 2011). And some people might initially have difficulty with noises at night, but habituate to them with repeated exposure (Basner, 2011).

In summary, **sleep is a complex biological state, important for health and well-being across a wide range of physiologic functions. To date, no study has adequately examined the influence of wind turbines on sleep.**

Future directions: The precise effects of noise-induced sleep disruption from wind turbines may benefit from further study that examines sound-pressure levels near the sleeper, while simultaneously measuring sleep physiology to determine responses of sleep to a variety of levels of noise produced by wind turbines. The purpose would be to understand the precise sound-pressure levels that are least likely to disturb sleep. It would also be helpful to examine whether sleepers might habituate to these noises, making the impact of a given sound less and less over time. Finally, it would be helpful to study these effects in susceptible populations, including those with insomnia or mood disorders or in aging populations, in addition to the general population.

Summary of Sleep Data

In summary, sleep is a complex biological state, important for health and well-being across a wide range of physiologic functions. **To date, no study has adequately examined the influence of wind turbines and their effects on sleep.**

3.4.b Shadow Flicker Considerations and Potential Health Effects

Shadow flicker is caused when changes in light intensity occur from rotating wind turbine blades that cast shadows (see Appendix B for more details on the physics of the phenomenon.) These shadows move on the ground and on buildings and structures and vary in terms of frequency rate and intensity. Shadow flicker is reported to be less of a problem in the United States than in Northern Europe due to higher latitudes and lower sun angles in Europe. Nonetheless, it can still be a considerable nuisance to individuals exposed to shadow flicker for considerable amounts of time per day or year in the United States as well. Shadow flicker can vary significantly by wind speed and duration, geographic location of the sunlight, and the distance from the turbine blades to any relevant structures or buildings. In general, shadow flicker branches out from the wind turbine in a declining butterfly wing characteristic geographic area with higher amounts of flicker being closer to the turbine and less flicker in the outer parts of the geographic area (New England Wind Energy Education Project (NEWEEP), 2011; Smedley et al., 2010). Shadow flicker is present up until approximately 1400 m, but the strongest flicker is up to 400 m from the turbine when it occurs (NEWEEP, 2011). In addition, shadow flicker usually occurs in the morning and evening close to sunrise and sunset when shadows are the longest. Furthermore, shadow flicker can fluctuate in different seasons of the year depending on the geographic location of the turbine such that some sites will only report flicker during the winter months while others will report it during summer months. Other factors that determine shadow flicker rates and intensity include objects in the landscape (i.e., trees and other existing shadows) and weather patterns. For instance, there is no shadow flicker on cloudy days without sun as compared with sunny days. Also, shadow flicker speed (shadows passing per second) increases with the rotor speed (NRC, 2007). In addition, when several turbines are located relatively close to one another there can be combined flicker from the different blades of the different turbines and conversely, if situated on different geographic areas around structures, shadow flicker can occur at different times of the day at the same site from the different turbines so pre-planning of siting location is very important (Harding et al., 2008). General consensus in Germany resulted in the guidance of 30 hours per year and 30 minutes per day (based on astronomical, clear sky calculations) as acceptable limits for shadow flicker from wind turbines (NRC, 2007). This is similar to the Denmark guidance of 10 hours per year based on actual conditions.

3.4.b.i Potential Health Effects of Flicker

Because some individuals are predisposed to have seizures when exposed to certain types of flashing lights, there has been concern that wind turbines had the potential to cause seizures in these vulnerable individuals. In fact, seizures caused by visual or photic stimuli are typically observed in people with certain types of epilepsy (Guerrini & Genton, 2004), particularly generalized epilepsy. While it is not precisely known how many people have photosensitivity that causes seizures, it appears to be approximately 5% of people with epilepsy, amounting to about 100,000 people in the United States. And many of these people will already be treated with antiepileptic medications thus reducing this risk further.

Fortunately, not all flashing light will elicit a seizure, even in untreated people with known photosensitivity. There are several key factors that likely need to simultaneously occur in order for the stimulus to induce a seizure, even among the fraction of people with photosensitive seizures. The frequency of the stimulus is important as is the stimulus area and pattern (See below) (http://www.epilepsyfoundation.org/aboutepilepsy/seizures/photosensitivity/gerba.cfm).

Frequencies above 10 Hz are more likely to cause epileptic seizures in vulnerable individuals, and seizures caused by photic stimulation are generally produced at frequencies ranging from greater than 5 Hz. However, shadow flicker frequencies from wind turbines are related to the rotor frequency and this usually results in 0.3–1.0 Hz, which is outside of the range of seizure thresholds according to the National Resource Council and the Epilepsy Foundation (NRC, 2007). In fact, studies performed by Harding et al. (2008) initially concluded that because light flicker can affect the entire retina, and even if the eyes are closed that intermittent light can get in the retina, suggested that 4 km would be a safe distance to avoid seizure risk based on shadow flicker (Harding et al., 2008). However, a follow-up analysis considering different meteorological conditions and shadow flicker rates concluded that there appeared to be no risk for seizures unless a vulnerable individual was closer than 1.2 times the total turbine height on land and 2.8 times the total turbine height in the water, which could potentially result in frequencies of greater than 5 Hz (Smedley et al., 2010).

Although some individuals have complained of additional health complaints including migraines, nausea, dizziness, or disorientation from shadow flicker, only one government-sponsored study from Germany (Pohl et al., 1999) was identified for review. This German study was performed by the Institute of Psychology, Christian-Albrechts-University Kiel on behalf of the Federal Ministry of Economics and Technology (BMWi) and supported by the Office of Biology, Energy, and Environment of the Federal Ministry for Education and Research (BMBF), and on behalf of the State Environmental Agency of Schleswig. The purpose of this government-sponsored study was to determine whether periodic shadow with a duration of more than 30 minutes created significant stress-related health effects. The shadows were created by a projection system, which simulated the flicker from actual wind turbines.

Two groups of different aged individuals were studied. The first group consisted of 32 students (average age 23 years). The second group included 25 professionals (average age 47 years). Both men and women were included. The subjects were each randomly assigned to one of two experimental groups, so there was a control group and an experimental group. The experimental group was exposed to 60 minutes of simulated flicker. For the control group lighting conditions were the same as in the experimental group, but without periodic shadow. The main part of the study consisted of a series of six test and measurement phases, two before the light was turned on, three each at intervals of 20 minutes while the simulated shadow flickering was taking place, and one more after the flicker light was turned off. Among the variables measured were general performance indicators of stress (arithmetic, visual search tasks) and those of mental and physical well-being, cognitive processing, and stress in the autonomic nervous system (heart rate, blood pressure, skin conductance, and finger temperature). Systematic effects due to the simulated flicker could be detected in comparable ways in both exposure groups studied. Both physical and cognitive effects were found in this exposure scenario for shadow flicker.

It appears clear that shadow flicker can be a significant annoyance or nuisance to some individuals, particularly if they are wind project non-participants (people who do not benefit economically or receive electricity from the turbine) whose land abuts the property where the turbine is located. In addition, flashing (a phenomenon closely related to shadow flicker, but due to the reflection of sunlight – see Appendix B) can be a problem if turbines are sited too close to highways or other roadways. This could cause dangerous conditions for drivers. Accordingly, turbine siting near highways should be planned so as to reduce flashing as much as possible to protect drivers. However, use of low reflective turbine blades is commonly employed to reduce this potential flashing problem. Provisions to avoid many of these potential health and annoyance problems appear to be employed as current practice in many pre-planning sites with the use of computer programs such as WindPro. These programs can accurately determine shadow flicker rates based on input of accurate analysis area, planned turbine location, the turbine design (height, length, hub height, rotor diameter, and blade width), and residence or roadway locations. Many of these computer programs can then create maps indicating the location and incidence of shadow flicker. Such programs may also provide estimates of daily minutes and hours per year of expected shadow flicker that can then be used for wind turbine planning and siting or for mitigation efforts. Several states require these analyses to be performed before any new turbine projects can be implemented.

3.4.b.ii Summary of Impacts of Flicker

Collectively, although shadow flicker can be a considerable nuisance particularly to wind turbine project non-participants, the evidence suggests that there is no risk of seizure from shadow flicker caused by wind turbines. In addition, there is limited evidence primarily from a German government-sponsored study (Pohl et al., 1999) that prolonged shadow flicker (more than 30 minutes) can result in transient stress-related effects on cognition (concentration, attention) and autonomic nervous system functioning (heart rate, blood pressure). There was insufficient documentation to evaluate other than anecdotal reports of additional health effects including migraines or nausea, dizziness or disorientation. There are documented mitigation methods for addressing shadow flicker from wind turbines and these methods are presented in Appendix B.

3.4.c Ice Throw and its Potential Health Effects

Under certain weather conditions ice may form on the surface of wind turbine blades. Normally, wind turbines intended for use in locations where ice may form are designed to shut down when there is a significant amount of ice on the blades. The means to prevent operation when ice is present may include ice sensor and vibration sensors. Ice sensors are used on most wind turbines in cold climates. Vibration sensors are used on nearly all wind turbines. They would cause the turbine to shut down, for example, if ice buildup on the blades resulted in an imbalance of the rotor and hence detectable vibrations in the structure.

Ice built up on blades normally falls off while the turbine is stationary. If that occurs during high winds, the ice could be blown by the wind some distance from the tower. In addition, it is conceivable that ice could be thrown from a moving wind turbine blade under some circumstances, although that would most likely occur only during startup (while the rotational speed is still relatively low) or as a result of the failure of the control system. It is therefore worth considering the maximum plausible distance that a piece of ice could land from the turbine under two "worst case" circumstances: 1) ice falls from a stopped turbine during very high winds, and 2) ice is suddenly released from a blade when the rotor is rotating at its normal operating speed.

Ice is a physical hazard, that depending on the mass, velocity, and the angle of throw can result in a wide range of effects to humans: alarm and surprise to abrasions, organ damage, concussions, and perhaps death. Avoidance of ice throw is critical. More detail on ice throw and options for mitigation are presented in Appendix C.

3.5 Effects of Noise and Vibration in Animal Models

Domestic animals such as cats and dogs can serve as sentinels of problematic environmental conditions. The Panel searched for literature that might point to non-laboratory animal studies or well-documented cases of animals impacted by wind turbines. Anecdotal reports in the press of goat deaths (UK), premature births and adverse effects in cows (Japan, US) provide circumstantial evidence, but lack specifics regarding background rates of illness or extent of impact.

Laboratory-based animal models are often used to predict and to develop mechanistic explanations of the causes of disease by external factors, such as noise or chemicals in humans. In the absence of robust epidemiological data, animal models can provide clues to complex biological responses. However, the limitations of relying on animal models are well documented, particularly for endpoints that involve the brain. The benefits of using an animal model include ease of experimental manipulation such as multiple exposures, typically well-controlled experimental conditions, and genetically identical groups of animals.

Evaluation of biological plausibility for the multitude of reported health effects of wind turbines requires a suitable animal model documented with data that demonstrate cause and effect. Review of this literature began with a PubMed and ToxNet search for "wind turbine" or "wind turbines"; or "infrasound" or "low frequency noise"; and "animal" or "mammal" to identify peer-reviewed studies in which laboratory animals were exposed to noise or vibration intended to mimic that of wind turbines. Titles and abstracts of identified papers were read to make a first pass determination of whether the paper was a study on effects in mammals or might contain relevant references to other relevant studies. The searches yielded several studies, many of which were not peer-reviewed, were not whole-animal mammalian or were not experimental, but were reviews in which animal studies were mentioned or experiments conducted in dissected cochlea. The literature review yielded eight peer-reviewed studies, all relying on the laboratory rat as the model. The studies fall into two groups—those conducted in the 1970's and early 1980's and those conducted in 2007–2010. The most recent studies are conducted in China and are funded by the National Natural Science Foundation of China. Table AG.1 (in Appendix G) provides a summary of the studies.

There is no general agreement about the specific biological activity of infrasound on rodents, although at high doses it appears to negatively affect the cardiovascular, brain, and respiratory systems (Sienkiewicz, 2007). Early studies lacked the ability to document the doses of infrasound given the rats, did not report general pathologies associated with the exposures and lacked suitable controls. Since then, researchers have focused on the brain and cardiac systems as sensitive targets of infrasound. Experimental conditions in these studies lack a documented rationale for the selection and the use of infrasound of 5-15 Hz at 130 dB. While this appears to be standard practice, the relevance of these frequencies and pressures is unclear—both to the rat and more importantly to the human. The exposures are acute—short-term, high dose. Researchers do not document rat behaviors (including startle responses), pathologies, frank toxicities, and outcomes due to these exposures. Therefore, interpretation of all of the animal model data for infrasound outcomes must be with the lens of any high-dose, short-term exposure in toxicology, specifically questioning whether the observations are readily translatable to low-dose, chronic exposures.

Pei et al., (2007 and 2009) examine changes in cardiac ultrastructure and function in adult male Sprague-Dawley rats exposed to 5 Hz at 130 dB for 2 hours for 1, 7, or 14 successive days. Cardiomyocytes were enzymatically isolated from the adult left ventricular hearts after sacrifice. Whole cell patch-clamp techniques were employed to measure whole cell L-Type Ca^{2+} currents. The objective of these studies was to determine whether there was a cumulative effect of insult as measured by influx of calcium into cardiomyocytes. After infrasound exposure, rats in the 7– and 14–day exposure groups demonstrated statistically significant changes in intracellular Ca^{2+} homeostasis in cardiomyocytes as demonstrated by electrochemical stimulation of the cells, molecular identification of specific heart-protein levels, and calcium transport measurements.

Several studies examine the effects of infrasound on behavioral performance in rats. The first of these studies was conducted under primitive acoustic conditions compared with those of today (Petounis et al., 1977). In this study the researchers examined the behavior of adult female rats (undisclosed strain) exposed to increasing infrasound (2 Hz, 104 dB; 7 Hz, 122 dB; and 16

Hz, 124 dB) for increasing time (5-minute increments for up to 120 minutes). Decreased activity levels (sleeping more) and exploratory behavior were documented as dose and duration of exposure increased. The authors fail to mention that frank toxicity including pain is associated with these behaviors, raising the question of relevance of high dose exposures. In response to this and similar studies that identify increase in sleep, increase in avoidance behaviors and suppression of locomotor activity, Spyraki et al., (1977) hypothesized that these responses are mediated by norepinephrine levels in the brain and as such, exposed adult male Wistar rats to increasing doses of infrasound for one hour. Using homogenized brain tissue, norepinephrine concentrations were measured using fluorometric methods. Researchers demonstrated a dose-dependent decrease in norepinephrine levels in brain tissue from infrasound-treated rats, beginning at a dose of 7 Hz and 122 dB for one hour. No observations of frank toxicity were recorded. Liu et al., (2010) hypothesized that since infrasound could affect the brain, it potentially could increase cell proliferation (neurogenesis) in the dentate gyrus of the rat hippocampus, specifically a region that continues to generate new neurons in the adult male Sprague-Dawley rat. Using a slightly longer exposure period of 2 hours/day for 7 days at 16 Hz and 130 dB, the data suggest that infrasound exposure inhibits cell proliferation in the dentate gyrus, yet has no affect on early migration and differentiation. This study lacks suitable positive and negative controls that allow these conclusions to be drawn.

Several unpublished or non-peer reviewed studies reported behavioral responses as relevant endpoints of infrasound exposure. These data are not discussed, yet are the basis for several recent studies. In one more recent peer-reviewed behavioral rat study, adult male Wistar rats were classified as "superior endurance" and those as "inferior endurance" using the Rota-rod Treadmill (Yamamura et al., 1990). A range of frequencies and pressures were used to expose the rats for 60—150 minutes. Comparison of the pre-exposure endurance time on the Rota-Rod Treadmill with endurance after exposure to infrasound showed that the endurance time of the superior group after exposure to 16 Hz, 105 dB was not reduced. The endurance of the inferior group was reduced by exposure to 16 Hz, 105 dB after 10 minutes, to 16 Hz, 95 dB after 70 minutes, and to 16 Hz, 85 dB after 150 minutes. Of most relevance is the identification of a subset of rats that may be more responsive to infrasound due to their genetic makeup. There has been no follow-up regarding intra-strain susceptibility since this study.

More recent studies have focused on the mechanisms by which infrasound may disrupt normal brain function. As stated above, the infrasound exposures are acute—short-term, high dose. At the very least, researchers should document rat behaviors, pathologies, frank toxicities, and outcomes due to these high dose exposures in addition to measuring specific subcellular effects.

Some of the biological stress literature suggests that microglial activation can occur with heightened stress, but it appears to be short-lived and transitory affecting the autonomic nervous system and neuroendocrine system, resulting in multiple reported effects. To investigate the effect of infrasound on hippocampus-dependent learning and memory, Yuan et al. (2009) measure cognitive abilities and activation of molecular signaling pathways in order to determine the role of the neuronal signaling transduction pathway, BDNF-TRkB, in infrasound-induced impairment of memory and learning in the rat. Adult male Sprague-Dawley rats were exposed to infrasound of 16 Hz and 130 dB for 2 hours daily for 14 days. The acoustic conditions appeared to be well monitored and documented. The Morris water maze was used to determine spatial learning and retention, and molecular techniques were used to measure cell proliferation and concentrations of signaling pathway proteins. Using these semi-quantitative methods, rats exposed to infrasound demonstrated impaired hippocampal-dependent spatial learning acquisition and retention performance in the maze scheme compared with unexposed control rats, demonstrable downregulation of the BDNF-TRkB pathway, and decreased BrdU-labeled cell proliferation in the dentatel gyrus.

In another study, Du et al. (2010) hypothesize that microglial cells may be responsible for infrasound-induced stress. To test this hypothesis, 60 adult male Sprague-Dawley rats were exposed in an infrasonic chamber to 16 Hz at 130 dB for 2 hours. Brains were removed and sectioned and the hypothalamic paraventricular nucleus (PVN) examined. Primary microglial cells were isolated from whole brains of neonatal rats and grown in culture before they were exposed to infrasound under the same conditions as the whole animals. Molecular methods were used to identify the presence and levels of proteins indicative of biological stress (corticotrophin-releasing hormone (CRH) and corticotrophin-releasing hormone receptor (CRH type 1 receptor) in areas of the brain that control the stress response. Specifically, studies were done to determine whether microglial cells are involved in infrasound-response, changes in microglial activation, and CRH-R1 expression in vivo in the PVN and in vitro at time points after the two-hour infrasound exposure. The data show that the exposures resulted in microglial activation, beginning at 0.5 hours post exposure, and up-regulation of CRH-R1 expression. The magnitude of the response increased significantly from the control to 6 hours post exposure, returning to control levels, generally by 24 hours post-exposure. This study is well controlled, and while it does rely on a specific antagonist for dissecting the relative involvement of the neurons and the microglial cells, the data suggest that infrasound as administered in this study to rats can activate microglial cells, suggesting a possible mechanism for infrasound-induced "stress" or nuisance at a physical level (i.e., proinflammatory cytokines causing sickness response behaviors).

In summary, there are no studies in which laboratory animals are subjected to exposures that mimic wind turbines. There is insufficient evidence from laboratory animal studies of effects of low frequency noise on the respiratory system. There is limited evidence that rats are a robust model for human infrasound exposure and effects. The reader is referred to Appendix G for specific study conditions. In any case, the infrasound levels and exposure conditions to which the rodents are exposed are adequate to cause pain to the rodents. When exposed to these levels of infrasound, there is some evidence of reversible molecular effects including short-lived biochemical alterations in cardiac and brain cells, suggesting a possible mechanism for high-dose, infrasound-induced effects in rats.

3.6 Health Impact Claims Associated with Noise and Vibration Exposure

The popular media contain a large number of articles that claim the noise and vibration from wind turbines adversely affect human health. In this section the Panel examines the physical and biological basis for these assertions. Additionally, the scientific articles from which these assertions are made are examined in light of the methods used and their limitations.

Pierpont (2009) has been cited as offering evidence of the physical effects of ILFN, referring to "Wind Turbine Syndrome" and its impact on the vestibular system—by disturbed sensory input to eyes, inner ears, and stretch and pressure receptors in a variety of body locations. The basis for the syndrome relies on data from research carried out for reasons (e.g., space missions) other than assessment of wind turbines on health. Such research can be valuable to understanding new conditions, however, when the presentation of data is incomplete, it can lead to inaccurate conclusions. A few such cases are mentioned here:

Pierpont (2009) notes that von Dirke and Parker (1994) show that the abdominal area resonates between 4 and 6 Hz and that wind turbines can produce infrasound within this range (due to the blade rotation rate). However, the von Dirke paper states that our bodies have evolved to be tolerant of the 4–6 Hz abdominal motion range: this range coincides with jogging and running. The paper also reveals that motion sickness (which was the focus of the study) only occurred when the vibrations to which people were subjected were between 0.01 and 0.5 Hz. The study exposed people to vibration from positive to negative 1 G forces. Subjects were also rotated around various axes to achieve the vibration levels and frequencies of interest in the study. Interpretation of these data may allow one to conclude that while the abdominal area has a resonance in a region at which there is infrasound being emitted by wind turbines, there will be no impact. Further, the infrasound emitted by wind turbines in the range of frequencies at which subjects did note motion sickness is orders of magnitude less than the level that induced motion sickness (see Table 2). So while a connection is made, the evidence at this point is not sufficient to draw a conclusion that a person's abdominal area or stretch point can be excited by turbine infrasound. If it were, this might lead to symptoms of motion sickness.

Pierpont (2009) points to a study by Todd et al. (2008) as potential proof that the inner ear may be playing a role in creating the symptoms of "Wind Turbine Syndrome." Todd et al. (2008) show that the vestibular system shows a best frequency response around 100 Hz. This is a fact, but again it is unclear how it relates to low frequency noise from wind turbines. The best frequency response was assessed by moving subjects' heads (knocking the side of the head) in a very specific direction because the portion of the inner ear that is being discussed acts as a gravitational sensor or an accelerometer; therefore, it responds to motion. A physical mechanism by which the audible sound produced by a wind turbine at 100 Hz would couple to the human body in a way to create the necessary motion to which this portion of the inner ear would respond is unknown.

More recently, Salt and Hullar (2010) have looked for something physical about the ear that could be responding to infrasonic frequencies. They describe how the outer (OHC) and inner (IHC) hair cells of the cochlea respond to different types of stimuli: the IHC responding to velocity and OHC responding to displacement. They discuss how the OHC respond to lower frequencies than the IHC, and how the OHC acts as an amplifier for the IHC. They state that it is known that low frequencies present in a sound signal can mask the higher frequencies—presumably because the OHC is not amplifying the higher frequency correctly when the OHC is responding to low frequency disturbances. However, they emphatically state that "although vestibular hair cells are maximally sensitive to low frequencies they typically do not respond to airborne infrasound. Rather, they normally respond to mechanical inputs resulting from head movements and positional changes with their output controlling muscle reflexes to maintain posture and eye position." It is completely unknown how the very few neural paths from the OHC to the brain respond, if they do at all (95% of the connections are between the IHC and the brain). So at this moment, inner ear experts have not found a method for airborne infrasound to impact the inner ear. The potential exists such that the OHC respond to infrasound, but that the functional role of the connection between the OHC and the brain remains unknown. Further, the modulation of the sound received at the IHC itself has not been shown to cause nausea, headaches, or dizziness.

In the discussion of amplitude-modulated noise, it was already noted that wind turbines produce audible sound in the low frequency regime (20–200Hz). It has been shown that the sound levels in this range from some turbines are above the levels for which subjects in a Korean study have complained of psychological effects (Jung & Cheung, 2008). O'Neal (2011) also shows that the sound pressure level for frequencies between 30 and 200 Hz from two modern wind turbines at roughly 310 m are above the threshold of hearing but below the criterion for creating window rattle or other perceptible vibrations. The issue of vibration is discussed more in the next section. It is noted that the amplitude-modulated noise is most likely at the heart of annoyance complaints. In addition, amplitude-modulated noise may be a source of sleep disturbance noted by survey respondents. However, direct health impacts have not been demonstrated.

3.6.a Vibration

Vibroacoustics disease (VAD) has been identified as a potential health impact of wind turbines in the Pierpont book. Most of the literature around VAD is attributed to Branco and Alves-Pereira. Related citations attributed to Takahashi (2001), Hedge and Rasmussen (1982) though are also provided. These studies all required very clear coupling to large vibration sources such as jackhammers and heavy equipment. The latter references focus on high levels of low frequency vibrations and noise. In particular, Rasmussen studied the response of people to vibrating floors and chairs. The vibration displacements in the study were on the order of 0.01 cm (or 1000 times larger than the motion found 100 m from a wind farm in a seismic study (Styles et al., 2005). Takahashi used loud speakers placed 2 m from subjects' bodies, only testing audible frequencies 20–50 Hz, using pressure levels on the order of 100–110 dB (roughly 30 dB higher than any sound measured from a wind turbine in this frequency range) to induce vibrations at various points on the body. The Hedge source is not a study but a bulleted list of points that seem to go along with a lecture in an ergonomics class for which no citations are provided. Branco's work is slightly different in that she considered very long-term exposures to moderately intense vibration inputs. While there may be possible connection to wind turbines, at present, the connection is not substantiated given the very low levels of vibration and airborne ILFN that have been measured from wind turbines.

While vibroacoustic disease may not be substantiated, vibration levels that lead to annoyance or feelings of uneasiness may be more plausible. Evidence for these responses is discussed below.

Pierpont refers to a paper by Findeis and Peters (2004). This reference describes a situation in Germany where complaints of disturbing sound and vibration were investigated through the measurement of the vibration and acoustics within the dwelling, noting that people complained about vibrations that were not audible. The one figure provided in the text shows that people were disturbed by what was determined to be structure-borne sound that was radiated by walls and floors at levels equivalent to 65 dB at 10 Hz and 40 dB at 100 Hz. The 10 Hz level is just below audible. The level reported at 100 Hz, however, is just above the hearing threshold. The authors concluded that the disturbances were due to a component of the HVAC system that coupled directly to the building.

The Findeis and Peters (2004), report is reminiscent of papers related to investigations of "haunted" spaces (Tandy, 1998, 1999). In these studies room frequencies around 18 Hz were found. The studies hypothesized that apparitions were the result of eye vibrations (the eye is sensitive to 18 Hz) induced by the room vibration field. In one of these studies, a ceiling fan was found to be the source of the vibration. In the other, the source was not identified.

When the source was identified in the previously mentioned studies, there appears to be an obvious physical coupling mechanism. In other situations it has been estimated that airborne disturbances have influenced structures. A NASA report from 1982 gives a figure that estimates the necessary sound pressure level at various frequencies to force vibrations in windows, walls, and floors of typical buildings (Stephens, 1982). The figure on page 14 of that report shows infrasound levels of 70–80 dB can induce wall and floor vibrations. On page 39 the report also shows some floor vibration levels that were associated with a wind turbine. On the graph these were the lowest levels of vibration when compared to vibrations from aircraft noise and sonic booms. Another figure on page 43 shows vibrations and perception across the infrasonic frequency range. Again, wind turbine data are shown, and they are below the perception line.

A second technical report (Kelley, 1985) from that timeframe describes disturbances from the MOD-1 wind turbine in Boone, North Carolina. This was a downwind turbine mounted on a truss tower. Out of 1000 homes within about 2 km, 10 homes experienced room vibrations under certain wind conditions. A careful measurement campaign showed that indeed these few homes had room vibrations related to the impulsive noise unique to downwind turbines. The report contains several findings including the following: 1) the disturbances inside the homes were linked to the impulsive sound generated by the turbine (due to tower wake/blade interaction) and not seismic waves, 2) the impulsive signal was feeding energy into the vibrational modes of the rooms, floors, and walls where the floor/wall modes were the only modes in the infrasonic range, 3) people felt the disturbance more than they heard it, 4) peak vibration values were measured in the frequency range 10–20 Hz (floor/wall resonances) and it was deduced that the wall facing the turbine was being excited, 5) the fact that only 10 homes out of 1000 (scattered in various directions around the turbine) were affected was shown to be related to complicated sound propagation paths, and 6) while the shape of the impulse itself was given much attention and was shown to be a driving force in the coupling to the structural vibrations, comments were made in the report to the effect that nonimpulsive signals with energy at the right frequency could couple into the structure. The report describes a situation in Oregon where resonances in the flow through an exhaust stack of a gas-run turbine plant had an associated slow modulation of the sound leading to annoyance near the plant. Again it was found that structural modes in nearby homes were being excited but this time by an acoustic field that was not impulsive in nature. This is an important point because modern wind turbines do not create impulsive noise with strong content around 20 Hz like the downwind turbine in North Carolina. Instead, they generate amplitude-modulated sound around 1 kHz as well as broadband infrasound (van den Berg, 2004). The broadband infrasound that also existed for the North Carolina turbine was not shown to be responsible for the disturbances. As well, the amplitude-modulated noise that existed was not shown to be responsible for the disturbances. So, while there are comparisons made to the gas turbine power plant and to the HVAC system component where the impulsiveness of the sound was not the same, direct comment on the effect of modern turbines on the vibration of homes is not possible.

A recent paper by Bolin et al. (2011), surveys much of the low frequency literature pertinent to modern wind turbines and notes that all measurements of indoor and outdoor levels of sound simultaneously do not show the same amplification and ringing of frequencies associated with structural resonances similar to what was found in North Carolina. Instead the sound inside is normally less than the sound outside the structure. Bolin et al. (2011) note that measurements indicate that the indoor ILFN from wind turbines typically comply with national guidelines (such as the Danish guideline for 44 dB(A) outside a dwelling). However, this does not preclude a situation where levels would be found to be higher than the standards. They propose that further investigations of an individual dwelling should be conducted if the measured difference between C-weighted and A-weighted sound pressure level of outdoor exposure is greater than 15 dB. A similar criterion is noted in the non-peer reviewed report by Kamperman et al. (2008).

Related to room vibration is window rattle. This topic is described in the NASA reports, discussed above (Stephens, 1982) and discussed in the articles by Jung and Cheung (2008) and O'Neal (2011). In these articles it has been noted that window rattle is often induced by vibrations between 5 and 9 Hz, and measurements from wind turbines show that there can be enough energy in this range to induce window rattle. Whether the window rattle then generates its own sound field inside a room at an amplitude great enough to disturb the human body is unknown.

Seismic transmission of vibration at the North Carolina site was considered. In that study the seismic waves were ruled out as too low of amplitude to induce the room vibrations that were generated. Related are two sets of measurements that were taken near wind farms to assess the potential impact of seismic activity on extremely sensitive seismic measurement stations (Styles, 2005, Schofield, 2010). One study considered both waves traveling in the ground and the coupling of airborne infrasound to the ground, showing that the dominant source of seismic motion is the Rayleigh waves in the ground transmitted directly by the tower, and that the airborne infrasound is not playing a role in creating measurable seismic motion. The two reports indicate that at 100 meters from a wind turbine farm (>6 turbines) the maximum motion that is induced is 120 nanometers (at about 1 Hz). A nanometer is 10^{-9} m. So this is 1.2×10^{-7} m of ground displacement. Extremely sensitive measuring devices have been used to detect this slight motion. To put the motion in perspective, the diameter of a human hair is on the order of 10^{-6} m. These findings indicate that seismic motion induced from one or two turbines is so small that it would be difficult to induce any physical or structural response.

Hessler and Hessler, (2010) reviewed various state noise limits and discussed them in connection with wind turbines. The article contains a few comments related to low frequency noise. It is stated that, "a link between health complaints and turbine noise has only been asserted based on what is essentially anecdotal evidence without any valid epidemiological studies or scientific proof of any kind." The article states that if a metric for low frequency noise is needed, then a limit of 65 dB(C) could be used. This proposed criterion is not flexible for use in different environments such as rural vs. city. In this sense, Bolin et als' suggestion of checking for a difference between C-weighted and A-weighted sound pressure level of outdoor exposure greater than 15 dB is more appropriate. This value of 15 dB, was based on past complaints associated with combustion turbines. The Bolin article, however, also cautions that obtaining accurate low frequency measurements for wind turbines is difficult because of the presence of wind. Even sophisticated windscreens cannot eliminate the ambient low frequency wind noise.

Leventhal (2006) notes that when hearing and deaf subjects are tested simultaneously, the subjects' chests would resonate with sounds in the range of 50–80 Hz. However, the amplitude of the sound had to be 40–50 dB higher than the human hearing threshold for the deaf subjects to report the chest vibration. This leads one to conclude that chest resonance in isolation should not be associated with inaudible sound. If a room is vibrating due to a structural resonance, such levels may be obtained. Again, this effect has never been measured associated with a modern wind turbine.

The stimulation of house resonances and self-reported ill-effects due to a modern wind turbine appear in a report by independent consultants that describes pressure measurements taken inside and outside of a home in Falmouth Massachusetts in the spring of 2011 (Ambrose & Rand, 2011). The measurements were taken at roughly 500 meters from a single 1.65 MW stall-regulated turbine when the wind speeds were relatively high: 20-30 m/s at hub height. The authors noted feeling ill when the dB(A) levels indoors were between 18 and 24 (with a corresponding dB(G) level of 51-64). They report that they felt effects both inside and outside but preferred to be outside where the dB(A) levels ranged from 41-46 (with corresponding dB(G) levels from 54-65.) This is curious because weighted measurements account for human response and the weighted values were higher outside. However, the actual dB(L) levels were higher inside.

The authors present some data indicating that the G-weighted value of the pressure signal is often greater than 60 dB(G), the averaged threshold value proposed by Salt and Hullar (2011) for OHC activation. However, the method used to obtain the data is not presented, and the time scale over which the data are presented (< 0.015 seconds or 66 Hz) is too short to properly capture the low frequency content.

The data analysis differed from the common standard of practice in an attempt to highlight weaknesses in the standard measurement approach associated with the capture of amplitude modulation and ILFN. This departure from the standard is a useful step in defining a measurement technique such as that called for in a report by HGC Engineering (HGC, 2010), that notes policy making entities should "consider adopting or endorsing a proven measurement procedure that could be used to quantify noise at infrasonic frequencies."

The measurements by Ambrose and Rand (2011) show a difference in A and C weighted outdoor sound levels of around 15 dB at the high wind speeds (which is Bolin et. al.'s recommended value for triggering further interior investigations). The simultaneous indoor and outdoor measurements indicate that at very low frequencies (2-6 Hz) the indoor pressure levels are greater than those outdoors. It is useful to note that the structural forcing at the blade-passage-frequency, the time delay and the subsequent ringing that was present in the Boone homes (Kelley, 1985) is not demonstrated by Ambrose and Rand (2011). This indicates that the structural coupling is not forced by the amplitude modulation and is due to a much subtler process. Importantly, while there is an amplification at these lower frequencies, the indoor levels (unweighted) are still far lower than any levels that have ever been shown to cause a physical response (including the activation of the OHC) in humans.

The measurements did reveal a 22.9 Hz tone that was amplitude modulated at approximately the blade passage frequency. The source of the tone was not identified, and no indication as to whether the tone varied with wind speed was provided, a useful step to help determine whether the tone is aerodynamically generated. The level of this tone is shown to be higher than the OHC activation threshold. The 22.9 Hz tone did not couple to the structure and showed the normal attenuation from outside to inside the structure. In order to determine if the results that show potential tonal activation of the OHC are generalizable, it is necessary to identify the source of this tone which could be unique to stall-regulated turbines or even unique to this specific brand of turbine.

Finally, the measurements shown in the report are atypical within the wind turbine measurement literature and the data analysis is not fully described. Also, the report offers no plausible coupling mechanism of the sound waves to the body beyond that proposed by Salt and Hullar (2011). Because of this, the results are suggestive but require corroboration of the measurements and scientifically based mechanisms for human health impact.

3.6.b Summary of Claimed Health Impacts

In this section, the potential health impacts due to noise and vibration from wind turbines was discussed. Both the infrasonic and low frequency noise ranges were considered. Assertions that infrasound and low frequency noise from turbines affect the vestibular system either through airborne coupling to humans are not empirically supported. In the multitude of citations given in the popular media as to methods in which the vestibular system is influenced, all refer to situations in which there is direct vibration coupling to the body or when the wave amplitudes are orders of magnitudes greater than those produced by wind turbines. Recent research has found one potential path in the auditory system, the OHC, in which infrasound might be sensed. There is no evidence, however, that when the OHC sense infrasound, it then leads to any of the symptoms reported by complainants. That the infrasound and low frequency noise couple to humans through the forcing of structural vibration is plausible but has not been demonstrated for modern wind turbines. In addition, should it be shown that such a coupling occurs, research indicates that the coupling would be transient and highly dependent on wind conditions and localized to very few homes surrounding a turbine.

Seismic activity near a turbine due to vibrations transmitted down the tower has been measured, and the levels are too low to produce vibrations in humans.

The audible noise from wind turbines, in particular the amplitude modulated trailing edge noise, does exist, changes level based on atmospheric conditions, can change character from swish to thump-based on atmospheric effects, and can be perceived from home to home differently based on propagation effects. This audible sound has been noted by complainants as a source of annoyance and a cause for sleep disruption. Some authors have proposed nighttime noise regulations and regulations based on shorter time averages (vs. annual averages) as a means to reduce annoyance from this noise source. Some have conjectured that the low frequency content of the amplitude-modulated noise is responsible for the annoyance. They have proposed that the difference between the measured outdoor A- and C- weighted sound pressure levels could be used to identify situations in which the low frequency content is playing a larger role. Further, they note that this difference might be used as part of a regulation as a means to reduce annoyance.

Chapter 4

Findings

Based on the detailed review of the scientific literature and other available reports and consideration of the strength of scientific evidence, the Panel presents findings relative to three factors associated with the operation of wind turbines: noise and vibration, shadow flicker, and ice throw. The findings that follow address specifics in each of these three areas.

4.1 Noise

4.1.a Production of Noise and Vibration by Wind Turbines

1. Wind turbines can produce unwanted sound (referred to as noise) during operation. The nature of the sound depends on the design of the wind turbine. Propagation of the sound is primarily a function of distance, but it can also be affected by the placement of the turbine, surrounding terrain, and atmospheric conditions.
    a. Upwind and downwind turbines have different sound characteristics, primarily due to the interaction of the blades with the zone of reduced wind speed behind the tower in the case of downwind turbines.
    b. Stall regulated and pitch controlled turbines exhibit differences in their dependence of noise generation on the wind speed
    c. Propagation of sound is affected by refraction of sound due to temperature gradients, reflection from hillsides, and atmospheric absorption. Propagation effects have been shown to lead to different experiences of noise by neighbors.
    d. The audible, amplitude-modulated noise from wind turbines ("whooshing") is perceived to increase in intensity at night (and sometimes becomes more of a "thumping") due to multiple effects: i) a stable atmosphere will have larger wind gradients, ii) a stable atmosphere may refract the sound downwards instead of upwards, iii) the ambient noise near the ground is lower both because of the stable atmosphere and because human generated noise is often lower at night.
2. The sound power level of a typical modern utility scale wind turbine is on the order of 103 dB(A), but can be somewhat higher or lower depending on the details of the design and the rated power of the turbine. The perceived sound decreases rapidly with the distance from the wind turbines. Typically, at distances larger than 400 m, sound

pressure levels for modern wind turbines are less than 40 dB(A), which is below the level associated with annoyance in the epidemiological studies reviewed.

3. Infrasound refers to vibrations with frequencies below 20 Hz. Infrasound at amplitudes over 100–110 dB can be heard and felt. Research has shown that vibrations below these amplitudes are not felt. The highest infrasound levels that have been measured near turbines and reported in the literature near turbines are under 90 dB at 5 Hz and lower at higher frequencies for locations as close as 100 m.
4. Infrasound from wind turbines is not related to nor does it cause a "continuous whooshing."
5. Pressure waves at any frequency (audible or infrasonic) can cause vibration in another structure or substance. In order for vibration to occur, the amplitude (height) of the wave has to be high enough, and only structures or substances that have the ability to receive the wave (resonant frequency) will vibrate.

4.1.b Health Impacts of Noise and Vibration

1. Most epidemiologic literature on human response to wind turbines relates to self-reported "annoyance," and this response appears to be a function of some combination of the sound itself, the sight of the turbine, and attitude towards the wind turbine project.
    a. There is limited epidemiologic evidence suggesting an association between exposure to wind turbines and annoyance.
    b. There is insufficient epidemiologic evidence to determine whether there is an association between noise from wind turbines and annoyance independent from the effects of seeing a wind turbine and vice versa.
2. There is limited evidence from epidemiologic studies suggesting an association between noise from wind turbines and sleep disruption. In other words, it is possible that noise from some wind turbines can cause sleep disruption.
3. A very loud wind turbine could cause disrupted sleep, particularly in vulnerable populations, at a certain distance, while a very quiet wind turbine would not likely disrupt even the lightest of sleepers at that same distance. But there is not enough evidence to

provide particular sound-pressure thresholds at which wind turbines cause sleep disruption. Further study would provide these levels.

4. Whether annoyance from wind turbines leads to sleep issues or stress has not been sufficiently quantified. While not based on evidence of wind turbines, there is evidence that sleep disruption can adversely affect mood, cognitive functioning, and overall sense of health and well-being.
5. There is insufficient evidence that the noise from wind turbines is *directly (i.e., independent from an effect on annoyance or sleep)* causing health problems or disease.
6. Claims that infrasound from wind turbines directly impacts the vestibular system have not been demonstrated scientifically. Available evidence shows that the infrasound levels near wind turbines cannot impact the vestibular system.
    a. The measured levels of infrasound produced by modern upwind wind turbines at distances as close as 68 m are well below that required for non-auditory perception (feeling of vibration in parts of the body, pressure in the chest, etc.).
    b. If infrasound couples into structures, then people inside the structure could feel a vibration. Such structural vibrations have been shown in other applications to lead to feelings of uneasiness and general annoyance. The measurements have shown no evidence of such coupling from modern upwind turbines.
    c. Seismic (ground-carried) measurements recorded near wind turbines and wind turbine farms are unlikely to couple into structures.
    d. A possible coupling mechanism between infrasound and the vestibular system (via the Outer Hair Cells (OHC) in the inner ear) has been proposed but is not yet fully understood or sufficiently explained. Levels of infrasound near wind turbines have been shown to be high enough to be sensed by the OHC. However, evidence does not exist to demonstrate the influence of wind turbine-generated infrasound on vestibular-mediated effects in the brain.
    e. Limited evidence from rodent (rat) laboratory studies identifies short-lived biochemical alterations in cardiac and brain cells in response to short exposures to emissions at 16 Hz and 130 dB. These levels exceed measured infrasound levels from modern turbines by over 35 dB.

7. There is no evidence for a set of health effects, from exposure to wind turbines, that could be characterized as a "Wind Turbine Syndrome."
8. The strongest epidemiological study suggests that there is not an association between noise from wind turbines and measures of psychological distress or mental health problems. There were two smaller, weaker, studies: one did note an association, one did not. Therefore, we conclude the weight of the evidence suggests no association between noise from wind turbines and measures of psychological distress or mental health problems.
9. None of the limited epidemiological evidence reviewed suggests an association between noise from wind turbines and pain and stiffness, diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and headache/migraine.

4.2 Shadow Flicker

4.2.a Production of Shadow Flicker

Shadow flicker results from the passage of the blades of a rotating wind turbine between the sun and the observer.

1. The occurrence of shadow flicker depends on the location of the observer relative to the turbine and the time of day and year.
2. Frequencies of shadow flicker elicited from turbines is proportional to the rotational speed of the rotor times the number of blades and is generally between 0.5 and 1.1 Hz for typical larger turbines.
3. Shadow flicker is only present at distances of less than 1400 m from the turbine.

4.2.b Health Impacts of Shadow Flicker

1. Scientific evidence suggests that shadow flicker does not pose a risk for eliciting seizures as a result of photic stimulation.
2. 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.

4.3 Ice Throw

4.3.a Production of Ice Throw

Ice can fall or be thrown from a wind turbine during or after an event when ice forms or accumulates on the blades.

1. The distance that a piece of ice may travel from the turbine is a function of the wind speed, the operating conditions, and the shape of the ice.
2. In most cases, ice falls within a distance from the turbine equal to the tower height, and in any case, very seldom does the distance exceed twice the total height of the turbine (tower height plus blade length).

4.3.b Health Impacts of Ice Throw

1. There is sufficient evidence that falling ice is physically harmful and measures should be taken to ensure that the public is not likely to encounter such ice.

4.4 Other Considerations

In addition to the specific findings stated above for noise and vibration, shadow flicker and ice throw, the Panel concludes the following:

1. Effective public participation in and direct benefits from wind energy projects (such as receiving electricity from the neighboring wind turbines) have been shown to result in less annoyance in general and better public acceptance overall.

Chapter 5

Best Practices Regarding Human Health Effects Of Wind Turbines

Broadly speaking, the term "best practice" refers to policies, guidelines, or recommendations that have been developed for a specific situation. Implicit in the term is that the practice is based on the best information available at the time of its institution. A best practice may be refined as more information and studies become available. The panel recognizes that in countries which are dependent on wind energy and are protective of public health, best practices have been developed and adopted.

In some cases, the weight of evidence for a specific practice is stronger than it is in other cases. Accordingly, best practice* may be categorized in terms of the evidence available, as shown in Table 3:

Table 3

Descriptions of Three Best Practice Categories

Category	Name	Description
1	Research Validated Best Practice	A program, activity, or strategy that has the highest degree of proven effectiveness supported by objective and comprehensive research and evaluation.
2	Field Tested Best Practice	A program, activity, or strategy that has been shown to work effectively and produce successful outcomes and is supported to some degree by subjective and objective data sources.
3	Promising Practice	A program, activity, or strategy that has worked within one organization and shows promise during its early stages for becoming a best practice with long-term sustainable impact. A promising practice must have some objective basis for claiming effectiveness and must have the potential for replication among other organizations.

**These categories are based on those suggested in "Identifying and Promoting Promising Practices." Federal Register, Vol. 68. No 131. 131. July 2003.*
www.acf.hhs.gov/programs/ccf/about_ccf/gbk_pdf/pp_gbk.pdf

5.1 Noise

Evidence regarding wind turbine noise and human health is limited. There is limited evidence of an association between wind turbine noise and both annoyance and sleep disruption, depending on the sound pressure level at the location of concern. However, there are no research-based sound pressure levels that correspond to human responses to noise. A number of countries that have more experience with wind energy and are protective of public health have developed guidelines to minimize the possible adverse effects of noise. These guidelines consider time of day, land use, and ambient wind speed. Table 4 summarizes the guidelines of Germany (in the categories of industrial, commercial and villages) and Denmark (in the categories of sparsely populated and residential). The sound levels shown in the table are for nighttime and are assumed to be taken immediately outside of the residence or building of concern. In addition, the World Health Organization recommends a maximum nighttime sound pressure level of 40 dB(A) in residential areas. Recommended setbacks corresponding to these values may be calculated by software such as WindPro or similar software. Such calculations are normally to be done as part of feasibility studies. The Panel considers the guidelines shown below to be Promising Practices (Category 3) but to embody some aspects of Field Tested Best Practices (Category 2) as well.

Table 4

Promising Practices for Nighttime Sound Pressure Levels by Land Use Type

Land Use	**Sound Pressure Level, dB(A) Nighttime Limits**
Industrial	70
Commercial	50
Villages, mixed usage	45
Sparsely populated areas, 8 m/s wind*	44
Sparsely populated areas, 6 m/s wind*	42
Residential areas, 8 m/s wind*	39
Residential areas, 6 m/s wind*	37

**measured at 10 m above ground, outside of residence or location of concern*

The time period over which these noise limits are measured or calculated also makes a difference. For instance, the often-cited World Health Organization recommended nighttime noise cap of 40 dB(A) is averaged over one year (and does not refer specifically to wind turbine noise). Denmark's noise limits in the table above are calculated over a 10-minute period. These limits are in line with the noise levels that the epidemiological studies connect with insignificant reports of annoyance.

The Panel recommends that noise limits such as those presented in the table above be included as part of a statewide policy regarding new wind turbine installations. In addition, suitable ranges and procedures for cases when the noise levels may be greater than those values should also be considered. The considerations should take into account trade-offs between environmental and health impacts of different energy sources, national and state goals for energy independence, potential extent of impacts, etc.

The Panel also recommends that those involved in a wind turbine purchase become familiar with the noise specifications for the turbine and factors that affect noise production and noise control. Stall and pitch regulated turbines have different noise characteristics, especially in high winds. For certain turbines, it is possible to decrease noise at night through suitable control measures (e.g., reducing the rotational speed of the rotor). If noise control measures are to be considered, the wind turbine manufacturer must be able to demonstrate that such control is possible.

The Panel recommends an ongoing program of monitoring and evaluating the sound produced by wind turbines that are installed in the Commonwealth. IEC 61400-11 provides the standard for making noise measurements of wind turbines (International Electrotechnical Commission, 2002). In general, more comprehensive assessment of wind turbine noise in populated areas is recommended. These assessments should be done with reference to the broader ongoing research in wind turbine noise production and its effects, which is taking place internationally. Such assessments would be useful for refining siting guidelines and for developing best practices of a higher category. Closer investigation near homes where outdoor measurements show A and C weighting differences of greater than 15 dB is recommended.

5.2 Shadow Flicker

Based on the scientific evidence and field experience related to shadow flicker, Germany has adopted guidelines that specify the following:

1. Shadow flicker should be calculated based on the astronomical maximum values (i.e., not considering the effect of cloud cover, etc.).
2. Commercial software such as WindPro or similar software may be used for these calculations. Such calculations should be done as part of feasibility studies for new wind turbines.
3. Shadow flicker should not occur more than 30 minutes per day and not more than 30 hours per year at the point of concern (e.g., residences).
4. Shadow flicker can be kept to acceptable levels either by setback or by control of the wind turbine. In the latter case, the wind turbine manufacturer must be able to demonstrate that such control is possible.

The guidelines summarized above may be considered to be a Field Tested Best Practice (Category 2). Additional studies could be performed, specifically regarding the number of hours per year that shadow flicker should be allowed, that would allow them to be placed in Research Validated (Category 1) Best Practices.

5.3 Ice Throw

Ice falling from a wind turbine could pose a danger to human health. It is also clear that the danger is limited to those times when icing occurs and is limited to relatively close proximity to the wind turbine. Accordingly, the following should be considered Category 1 Best Practices.

1. In areas where icing events are possible, warnings should be posted so that no one passes underneath a wind turbine during an icing event and until the ice has been shed.
2. Activities in the vicinity of a wind turbine should be restricted during and immediately after icing events in consideration of the following two limits (in meters).

For a turbine that may not have ice control measures, it may be assumed that ice could fall within the following limit:

$$x_{\max, throw} = 1.5(2R + H)$$

Where: R = rotor radius (m), H = hub height (m)

For ice falling from a stationary turbine, the following limit should be used:

$$x_{\max, fall} = U(R + H)/15$$

Where: U = maximum likely wind speed (m/s)

The choice of maximum likely wind speed should be the expected one-year return maximum, found in accordance to the International Electrotechnical Commission's design standard for wind turbines, IEC 61400-1.

Danger from falling ice may also be limited by ice control measures. If ice control measures are to be considered, the wind turbine manufacturer must be able to demonstrate that such control is possible.

5.4 Public Participation/Annoyance

There is some evidence of an association between participation, economic or otherwise, in a wind turbine project and the annoyance (or lack thereof) that affected individuals may express. Accordingly, measures taken to directly involve residents who live in close proximity to a wind turbine project may also serve to reduce the level of annoyance. Such measures may be considered to be a Promising Practice (Category 3).

5.5 Regulations/Incentives/Public Education

The evidence indicates that in those parts of the world where there are a significant number of wind turbines in relatively close proximity to where people live, there is a close coupling between the development of guidelines, provision of incentives, and educating the public. The Panel suggests that the public be engaged through such strategies as education, incentives for community-owned wind developments, compensations to those experiencing documented loss of property values, comprehensive setback guidelines, and public education related to renewable energy. These multi-faceted approaches may be considered to be a Promising Practice (Category 3).