

**Wind Turbine Health Impact Study:  
Report of Independent Expert Panel  
January 2012**

**Prepared for:  
Massachusetts Department of Environmental Protection  
Massachusetts Department of Public Health**

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## Table of Contents

<b>Executive Summary</b> .....	<b>ES-1</b>
<b>ES 1 Panel Charge</b> .....	<b>ES-2</b>
<b>ES 2 Process</b> .....	<b>ES-2</b>
<b>ES 3 Report Introduction and Description</b> .....	<b>ES-2</b>
<b>ES 4 Findings</b> .....	<b>ES-4</b>
ES 4.1 Noise.....	ES-4
ES 4.1.a Production of Noise and Vibration by Wind Turbines .....	ES-4
ES 4.1.b Health Impacts of Noise and Vibration .....	ES-5
ES 4.2 Shadow Flicker.....	ES-7
ES 4.2.a Production of Shadow Flicker .....	ES-7
ES.4.2. b Health Impacts of Shadow Flicker.....	ES-7
ES 4.3 Ice Throw .....	ES-8
ES 4.3.a Production of Ice Throw .....	ES-8
ES 4.3.b Health Impacts of Ice Throw.....	ES-8
ES 4.4 Other Considerations .....	ES-8
<b>ES 5 Best Practices Regarding Human Health Effects of Wind Turbines</b> .....	<b>ES-8</b>
ES 5.1 Noise .....	ES-9
ES 5.2 Shadow Flicker.....	ES-11
ES 5.3 Ice Throw .....	ES-12
ES 5.4 Public Participation/Annoyance.....	ES-12
ES 5.5 Regulations/Incentives/Public Education .....	ES-13
<b>Chapter 1: Introduction to the Study</b> .....	<b>1</b>
<b>Chapter 2: Introduction to Wind Turbines</b> .....	<b>3</b>
<b>2.1 Wind Turbine Anatomy and Operation</b> .....	<b>3</b>
<b>2.2 Noise from Turbines</b> .....	<b>6</b>
2.2.a Measurement and Reporting of Noise.....	9
2.2.b Infrasound and Low-Frequency Noise (IFLN).....	10
<b>Chapter 3: Health Effects</b> .....	<b>14</b>
<b>3.1 Introduction</b> .....	<b>14</b>
<b>3.2 Human Exposures to Wind Turbines</b> .....	<b>15</b>
<b>3.3 Epidemiological Studies of Exposure to Wind Turbines</b> .....	<b>15</b>
3.3.a Swedish Studies.....	16
3.3.b Dutch Study .....	19
3.3.c New Zealand Study.....	20
3.3.d Additional Non-Peer Reviewed Documents .....	22
3.3.e Summary of Epidemiological Data.....	27
<b>3.4 Exposures from Wind Turbines: Noise, Vibration, Shadow Flicker, and Ice Throw</b> .....	<b>29</b>
3.4.a Potential Health Effects Associated with Noise and Vibration.....	29
3.4.a.i Impact of Noise from Wind Turbines on Sleep.....	30

3.4.b Shadow Flicker Considerations and Potential Health Effects.....	34
3.4.b.i Potential Health Effects of Flicker .....	35
3.4.b.ii Summary of Impacts of Flicker .....	38
3.4.c. Ice Throw and its Potential Health Effects .....	38
<b>3.5 Effects of Noise and Vibration in Animal Models .....</b>	<b>39</b>
<b>3.6 Health Impact Claims Associated with Noise and Vibration Exposure.....</b>	<b>43</b>
3.6.a Vibration.....	45
3.6.b Summary of Claimed Health Impacts .....	51
<b>Chapter 4: Findings .....</b>	<b>53</b>
<b>4.1 Noise.....</b>	<b>53</b>
4.1.a Production of Noise and Vibration by Wind Turbines.....	53
4.1.b Health Impacts of Noise and Vibration.....	54
<b>4.2 Shadow Flicker .....</b>	<b>56</b>
4.2.a Production of Shadow Flicker.....	56
4.2.b Health Impacts of Shadow Flicker .....	56
<b>4.3 Ice Throw .....</b>	<b>57</b>
4.3.a Production of Ice Throw.....	57
4.3.b Health Impacts of Ice Throw .....	57
<b>4.4 Other Considerations .....</b>	<b>57</b>
<b>Chapter 5: Best Practices Regarding Human Health Effects of Wind Turbines .....</b>	<b>58</b>
<b>5.1 Noise.....</b>	<b>59</b>
<b>5.2 Shadow Flicker .....</b>	<b>61</b>
<b>5.3 Ice Throw .....</b>	<b>62</b>
<b>5.4 Public Participation/Annoyance .....</b>	<b>62</b>
<b>5.5 Regulations/Incentives/Public Education.....</b>	<b>62</b>
<b>Appendix A: Wind Turbines – Introduction to Wind Energy .....</b>	<b>AA-1</b>
<b>AA.1 Origin of the Wind.....</b>	<b>AA-3</b>
<b>AA.2 Variability of the Wind .....</b>	<b>AA-3</b>
<b>AA.3 Power in the Wind .....</b>	<b>AA-7</b>
<b>AA.4 Wind Shear.....</b>	<b>AA-7</b>
<b>AA.5 Wind and Wind Turbine Structural Issues.....</b>	<b>AA-7</b>
AA.5.a Turbulence .....	AA-8
AA.5.b Gusts .....	AA-8
AA.5.c Extreme Winds .....	AA-8
AA.5.d Soils.....	AA-8
<b>AA.6 Wind Turbine Aerodynamics .....</b>	<b>AA-8</b>
<b>AA.7 Wind Turbine Mechanics and Dynamics .....</b>	<b>AA-14</b>
AA.7.a Rotor Motions .....	AA-15
AA.7.b Fatigue .....	AA-17
<b>AA.8 Components of Wind Turbines .....</b>	<b>AA-19</b>
AA.8.a Rotor Nacelle Assembly.....	AA-19
AA.8.b Rotor .....	AA-20
AA.8.c Drive Train.....	AA-21
AA.8.d Shafts .....	AA-21
AA.8.e Gearbox.....	AA-21

WIND TURBINE HEALTH IMPACT STUDY

AA.8.f Brake .....	AA-22
AA.8.g Generator .....	AA-22
AA.8.h Bedplate .....	AA-23
AA.8.i Yaw System .....	AA-23
AA.8.j Control System .....	AA-23
AA.8.k Support Structure .....	AA-23
AA.8.l Materials for Wind Turbines .....	AA-24
<b>AA.9 Installation.....</b>	<b>AA-24</b>
<b>AA.10 Energy Production.....</b>	<b>AA-24</b>
<b>AA.11 Unsteady Aspects of Wind Turbine Operation.....</b>	<b>AA-25</b>
AA.11.a Periodicity of Unsteady Aspects of Wind Turbine Operation.....	AA-26
<b>AA.12 Wind Turbines and Avoided Pollutants .....</b>	<b>AA-26</b>
<b>Appendix B: Wind Turbines – Shadow Flicker .....</b>	<b>AB-1</b>
<b>AB.1 Shadow Flicker and Flashing.....</b>	<b>AB-2</b>
<b>AB.2 Mitigation Possibilities .....</b>	<b>AB-2</b>
<b>Appendix C: Wind Turbines – Ice Throw.....</b>	<b>AC-1</b>
<b>AC.1 Ice Falling or Thrown from Wind Turbines .....</b>	<b>AC-1</b>
<b>AC.2 Summary of Ice Throw Discussion .....</b>	<b>AC-5</b>
<b>Appendix D: Wind Turbine – Noise Introduction.....</b>	<b>AD-1</b>
<b>AD.1 Sound Pressure Level.....</b>	<b>AD-1</b>
<b>AD.2 Frequency Bands .....</b>	<b>AD-2</b>
<b>AD.3 Weightings.....</b>	<b>AD-3</b>
<b>AD.4 Sound Power .....</b>	<b>AD-5</b>
<b>AD.5 Example Data Analysis .....</b>	<b>AD-6</b>
<b>AD.6 Wind Turbine Noise from Some Turbines.....</b>	<b>AD-8</b>
<b>AD.7 Definition of Infrasound.....</b>	<b>AD-9</b>
<b>Appendix E: Wind Turbine – Sound Power Level Estimates and Noise Propagation.....</b>	<b>AE-1</b>
<b>AE.1 Approximate Wind Turbine Sound Power Level Prediction Models.....</b>	<b>AE-1</b>
<b>AE.2 Sound Power Levels Due to Multiple Wind Turbines.....</b>	<b>AE-1</b>
<b>AE.3 Noise Propagation from Wind Turbines .....</b>	<b>AE-2</b>
<b>AE.4 Noise Propagation from Multiple Wind Turbines.....</b>	<b>AE-3</b>
<b>Appendix F: Wind Turbine – Stall vs. Pitch Control Noise Issues .....</b>	<b>AF-1</b>
<b>AF.1 Typical Noise from Pitch Regulated Wind Turbine .....</b>	<b>AF-1</b>
<b>AF.2 Noise from a Stall Regulated Wind Turbine .....</b>	<b>AF-2</b>
<b>Appendix G. Summary of Lab Animal Infrasound and Low Frequency Noise (IFLN) Studies .....</b>	<b>AG-1</b>
<b>References.....</b>	<b>R-1</b>
<b>Bibliography .....</b>	<b>B-1</b>

**List of Tables**

1: Sources of Aerodynamic Sound from a Wind Turbine ..... 7

2: Literature-based Measurements of Wind Turbines .....12

3: Descriptions of Three Best Practice Categories. ....59

4: Promising Practices for Nighttime Sound Pressure Levels by Land Use Type.....60

## 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.

#### **ES 4.1 Noise**

##### ***ES 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.

***ES 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.

## **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.

### ***ES 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.

### **ES 4.3 Ice Throw**

#### ***ES 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).

#### ***ES 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.

### **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](http://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

<b>Land Use</b>	<b>Sound Pressure Level, dB(A) Nighttime Limits</b>
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:

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

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

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

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

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.

### **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<sub>2</sub> 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

## WIND TURBINE HEALTH IMPACT STUDY

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.

WIND TURBINE HEALTH IMPACT STUDY

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 ( $770 \text{ Hz} < f < 2 \text{ kHz}$ )
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

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

the resulting number having the units of decibels (dB). The reference pressure  $p_{\text{ref}}$  for airborne sound is  $20 \times 10^{-6}$  Pa (i.e., 20  $\mu$ Pa 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

<b>Turbine Rating (kW)</b>	<b>Distance (m)</b>	<b>Frequency</b>	<b>Sound Pressure Level</b>	<b>Reference</b>
500	200	5	55 dB(G) <sup>2</sup>	Jakobsen, 2005 <sup>3</sup>
		20	35 dB(G) <sup>2</sup>	
3200	68	4	72 dB(G) <sup>2</sup>	Jakobsen, 2005 <sup>3</sup>
		20	50 dB(G) <sup>2</sup>	
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 <sup>3</sup>
		20	65 dB	
		200	55 dB	
1500	98	1	90 dB	Jung, 2008 <sup>3</sup>
		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 <sup>3</sup>
		20	55 dB(A) - 95	
		100	50 dB(A) - 70	

<sup>1</sup>dB alone refers to un-weighted values.

<sup>2</sup>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).

<sup>3</sup>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 et 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 & Wayne, 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 20<sup>th</sup> 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 WINDFARM perception: 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, 2<sup>nd</sup> 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 (BMW) 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  $\text{Ca}^{2+}$  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  $\text{Ca}^{2+}$  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, Spyraiki 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 effect 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 dentate 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  $1.2 \times 10^{-7}$  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](http://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

<b>Land Use</b>	<b>Sound Pressure Level, dB(A) Nighttime Limits</b>
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:

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

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

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

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

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).

## **Appendix A:**

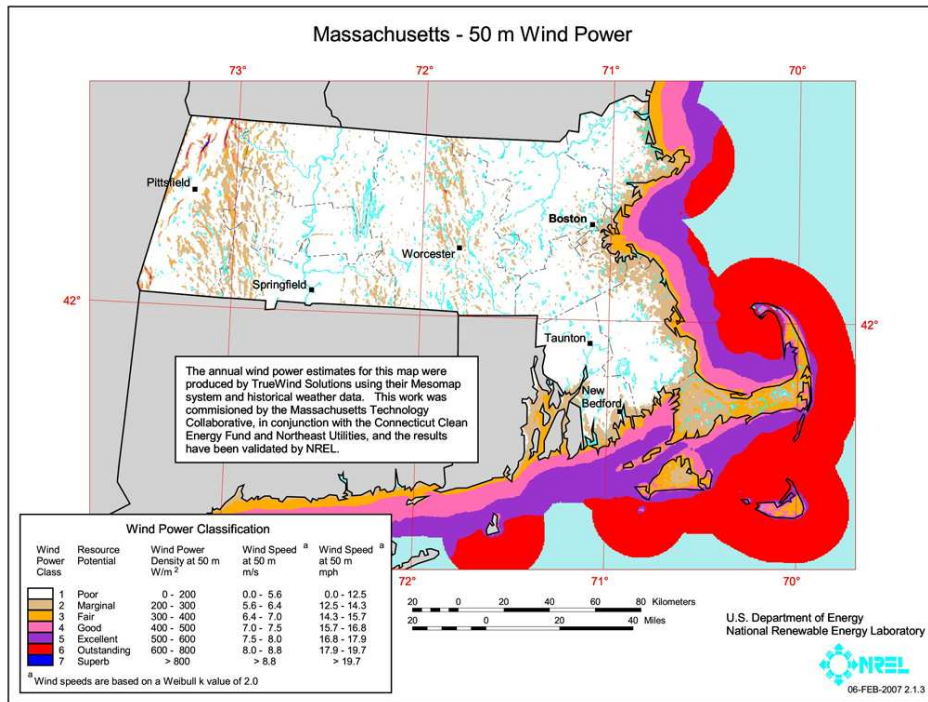
### **Wind Turbines - Introduction to Wind Energy**

Although wind energy for bulk supply of electricity is a relatively new technology, the historical precedents for it go back a long way. They are descendents of mechanical windmills that first appeared in Persia as early as the 7<sup>th</sup> century (Vowles, 1932) and then re-appeared in northern Europe in the Middle Ages. They were considerably developed during the 18<sup>th</sup> and 19<sup>th</sup> centuries, and then formed the basis for the first electricity generating wind turbine in the late 19<sup>th</sup> century. Development continued sporadically through the mid 20<sup>th</sup> century, with modern turbines beginning to emerge in the 1970's. It was the introduction of other technologies, such as electronics, computers, control theory, composite materials, and computer-based simulation capability that led to the successful development of the large scale, autonomously operating wind turbines that have become so widely deployed over the past twenty years.

The wind is the most important external factor in wind energy. It can be thought of as the “fuel” of the wind turbine, even though it is not consumed in the process. The wind determines the amount of energy that is produced, and is therefore referred to as the resource. The wind resource can vary significantly, depending on the location and the nature of the surface. In the United States, the Great Plains have a relatively energetic wind resource. In Massachusetts, winds tend to be relatively low inland, except for mountaintops and ridges. The winds tend to be higher close to the coast and then increase offshore. Average offshore wind speeds generally increase with distance from shore as well. The wind resource of Massachusetts is illustrated in

WIND TURBINE HEALTH IMPACT STUDY

Figure AA.1: Map of the Massachusetts Wind Resource (From National Renewable Energy Laboratory, [http://www.windpoweringamerica.gov/images/windmaps/ma\\_50m\\_800.jpg](http://www.windpoweringamerica.gov/images/windmaps/ma_50m_800.jpg))



This section summarizes the basic characteristics of the wind in so far as they relate to wind turbine power production. Much more detail on this topic is provided in (Manwell et al., 2009). The wind will also affect the design of the wind turbines, and for this purpose it is referred to as an “external design condition.” This aspect of the wind is discussed in more detail in a later section.

### **AA.1 Origin of the Wind**

The wind 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 earth's rotation. Considerations regarding the wind insofar as it relates to wind turbine operation include the following: (i) the winds aloft (geostrophic wind), (ii) atmospheric boundary layer meteorology, (iii) the variation of wind speed with height, (iv) surface roughness, and (v) turbulence.

The geostrophic wind is the wind in the upper atmosphere, which results from the combined effects of the pressure gradient and the earth's rotation (via the Coriolis force). The gradient wind can be thought of as an extension of the geostrophic wind, the difference in this case being that centrifugal effects are included. These result from curved isobars (lines of constant pressure) in the atmosphere. It is these upper atmosphere winds that are the source of most of the energy that eventually impinges on wind turbines. The energy in the upper atmosphere is transferred down closer to the surface via a variety of mechanisms, most notably turbulence, which is generated mechanically (via surface roughness) and thermally (via the rising of warm air and falling of cooler air).

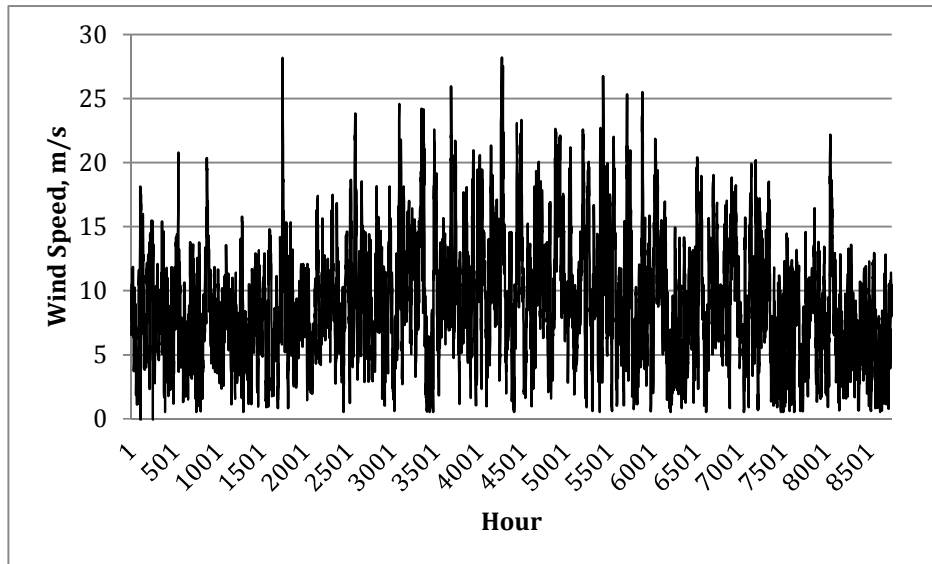
Although driven by higher altitude winds, the wind near the surface is affected by the surrounding topography (such as mountains and ridges) and surface conditions (such as tree cover or presence of buildings).

### **AA.2 Variability of the Wind**

One of the singular characteristics of the wind is its variability, both temporal and spatial. The temporal variability includes: (i) short term (gusts and turbulence), (ii) moderately short term (e.g., hr to hr means), (iii) diurnal (variations over a day), (iv) seasonal, and (v) inter-annual (year to year). The wind may vary spatially as well, both from one location to another or with height above ground.

Figure AA.2 illustrates the variability of the hourly average wind speeds for one year at one location.

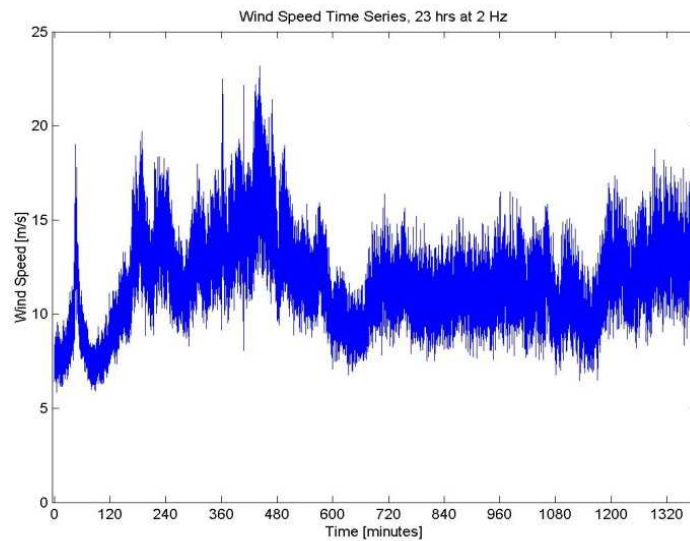
Figure AA.2: Typical hourly wind speeds over a year



As can be seen, the hourly average wind speed in this example varies significantly over the year, ranging from zero to nearly 30 m/s.

Figure AA.3 illustrates wind speed at another location recorded twice per second over a 23-hour period. There is significant variability here as well. Much of this variability in this figure is associated with short-term fluctuations, or turbulence. Turbulence has some effect on power generation, but it has a more significant effect on the design of wind turbines, due to the material fatigue that it tends to engender. Turbulence is discussed in more detail in a later section.

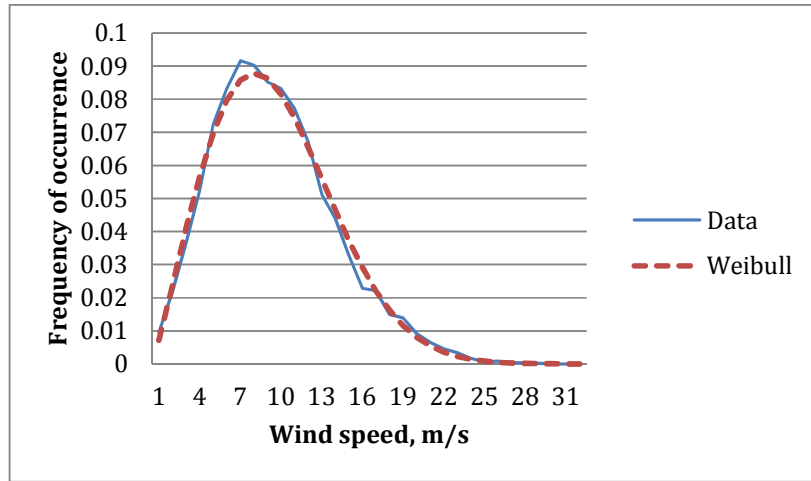
Figure AA.3: Typical wind data, sampled at 2 Hz for a 23-hr period



In spite of the variability in the wind time series, summary characteristics have much less variability. For example, the annual mean wind speed at a given location is generally within  $\pm 10\%$  of the long-term mean at that site. Furthermore, the distribution of wind speeds, that is to say the frequency of occurrence of winds in various wind speed ranges, also tends to be similar from year. The general shape of such distributions is also similar from one location to another, even if the means are different. In fact, statistical models such as the Weibull distribution can be used to model the occurrences of various wind speeds in most locations on the earth. For example, the number of occurrences of wind speed in various ranges from the data set illustrated in Figure AA.2 are shown in Figure AA.4, together with the those occurrences as modeled by the Weibull distribution.



Figure AA.4: Typical frequency of occurrence of wind speeds, based on data and statistical model



The Weibull distribution's probability density function is given by:

$$p(U) = \left(\frac{k}{c}\right) \left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^k\right] \quad (1)$$

Where  $c$  = Weibull scale factor (m/s) and  $k$  = Weibull shape factor (dimensionless)

For the purposes of modeling the occurrences of wind speeds, the scale and shape factors may be approximated as follows:

$$k \approx \left(\frac{\sigma_U}{\bar{U}}\right)^{-1.086} \quad (2)$$

$$c \approx \bar{U} (0.568 + 0.433 / k)^{-(1/k)} \quad (3)$$

Where  $\bar{U}$  is the long-term mean wind speed (m/s, based on 10 min or hourly averages) and  $\sigma_U$  is the standard deviation of the wind speed, based on the same 10 min or hourly averages.

### AA.3 Power in the Wind

The power available in the wind can be predicted from the fundamental principles of fluid mechanics. First of all, the energy per unit mass of a particle of air is given simply by  $\frac{1}{2}$  times the square of the velocity,  $U$  (m/s). The mass flow rate of the air (kg/s) through a given area  $A$  ( $\text{m}^2$ ) perpendicular to the direction of the wind is  $\dot{m} = \rho AU$ , where  $\rho$  is the density of the air ( $\text{kg}/\text{m}^3$ ). The power in the wind per unit area,  $P/A$ , ( $\text{W}/\text{m}^2$ ) is then:

$$P/A = (\dot{m}/A) \frac{1}{2} U^2 = \frac{1}{2} \rho U^3 \quad (4)$$

### AA.4 Wind Shear

Wind shear is the variation of wind speed with height. Wind shear has relevance to power generation, to turbine design, and to noise generation. The variation of wind speed with height is typically modeled with a power law as follows:

$$U_2 = U_1 [h_2 / h_1]^\alpha \quad (5)$$

Where  $U_1$  = speed at reference height  $h_1$ ,  $U_2$  is the wind speed to be estimated at height  $h_2$  and  $\alpha$  is the power law exponent. Values of the exponent typically range from a 0.1 for smooth surfaces to 0.4 for very rough surfaces (such as forests or built-up areas.)

Wind shear can also be affected by the stability of the atmosphere. Equations have been developed that allow the incorporation of stability parameters in the analysis, but these too are outside the scope of this overview.

### AA.5 Wind and Wind Turbine Structural Issues

As discussed previously, the wind is of particular interest in wind turbine applications, since it is the source of the energy. It is also the source of significant structural loads that the turbine must be able to withstand. Some of these loads occur when the turbine is operating; others occur when it is stopped. Extreme winds, for example, are likely to affect a turbine when it is stopped. High winds with sudden directional change during operation can also induce high loads. Turbulence during normal operation results in fatigue. The following is a summary of the key aspects of the wind that affect the design of wind turbines. More details may be found in (Manwell et al., 2009).

### **AA.5.a Turbulence**

Turbulence in the wind can have significant effect on the structure of a wind turbine as well as its operation, and so it must be considered in the design process. The term “turbulence” refers to the short-term variations in the speed and direction of the wind. It manifests itself as apparently random fluctuations superimposed upon a relatively steady mean flow. Turbulence is not actually random, however. It has some very distinct characteristics, at least in a statistical sense.

Turbulence is characterized by a number of measures. These include: (i) turbulence intensity, (ii) turbulence probability density functions (pdf), (iii) autocorrelations, (iv) integral time scales and length scales, and (v) power spectral density functions. Discussion of the physics of turbulence is outside the scope of this overview.

### **AA.5.b Gusts**

A gust is discrete increase and then decrease in wind speed, possibly associated with a change in wind direction, which can be of significance to the design of a wind turbine. Gusts are typically associated with turbulence.

### **AA.5.c Extreme Winds**

Extreme winds need to be considered for the design of a wind turbine. Extreme winds are normally associated with storms. They occur relatively rarely, but often enough that the possibility of their occurring cannot be ignored. Statistical models, such as the Gumbel distribution (Gumbel, 1958), are used to predict the likelihood of such winds occurring at least once every 50 or 100 years. Such intervals are called return periods.

### **AA.5.d Soils**

Soils are also important for the design and installation of a wind turbine. In particular, the nature of the soil will affect the design of the wind turbine foundations. Discussion of soils is outside the scope of this overview.

## **AA.6 Wind Turbine Aerodynamics**

The heart of the wind turbine is the rotor. This is a device that extracts the kinetic energy from the wind and converts it into a mechanical form. Below is a summary of wind turbine rotor aerodynamics. More details may be found in (Manwell et al., 2009).

A wind turbine rotor is comprised of blades that are attached to a hub. The hub is in turn attached to a shaft (the main shaft) which transfers the energy through the remainder of the drive

train to the generator where it is converted to electricity. The maximum power that a rotor can extract from the wind is first of all limited by the power in the wind, which passes through an area defined by the passage of the rotor. At the present time, most wind turbines utilize a rotor with a horizontal axis. That is, the axis of rotation is (nominally) parallel to the earth's surface. Accordingly, the area that is swept out by the rotor is circular. Assuming a rotor radius of  $R$  (m), the maximum power  $P$  (W) available in the wind is:

$$P = \frac{1}{2} \rho \pi R^2 U^3 \quad (6)$$

Early in the 20<sup>th</sup> century, it was shown by Betz (among others, see [4]) that the maximum power that could be extracted was less than the power in the wind; in fact, it was 16/27 times that value. Betz' work led to the definition of a power coefficient,  $C_p$ , which expresses the ratio of the actual power extracted by a rotor to the power in the wind. When considering efficiencies of other components in the drive train, as expressed by the  $\eta$ , the total power out a wind turbine,  $P_{WT}$ , would be given by:

$$P_{WT} = C_p \eta \frac{1}{2} \rho \pi R^2 U^3 \quad (7)$$

The maximum value of the power coefficient, known as the Betz limit, is thus 16/27.

Betz' original analysis was based on the fundamental principles of fluid mechanics including linear momentum theory. It also included the following assumptions: (i) homogenous, incompressible, steady state fluid flow; (ii) no frictional drag; (iii) a rotor with an infinite number of (very small) blades; (iv) uniform thrust over the rotor area; (v) a non-rotating wake; and (vi) the static pressure far upstream and far downstream of the rotor that is equal to the undisturbed ambient static pressure.

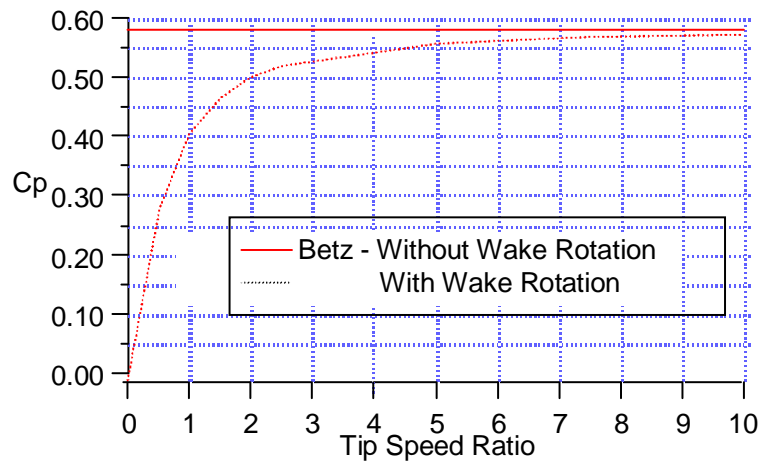
A real rotor operating on a horizontal axis will result in a rotating wake. Some of the energy in the wind will go into that rotation and will not be available for conversion into mechanical power. The result is that the maximum power coefficient will actually be less than the Betz limit. The derivation of the maximum power coefficient for the rotating wake case use a number of terms: (i) the rotational speed of turbine rotor,  $\Omega$ , in radians/sec; (ii) tip speed ratio,  $\lambda = \Omega R / U$ ; (iii) local speed ratio,  $\lambda_r = \lambda r / R$ ; (iv) rotational speed of wake,  $\omega$ ; (v) an axial induction factor,  $a$ , which relates the free stream wind speed to the wind speed at the rotor and

the wind speed in the far wake ( $U_{rotor} = (1 - a)U_{free\ stream}$  and  $U_{wake} = (1 - 2a)U_{free\ stream}$ ); and (vi) an angular induction factor,  $a' = \omega/2 \Omega$ . According to this analysis, the maximum possible power coefficient is given by:

$$C_{P,max} = \frac{8}{\lambda^2} \int_0^\lambda a'(1-a)\lambda_r^3 d\lambda_r \tag{8}$$

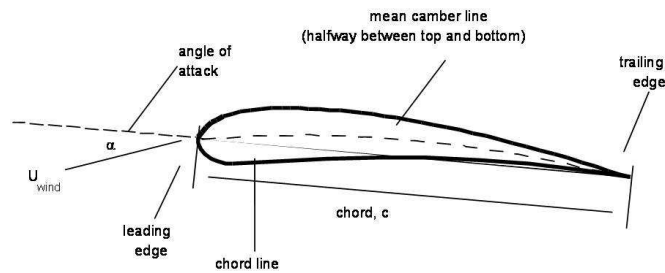
The maximum power coefficient for a rotor with a rotating wake and the Betz limit are illustrated in Figure AA.5.

Figure AA.5: Maximum theoretical power coefficients for rotating and non-rotating wakes



Neither of the analyses summarized above gives any indication as to what the blades of the rotor actually look like. For this purpose, a method called blade element momentum (BEM) theory was developed. This approach assumes that the blades incorporate an airfoil cross section. Figure AA.6 shows a typical airfoil, including some of the nomenclature.

Figure AA.6: Airfoil nomenclature



The BEM method equates the forces on the blades associated with air flowing over the airfoil with forces associated with the change in momentum of the air passing through the rotor. The starting point for this analysis is the assessment of the lift force on an airfoil. Lift is a force perpendicular to the flow. It is given by

$$\tilde{F}_L = C_L \frac{1}{2} \rho c U^2 \quad (9)$$

Where:

$\tilde{F}_L$  = force per unit length, N/m

$C_L$  = lift coefficient, -

$c$  = chord length (distance from leading edge to trailing edge of airfoil, m)

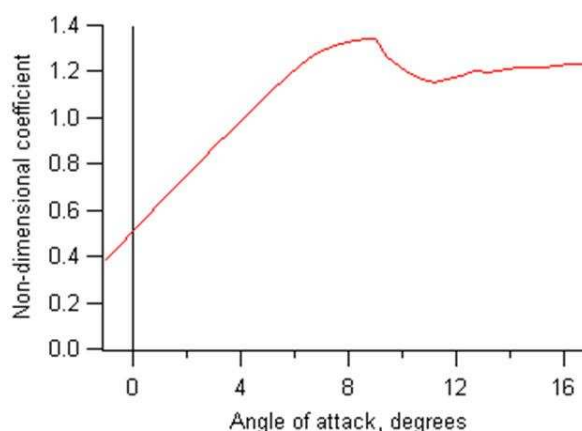
Thin airfoil theory predicts that for a very thin, ideal airfoil the lift coefficient is given by

$$C_L = 2\pi \sin \alpha \quad (11)$$

where  $\alpha$  is the angle of attack, which is the angle between the flow and the chord line of the airfoil.

The lift coefficient for real airfoils typically includes a constant term but the slope, at least for low angles of attack, is similar to that for an ideal airfoil. For greater angles of attack (above 10–15 degrees) the lift coefficient begins to decrease, eventually approaching zero. This is known as stall. A typical lift coefficient vs. angle of attack curve is illustrated in Figure AA.7.

Figure AA.7: Typical airfoil lift vs. angle of attack



There is always some drag force associated with fluid flow. This is a force in line with the flow. Drag force (per unit length) is given by:

$$\tilde{F}_D = C_D \frac{1}{2} \rho c U^2 \quad (12)$$

Where  $C_D$  = drag coefficient

When designing blades for a wind turbine, it is generally desired to minimize the drag to lift ratio at the design point. This generally results in a lift coefficient in the vicinity of 1.0 and a drag coefficient of approximately 0.006, although these values can differ depending on the airfoil.

Blade element momentum theory, as noted above, relates the blade shape to its performance. The following approach is used. The blade is divided into elements and the rotor is divided into annuli. Two simultaneous equations are developed: one expresses the lift and drag coefficient (and thus forces) on the blade elements as a function of airfoil data and the wind's angle of attack. The other expresses forces on the annuli as a function of the wind through the rotor, rotor characteristics, and changes in momentum. Some of the key assumptions are: (i) the forces on blade elements are determined solely by lift/drag characteristics of the airfoil, (ii) there is no flow along the blade, (iii) lift and drag force are perpendicular and parallel respectively to a "relative wind," and (iv) forces are resolved into components perpendicular to the rotor ("thrust") and tangential to it ("torque").

Using BEM theory, it may be shown for an ideal rotor that the angle of relative wind,  $\phi$ , as a function of tip speed ratio and radial position on the blade is given by:

$$\varphi = \left(\frac{2}{3}\right) \tan^{-1}(1/\lambda_r) \quad (13)$$

Similarly, the chord length is given by:

$$c = \frac{8\pi r}{BC_L} (1 - \cos\varphi) \quad (14)$$

Where  $B$  = the number of blades

There are some useful observations to be drawn out of the above equations. First of all, in the ideal case the blade will be twisted. In fact, the twist angle will differ from the angle of relative wind by the angle of attack and a reference pitch angle  $\theta_p$  as follows:

$$\theta_T = \varphi - \alpha - \theta_p \quad (15)$$

It may also be noted that the twist angle will at first increase slowly when moving from the tip inward and then increase more rapidly. Second, the chord of the blade will also increase upon moving from the tip inward, at first slowly and then more rapidly. In the ideal case then, a wind turbine blade is both significantly twisted and tapered. Real blades, however, are designed with a less than optimal shape for a variety of practical reasons.

Another important observation has to do with the total area of the blades in comparison to the swept area. The ratio of the projected blade area is known as the solidity,  $\sigma$ . For a given angle of attack, the solidity will decrease with increasing tip speed ratio. For example, assuming a lift coefficient  $C_L$  of 1.0, the solidity of an optimum rotor designed to operate at a tip speed ratio of 2.0 is 0.43 whereas an optimum rotor designed to operate at a tip speed ratio of 6.0 would have a solidity of 0.088. It is therefore apparent that in order to keep blade material (and thus cost) to a minimum, it is desirable to design for a tip speed ratio as high as possible.

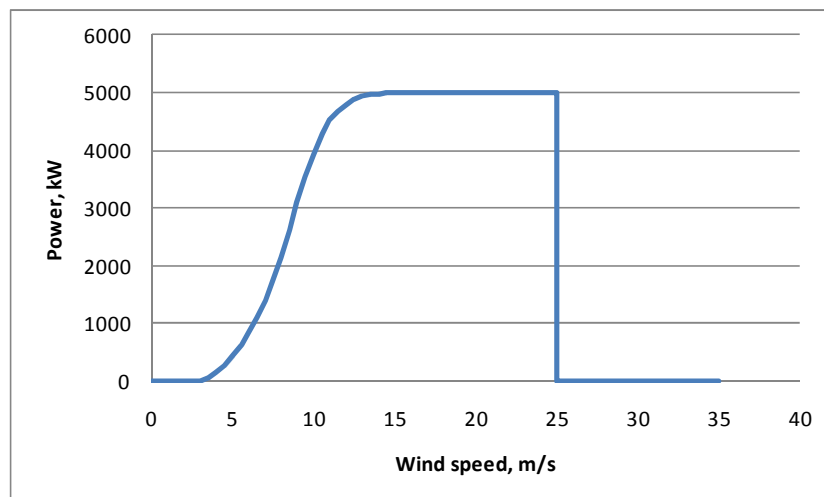
There are other considerations in selecting a design tip speed ratio for a turbine other than the solidity, however. On the one hand, higher tip speed ratios will result in gearboxes with a lower speed up ratio for a given turbine. On the other hand, the effect of drag and surface roughness of the blade surface may become more significant for a higher tip speed ratio rotor. This effect could result in decreased performance. Another concern is material strength. The total forces on the rotor are nearly the same on the rotor regardless of the solidity. Thus the stresses would be higher. A final consideration is noise. Higher tip speed ratios generally result in more noise produced by the blades.



There are numerous other considerations regarding the design of a wind turbine rotor, including tip losses, type of airfoil to be used, ease of manufacturing and transport, type of control used, selection of materials, etc. These are all outside the scope of this overview, however.

Real wind turbine rotors are designed taking into account many factors, including but not only their aerodynamic performance. In addition, the rotor must be controlled so as to generate electricity most effectively and so as to withstand continuously fluctuating forces during normal operation and extreme loads during storms. Accordingly, a wind turbine rotor does not in general 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 curve, known as a power curve, rather than an equation such as the one for  $P_{WT}$  which given earlier. Figure AA.8 illustrates a typical power curve. As shown there, below the cut-in speed (3 m/s in the example) no power is produced. Between cut-in and rated wind speed (14.5 m/s in this example), 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 (25 m/s in the example), the turbine is shut down.

Figure AA.8: Typical wind turbine power curve



### AA.7 Wind Turbine Mechanics and Dynamics

Earlier we discussed the aerodynamic aspects of a wind turbine, and how that related to its design, performance, and appearance. The next major consideration has to do with the turbine's survivability. This topic includes its ability to withstand the forces to which the turbine

will be subjected, deflections of various components, and vibrations that may result during operations.

Issues that need to be considered include: (i) ultimate strength, (ii) relative motion of components, (iii) vibrations, (iv) loads, (v) responses, (vi) stresses, (vii) unsteady motion, resulting in fatigue, and (viii) material properties.

The types of loads that a turbine may be subjected to are as follows: static (non-rotating), steady (rotating), cyclic, transient, impulsive, stochastic, or resonance-induced. Sources of loads may include aerodynamics, gravity, dynamic interactions, or mechanical control. To understand the various loads that a wind turbine may experience, the reader may wish to review the fundamentals of statics (no motion), dynamics (motion), Newton's second law, the various rotational relations (kinematics), strength of materials (including Hooke's law and finding stresses from moments and geometry), gyroscopic forces/moments, and vibrations. Among other topics, the cantilevered beam is particularly important, since rotor blades as well as towers have similar characteristics.

Wind turbines are frequently both the source of and are subject to vibrations. Although the topic can become quite complicated, it is worthwhile to recall that the natural frequency of simple oscillating mass,  $m$ , and spring, with spring constant,  $k$ , and is given by:

$$\omega = \sqrt{k/m} \quad (16)$$

Similarly, rotational natural frequency about an axis of rotation is given by:

$$\omega = \sqrt{k_{\theta}/J} \quad (17)$$

Where  $k_{\theta}$  is the rotational spring constant and  $J$  is the mass moment of inertia

A continuous body, such as a wind turbine blade, will actually have an infinite number of natural frequencies (although only the first few are important), and associated with each natural frequency will be a mode shape that characterizes its deflection. The vibration of a uniform cantilevered beam can be described relatively simply through the use of Euler's equation (see Manwell et al., 2009). Non-uniform elements require more complex methods for their analysis.

### **AA.7.a Rotor Motions**

There is a variety of motions that occur in the rotor that can be significant to the design or operation of the turbine. These include those in the flapwise, edgewise, and torsional directions.

Flapwise motions are those that are perpendicular to plane of the rotor, and are considered positive in the direction of the thrust. Flapwise forces are the source of the highest aerodynamic bending moments, and accordingly the most significant stresses.

Lead-lag, or edgewise, motions are in plane of rotor and are considered positive when in the direction of the torque. Fluctuating motions in this direction are reflected in the power.

Torsion refers to the twisting of blade about its long axis. Torsional moments in the blades must be accounted for in the design of pitch control mechanisms.

The most important rotor load is the thrust. This is the total force on the rotor in the direction of the wind (flapwise). It is associated with the conversion of the kinetic energy of the wind to mechanical energy. The thrust,  $T$ , (N) is given by:

$$T = C_T \frac{1}{2} \rho \pi R^2 U^2 \quad (18)$$

Where  $C_T$  is the thrust coefficient. For the ideal rotor in which the axial induction factor,  $a$ , is equal to 1/3 (corresponding to the Betz limit), it is easy to show that the thrust coefficient is equal to 8/9. For the same rotor, the thrust coefficient may be as high as 1.0, but this would not occur at  $C_p = C_{p,Betz}$ .

This thrust gives rise to flapwise bending moments at the root of the blade. For example, for the ideal rotor when  $a = 1/3$ , and assuming a very small hub, it may be shown that the flapwise bending moment  $M_\beta$  at the root of the blade would be given by:

$$M_\beta = \frac{T}{B} \frac{2}{3} R \quad (19)$$

Where  $B$  = number of blades

From the bending moment, it is straightforward to find the maximum bending stress in the blade. For example, suppose that a blade is  $2t$  m thick at the root, has a symmetrical airfoil, and that the thrust force is perpendicular to the chord line. Then the bending stress would be:

$$\sigma_{\beta,\max} = \frac{M_\beta t}{I_b} \quad (20)$$

(Note that for a real blade, the asymmetry and the angles would complicate the calculation, but the principle is the same.)

Another important load is torque,  $Q$  (Nm). Torque is given by:

$$Q = C_Q \frac{1}{2} \rho \pi R^2 U^2 \quad (21)$$

Where  $C_Q$  = the torque coefficient, which also equal to  $C_P/\lambda$ .

Note that torque is also given by:

$$Q = P / \Omega \quad (22)$$

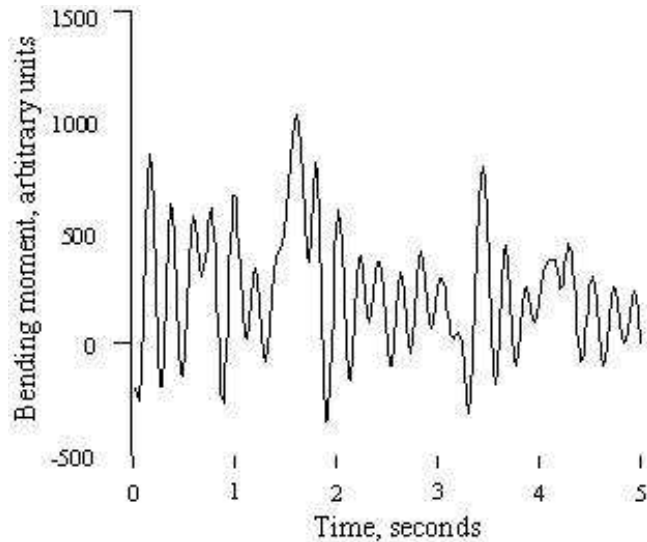
Where  $P$  = power (W)

The dynamics of a wind turbine rotor are quite complicated and do not lend themselves to simple illustrations. There is one approach, however, due to Stoddard (Eggleston and Stoddard, 1987) and summarized by (Manwell et al., 2009) which is relatively tractable, but will not be discussed here. In general, the dynamic response of wind turbine rotors must be simulated by numerical models, such as the FAST code (Jonkman, 2005) developed by the National Renewable Energy Laboratory.

#### **AA.7.b Fatigue**

Fatigue is an important phenomenon in all wind turbines. The term refers to the degradation of materials due to fluctuating stresses. Such stresses occur constantly in wind turbines due to the inherent variability of the wind, the rotation of the rotor and the yawing of the rotor nacelle assembly (RNA) to follow the wind as its direction changes. Fatigue results in shortened life of many materials and must be accounted for in the design. Figure AA.9 illustrates a typical time history of bending moment that would give rise to fluctuating stresses of similar appearance.

Figure AA.9: Typical wind turbine blade bending moment



The ability of a material to withstand stress fluctuations of various magnitudes is typically illustrated in an S-N curve. In such curves the stress level is shown on the y axis and is plotted against the number of cycles to failure. As is apparent from the figure above, stress fluctuations of a variety of magnitudes are likely. The effect of a number of cycles of different ranges is accounted for by the damage due to each cycle using “Miner’s Rule.” In this case, an amount of damage,  $d$ , due to  $n$  cycles, where the stress is such that  $N$  cycles will result in damage is found as follows:

$$d = n / N \tag{23}$$

Miner’s Rule states that the sum of all the damage,  $D$ , from cycles of all magnitudes must be less than 1.0, or failure is to be expected imminently:

$$D = \sum n_i / N_i \leq 1 \tag{24}$$

Miner’s Rule works best when the cycling is relatively simple. When cycles of varying amplitude follow each other, an algorithm called "rainflow" cycle counting” (Downing and Socie, 1982) is used.

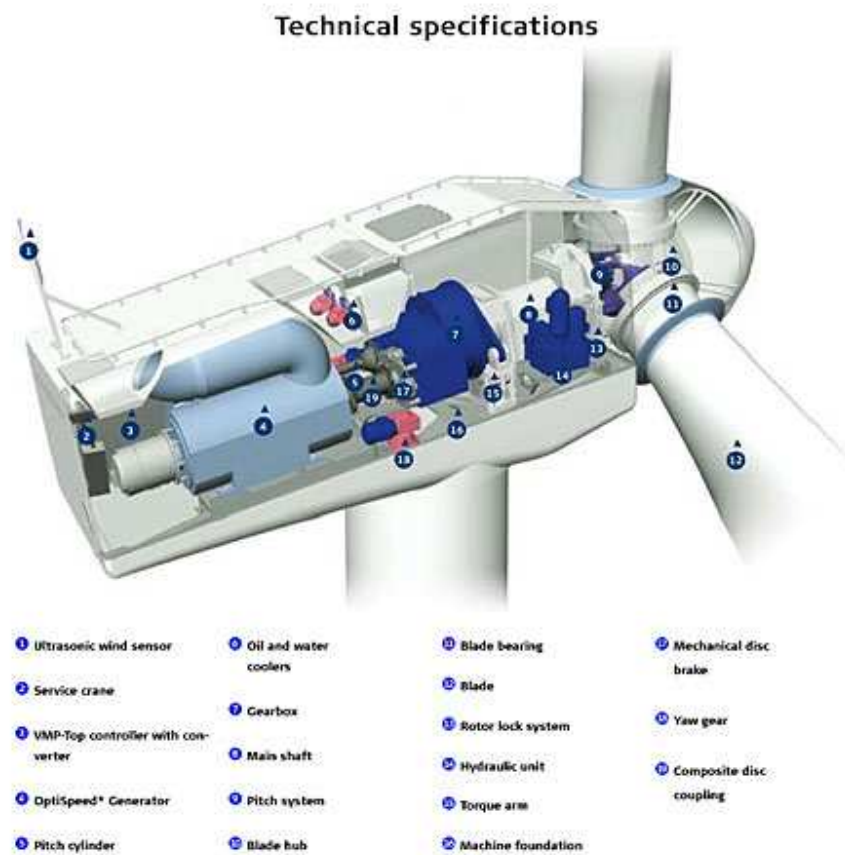
## **AA.8 Components of Wind Turbines**

Wind turbines consist of two main subsystems, the rotor nacelle assembly and the support structure, and each of these is comprised of many components. The following provides some more description of these subsystems. More details, particularly on the rotor nacelle assembly may be found in (Manwell et al., 2009).

### **AA.8.a Rotor Nacelle Assembly**

The rotor nacelle assembly (RNA) includes the majority of the components associated with the conversion of the kinetic energy of the wind into electrical energy. There are two major component groupings in the RNA as well as a number of ancillary components. The main groupings are the rotor and the drive train. The rotor includes the blades, the hub, and pitch control components. The drive train includes shafts, bearings, gearbox (if any), couplings, mechanical brake, and generator. Other components include the bedplate, yaw bearing and yaw drive, oil cooling system, climate control, other electrical components, and parts of the control system. An example of a typical rotor nacelle assembly is illustrated in Figure AA.10.

Figure AA.10: Typical Rotor Nacelle Assembly



(From Vestas [http://re.emsd.gov.hk/english/wind/large/large\\_to.html](http://re.emsd.gov.hk/english/wind/large/large_to.html))

### AA.8.b Rotor

The primary components of the rotor are the blades. At the present time, most wind turbines have three blades, and they are oriented so as to operate upwind of the tower. It is to be expected that in the future some wind turbines, particularly those intended for use offshore, will have two blades and will be oriented downwind of the tower, however. For a variety of reasons (including that downwind turbines tend to be noisier) it is less likely that they will be used on land, particularly in populated areas.

The general shape of the blades is chosen in accordance with the principles discussed previously. The other major factor is the required strength of the blades. For this reason, it is often the case that thicker airfoils are used nearer the root than are used closer to the tip. Blades

for most modern wind turbines are constructed of composites. The laminates are primarily fiberglass with some carbon fiber for additional strength. The binders are polyester or epoxy.

At the root of the blades the composite material is attached to a steel root, which can then be subsequently bolted to the hub. Most utility scale wind turbines at present include blade pitch control, so there is a mechanism present at the interface of the hub and the blades that will both secure the blades and facilitate their rotation about their long axis.

The hub of the wind turbine rotor is constructed from steel. It is designed so as to attach to the main shaft of the drive train as well as to connect with the blades.

#### **AA.8.c Drive train**

The drive train consists of a number of components, including shafts, couplings, a gearbox (usually), a generator, and a brake.

#### **AA.8.d Shafts**

The main shaft of the drive train is designed to transmit the torque from the rotor to the gearbox (if there is one) or directly to the generator if there is no gearbox. This shaft may also be required to carry some or all of the weight of the rotor. The applied torque will vary with the amount of power being produced, but in general it is given by the power divided by the rotational speed. As discussed previously, a primary consideration in the aerodynamic design of a wind turbine rotor is the tip speed ratio. A typical design tip speed ratio is 7. Consider a wind turbine with a diameter of 80 m, designed for most efficient operation at a wind speed 12 m/s. The rotational speed of the rotor and thus the main shaft under these conditions would be 20 rpm.

#### **AA.8.e Gearbox**

Wind turbines are intended to generate electricity, but most conventional generators are designed to turn at higher speeds than do wind turbine rotors (see below). Therefore, a gearbox is commonly used to increase the speed of the shaft that drives the generator relative to that of the main shaft. Gearboxes consist of a housing, gears, bearings, multiple shafts, seals, and lubricants. Gearboxes for wind turbines are typically either of the parallel shaft or planetary type. Frequently a gearbox incorporates multiple stages, since the maximum allowed ratio per stage is usually well under 10:1. There are trade-offs in the selection of gearbox. Parallel shaft gearboxes are generally less expensive than planetary ones but they are also heavier. Gearboxes are generally quite efficient. Thus the power out is very nearly equal to the power in. The torque in the shafts is then equal to the power divided by the speed of the shaft.



#### **AA.8.f Brake**

Nearly all wind turbines incorporate a mechanical brake somewhere on the drive train. This brake is normally designed to stop the rotor under all foreseeable conditions, although in some cases it might only serve as a parking brake for the rotor. Mechanical brakes on utility scale wind turbines are mostly of the caliper/disc type although other types are possible. Brakes may be placed on either the low speed or the high speed side of the gearbox. The advantage of placing it on the high speed side is that less braking torque is required to stop the rotor. On the other hand, the braking torque must then pass through the gearbox, possibly leading to premature failure of the gearbox. In either case, the brake must be designed to absorb all of the rotational energy in the rotor, which is converted into heat as the rotor stops.

#### **AA.8.g Generator**

Electrical generators operate via the rotation of a coil of wire in a magnetic field. The magnetic field is created by one or more pairs of magnetic poles situated opposite each other across the axis of rotation. The magnetic field may be created either by electromagnets (as in conventional synchronous generators), by induction in the rotor (as in induction generators,) or with permanent magnets. In alternating current systems the number of pairs of poles and the grid frequency determine the nominal operating speed of the generator. For example, in a 60 Hz AC system, such as the United States, a generator with two pairs of poles would have a nominal operating speed of 1800 rpm. In most AC generators, the field rotates and while the current is generated in a stationary armature (the stator).

The majority of utility scale wind turbines today use wound rotor induction generators (WRIG). This type of generator can function over a relatively wide range of speeds (on the order of 2:1). Wound rotor induction generators are employed together with a power electronic converter in the rotor circuit. In such an arrangement approximately 2/3 of the power is produced on the stator in the usual way. The other third of the power is produced on the rotor and converted to AC of the correct frequency by the power electronic converter. In this configuration the WRIG is often referred to as a doubly fed induction generator (DFIG).

A number of wind turbines use permanent magnet generators. Such generators often have multiple pole pairs as well. This can allow the generator to have the same nominal speed as the wind turbine rotor so the main shaft can be connected directly to the generator without the use of a gearbox. Most permanent magnet generators are designed to operate together with

power electronic converters. These converters facilitate variable speed operation of the turbine, while ensuring that the electricity that is produced is of constant frequency and compatible with the electrical grid to which the turbine is connected.

#### **AA.8.h Bedplate**

The bedplate is a steel frame to which components of the drive train and other components of the RNA are attached. It ensures that all the components are properly aligned.

#### **AA.8.i Yaw System**

Most wind turbines today include a yaw system. This system facilitates orienting the RNA into the wind as the wind direction changes. First of all, there is a slewing bearing that connects the top of the tower to the RNA, allowing the latter to rotate with respect to the former. Also attached to the top of the tower, and often to the outside perimeter of the slewing bearing, is a large diameter bull gear. A yaw motor connected to a smaller gear is attached to the bedplate. When the yaw motor is energized, the small gear engages the bull gear, causing the RNA to move relative to the tower. A yaw controller ensures that the motion is in the proper direction and that it continues until the RNA is aligned with the wind. A yaw brake holds the RNA fixed in position until the yaw controller commands a new orientation.

#### **AA.8.j Control System**

A wind turbine will have a control system that ensures the proper operation of the turbine at all times. The control system has two main functions: supervisory control and dynamic control. The supervisory control continuously monitors the external conditions and the operating parameters of the turbine, and starts it up or shuts it down as necessary. The dynamic control system ensures smooth operation of various controllable components, such the pitch of the blades or the electrical torque of the generator. The control system may also be integrated with or at least be in communication with a condition monitoring system that watches over the condition of various key components.

#### **AA.8.k Support Structure**

The support structure of a wind turbine is any part of the turbine that is below the main bearing. The support structure for land-based wind turbines may be conceptually divided into two main parts: the tower and the foundation. The tower of a wind turbine is normally constructed of tapered steel tubes. The tubes are bolted together on site to form a single structure of the desired height. The foundation of a wind turbine is the part of the support structure, which

is in contact with the ground. Foundations are typically constructed of reinforced concrete. When turbines are installed on rock, the foundations may be attached to the rock with rods, which are grouted into predrilled holes.

#### **AA.8.1 Materials for Wind Turbines**

The primary types of materials used in the various components of wind turbines are steel, copper, composites, and concrete.

#### **AA.9 Installation**

Installation of wind turbines may be a significant undertaking. It involves the following:

- Complete assessment of site conditions
- Detailed preparing for the installation
- Constructing the foundation
- Delivering the components to the site
- Assembling the components into sub-assemblies
- Lifting the sub-assemblies into place with a crane
- Installing the electrical equipment
- Final testing

More details may be found in (Manwell et al., 2009).

#### **AA.10 Energy Production**

The purpose of wind turbines is to produce energy. Energy production is usually considered annually. The amount of energy that a wind turbine will produce in a year,  $E_y$ , is a function of the wind resource at the site where it is installed and the power curve of the wind turbine. Estimates are usually done by calculating the expected energy that will be produced every hour of a representative year and then summing the energy from all of those hours as shown below:

$$E_y = \sum_{i=1}^{8760} P_{WT}(U_i) \Delta t \quad (25)$$

Where  $U_i$  is the wind speed in the  $i^{\text{th}}$  hour of the year,  $P_{WT}(U_i)$  is the average power (based on the power curve) during the  $i^{\text{th}}$  hour and  $\Delta t$  is the length of the time period of interest (here, one hr). The units of energy are Wh, but the amount of energy production is frequently expressed in either kWh or MWh for the sake of convenience.

It is sometimes cumbersome to characterize the performance of a wind turbine by its actual energy production. Accordingly, a normalized term known as the capacity factor,  $CF$ , is used. This is given by the actual energy that is 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,  $P_R$ , for the entire year. It is found from the following equation:

$$CF = \frac{E_y}{8760P_R} \quad (26)$$

### AA.11 Unsteady Aspects of Wind Turbine Operation

There are a number of unsteady aspects of wind turbine operation that are significant to the discussion of public reaction to wind turbines. These in particular include the variations in the wind field that can change the nature of the sound emitted from the rotor during operation. These unsteady effects include the following:

1. Wind shear – Wind shear refers to the variation of wind speed across some spatial dimension. Wind shear is most commonly thought of as a vertical phenomenon, that is to say, the increase of wind speed with height. Wind shear can also occur laterally across the rotor under some circumstances. Vertical wind shear is often modeled by a power law as discussed earlier. There are some situations, however, in which such a model is not applicable. One example has to do with highly stable atmosphere, such that the wind near the ground is relatively light, but at the height of the rotor the wind is high enough that turbine may be operating. Under such conditions there may be sound emanating from the rotor, but relatively little wind induced sound near the ground to mask that from the rotor. Wind shear may also result in a cyclically varying aspect to the sound produced by the blades as they rotate. This occurs due to the changing magnitude and direction of the relative wind as the blades pass through zones of different wind speed.
2. Tower shadow or blockage – The wind flow near the tower is inevitably somewhat different from where there is no tower. The effect is much more pronounced on wind turbines with downwind rotors, but it still occurs with up-wind rotors. This tower effect can result in a distinct change in sound once per revolution of each blade.

3. Turbulence – Turbulence refers to changes in magnitude and direction of the wind at varying time scales and length scales. The presence of turbulence can affect the nature of the sound.
4. Changes in wind direction – Wind turbines are designed to yaw in response to changes in wind direction. The yawing process takes a finite amount of time and during that time the wind impinging on the rotor will do so at a different direction than it will when the yawing process is complete. Sound produced during the yawing process may have a somewhat different character than after it is complete.
5. Stall – Under some conditions part or all of the airfoils on the blades may be in stall. That is, the angle of relative wind is high enough that the airfoil begins to lose lift. Additional turbulence may also be generated. Again, the nature of the sound produced by the rotor may be different than during an unstalled state. It may also be noted that some turbines intentionally take advantage of stall to limit power in high winds. Under such conditions there may also be a change in sound in comparison to normal operation.

#### **AA.11.a Periodicity of Unsteady Aspects of Wind Turbine Operation**

Due to the rotation of the rotor and the nature of the wind, there tend to be certain features of the turbine's operation that are periodic in nature. The most dominant of these have frequencies associated with the rotational speed of the rotor and the blade passage frequency, which is simply the rotational speed times the number of blades. For example, the dominant frequencies in a 3-blade wind turbine rotating at 20 rpm would be 0.33 Hz and 1 Hz. Other significant frequencies may be the first few harmonics of the rotational frequency and blade passage frequency.

#### **AA.12 Wind Turbines and Avoided Pollutants**

Wind turbines have a positive impact on human health via avoiding emission of pollutants that would result if the electricity that they generate were produced instead by other generators. While the average emissions of various pollutants per MWh produced from conventional generators is relatively easy to estimate, it is harder to estimate the actual impact of wind turbine generation. This is because the electricity distributed by the electrical grid is produced by different types of generators, and the operation of these generators will be affected differently as a result of the supply of part of the total electrical demand by the wind turbines.

In general, electricity in any large utility network comes from three types of generators: base load, intermediate load, and peaking plants. The fuel or energy source supplying these generators is likely to be coal, fuel oil, natural gas, uranium (nuclear plants), or water (hydroelectric plants). Base load plants are typically coal fired or nuclear plants. Intermediate load plants often use fuel oil or natural gas. Peaking plants are normally natural gas or hydroelectric. There are a considerable number of plants that may be operating at any given time. Which plants are actually operating is determined by the system operator in accordance with what the near term forecasted load is expected to be and the estimated (bid) cost per MWh from all the plant operators in the system. For thermal plants the bid cost is close to that projected fuel cost/MWh. This in turn is found from heat rate of the fuel (kg/MWh) for the plant in question times the unit cost of the fuel (\$/kg). Less efficient plants or those with higher unit fuel costs tend to have relatively high bid costs. (Note on the other hand, that wind turbines would have bid costs of zero, since they do not use fuel.)

If a large number of wind turbines are operating such that they are contributing a significant amount of electricity to the total load, the mix of generators may well be different than it would be if the turbines were not present. If only a small number of wind turbines are present, then the mix of generators may not change. However, certain of the plants would be curtailed so as to produce less energy and thus consume less fuel. The emissions of pollutants from all the operating plants could be calculated and so could the projected emissions that would have resulted if the wind turbines were not present. The difference in amount of pollutants produced could then be assigned to the wind turbine as the avoided emissions.

To do such an analysis properly involves estimating the actual impact of wind turbine generation on the mix of generators and the operating level of those generators for every hour of the year. This is a non-trivial exercise, but it has been done for an offshore wind farm that was proposed for the town of Hull, MA. That project was to have included four 3.6 MW turbines, for a total capacity of 14.4 MW. The pollutants considered in the study were CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>x</sub>. The results of that study are described in detail in (Rached, 2008). The results of that study are summarized in Table AA.1. The results in the table are normalized for a 1 MW (rated) wind turbine and use the medium estimated wind speed for the site. (Note under the assumptions of Rached's study, a one MW (rated) wind turbine in the medium wind speed scenario at the site would generate 2,580 MWh/yr).

## WIND TURBINE HEALTH IMPACT STUDY

Table AA.1:

Avoided emissions of pollutants for 14.4 MW wind project (based on Rached, 2008)

CO <sub>2</sub> (kg/MWyr)	SO <sub>x</sub> (kg/MWyr)	NO <sub>x</sub> (kg/MWyr)
1,970,000	3,480	1,490

A simpler but less accurate way to estimate the avoided emissions is to use the marginal rates for pollutants as specified by the Massachusetts Greenhouse Gas policy (MEPA, 2007). Applying this method Rached calculated avoided emissions per MW (rated) for the three pollutants for one year of 1,320,000 kg CO<sub>2</sub>, 2,080 kg of SO<sub>2</sub>, and 701 kg of NO<sub>x</sub>.

In the analysis summarized above the majority of the avoidance of pollutant production would be due to reduced consumption of natural gas. If a larger fraction of Massachusetts' energy were to be produced by wind energy, there could be significant reductions of the consumption of fuel oil and coal as well. This should result in larger amounts of avoided pollution per unit of wind turbine production

## Appendix B

### Wind Turbines – Shadow Flicker

#### AB.1 Shadow Flicker and Flashing

Shadow flicker occurs when the moving blades of a wind turbine rotor cast moving shadows that cause a flickering effect. This flicker could annoy people living close to the turbine. Similarly, it is possible for sunlight to be reflected from gloss-surfaced turbine blades and cause a “flashing” effect. This phenomenon will occur during a limited amount of time in a year, depending on the altitude of the sun,  $\alpha_s$ ; the height of the turbine,  $H$ , the radius of the rotor,  $R$ , and the height, direction and distance to the viewing point. At any given time the maximum distance from a turbine that a flickering shadow will extend is given by:

$$x_{shadow,max} = (H + R - h_{view}) / \tan(\alpha_s) \quad (27)$$

Where  $h_{view}$  is the height of the viewing point.

The solar altitude depends on the latitude, the day of the year, and the time as given in the following equations (Duffie and Beckman, 2006)

$$\alpha_s = 90^\circ - \cos^{-1}[\cos(\delta)\cos(\phi)\cos(\omega) + \sin(\delta)\sin(\phi)] \quad (28)$$

Where  $\delta$  = declination of the earth’s axis,  $\phi$  = latitude and  $\omega$  = the hour angle

The declination is found from the following equation:

$$\delta = 23.45 \sin(360(284 + n) / 365) \quad (29)$$

Where  $n$  = day of the year

The hour angle is found from the hours from noon (solar time, negative before noon, positive after noon), divided by 15 to convert to degrees.

Another relevant angle is the solar azimuth. This indicates the angle of the sun with respect to certain reference direction (usually north) at a particular time. For example, the sun is always in the south at solar noon, so its azimuth is  $180^\circ$  at that time. The solar azimuth is important since it determines the angle of the wind turbine’s shadow with respect to the tower. See Duffie and Beckman (2006) for details on calculating the solar azimuth.

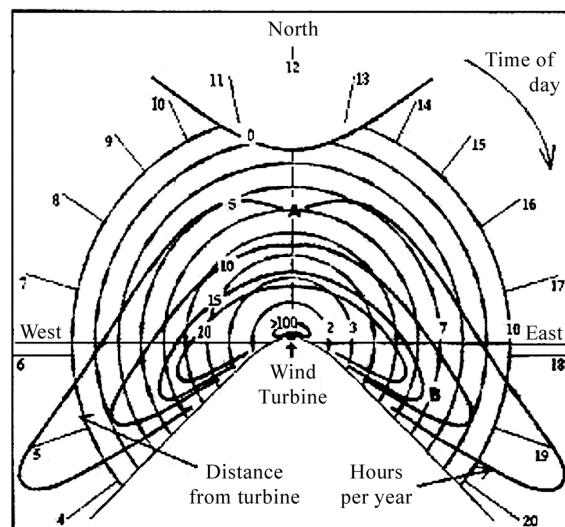


## WIND TURBINE HEALTH IMPACT STUDY

For example, consider a location that has a latitude of  $43^\circ$ . Assume that the day is March 1 (day 60) and the time is 3:00 in the afternoon. Also assume that the turbine has a tower height of 80 m and a radius of 30 m and that the viewing height is 2 m. The declination is  $-8.3^\circ$ , the solar altitude is  $24.4^\circ$ , and the solar azimuth is  $50.2^\circ$  W of S. The maximum extent of the shadow is 238 m from the turbine. The angle of the shadow is  $50.2^\circ$  E of N.

Sites are typically characterized by charts such the one illustrated in Figure AB.1 for a location in Denmark (EWEA, 2004). The chart gives the number of hours per year of flicker shadow as a function of direction and distance (measured in units of hub height). In the example shown, two viewing points are considered. One of them (A) is directly to the north of turbine at a distance of 6 times the hub height. The other (B) is located to the south east at a distance of 7 times the hub height. The figure shows that the first viewing point will experience shadow flicker from the turbine for 5 hours per year. The second point will experience flicker for about 12 hours per year.

Figure AB.1: Diagram of shadow flicker calculation (EWEA, 2004)



*A, B are viewing points*

*Note that the equations above assume a clear sky and the absence of rain, clouds, etc.*

### AB.2 Mitigation Possibilities

Most modern wind turbines allow for real-time control of turbine operation by computer in order to shut down during high shadow flicker times, if necessary. In addition, computer programs can allow for pre-planning of siting location ahead of time to know what a project specific impact will be in terms of shadow flicker when planning a wind turbine project (as

discussed in the previous paragraph). This planning can be site-specific in order to avoid potential problems with specific sites based on geographical location or weather patterns.

In terms of safe distances to reduce shadow flicker, these are often project-specific because it depends on whether there are residences or roadways present and what the geographic layout is. This could be particularly important in areas with more forestry and existing shadow, which could reduce nuisance from turbine produced shadow flicker or whether it is an otherwise open land area such as farmland that would be more susceptible to the annoyance of shadow flicker. A general estimate for modeling a shadow flicker risk zone includes 10 times the rotor diameter such that a 90-meter diameter would be equivalent to a 900-meter impact area. However, only certain portions of this zone are actually likely to experience shadow flicker for a significant amount of time. Other modeling considerations include when at least 20% of the sun is covered by the blade and whether to include the blade width in estimates as well. In terms of distance, 2,000 meters is the WindPro computer program default distance (NEWEEP, 2011) for calculations of wind turbine produced shadow flicker. Finally, due to atmospheric effects, 1400 m is the maximum distance from a turbine within which shadow flicker is likely to be significant.

In terms of existing regulations regarding shadow flicker rates, there are no current shadow flicker regulations in Massachusetts (or many other New England states, but there are statewide and local guidelines that have been implemented. These guidelines were provided by the Department of Energy Resources in March 2009 and state that, “wind turbines shall be sited in a manner that minimizes shadowing or flicker impacts” and, “the applicant has the burden of proving that this effect does not have significant adverse impact on neighboring or adjacent uses.” Local Massachusetts regulations include the Worcester, MA zoning ordinance, which requires, “The facility owner and operator shall make reasonable efforts to minimize shadow flicker to any occupied building on a non-participating landowner’s property.” Also, a shadow flicker assessment report is required as is a plan showing the “area of estimated wind turbine shadow flicker.” Similarly, the Newburyport, MA regulations require that wind turbines do not result in significant shadow or flicker impacts and an analysis is required for planned projects (NEWEEP, 2011).

The Maine model wind energy facility ordinance states that wind turbines should, “avoid unreasonable adverse shadow flicker effect at any occupied building located on a non-

participating landowner's property." They do not state any specific limit to shadow flicker other than these guidelines. However, the New Hampshire Model Small Wind Energy Systems Ordinance states that wind turbines, "shall be sited in a manner that does not result in significant shadow flicker impacts...significant shadow flicker is defined as more than 30 hours per year on abutting occupied buildings." Similar to Maine, several states in the US have adopted the German model of 30 hours per year of allowed shadow flicker that was primarily based on the government-sponsored study summarized above. However, other states or localities including Hutchinson, Minnesota have enacted stricter guidelines including no shadow flicker to be allowed at an existing residential structure, and up to 30 hours per year of shadow flicker allowed on roadways or residentially zoned properties and a computer analysis is required for project approval (NEWEEP, 2011).

In addition, computer programs such as WindPro are also recommended by most states and localities for use in all new planned installations to reduce this potential nuisance of shadow flicker on residential properties or potential health hazards to drivers on busy highways or roadways.

## Appendix C

### Wind Turbines – Ice Throw

#### AC.1 Ice Falling or Thrown from Wind Turbines

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 what 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.

In both cases, the distance that the ice may travel is governed by Newton’s laws and the principles of fluid mechanics. Calculations are quite simple when the effect of the air (and the wind) is ignored. For example, in that case if a piece of ice falls from a turbine, it will land directly below where it is released. The situation is a little more complex, but still readily solvable if the piece of ice is moving when it is released. For example, suppose that the ice is initially on the tip of a blade, and the blade is pointing vertically upward. Once the ice is released it will continue moving horizontally at the speed it had when it was still attached to the blade. But it will also begin to fall towards the ground, so the piece of ice will have two components of velocity until the ice hits the ground. The time  $t_g$  (s) it takes for the ice to reach the ground (assuming a horizontal surface) is  $t_g = \sqrt{2h/g}$  where  $h$  = height (m) at which the ice is released

and  $g =$  acceleration of gravity ( $9.81 \text{ m/s}^2$ ). The distance  $x$  (m) that the ice would travel is  $x = t_g \Omega R$  where  $\Omega$  is the rotational speed of the rotor (rad/s) and  $R$  is the length of the blade (m).

Such an analysis is overly simplified, however. It would underestimate the distance that the ice would travel if it fell from a stationary turbine in a high wind, and it would overestimate the distance that the ice would travel if it were suddenly released from a moving blade. It is necessary to consider the effect of the air and the force that it will impart upon the falling ice. For motion in the vertical ( $z$ ) direction the equation of motion is the following:

$$F_z = ma_z \quad (30)$$

where  $F_z$  is the net force (N),  $m$  is the mass (kg), and  $a_z$  is the acceleration ( $\text{m/s}^2$ ). The force includes two main components. One is the weight,  $W$  (N). It is due to gravity and acts in the negative  $z$  direction. The other one is due to the drag of the air and it acts opposite to the direction of the velocity. It is found from:

$$F_D = \frac{1}{2} C_D \rho A V_z^2 \quad (31)$$

where  $\rho$  is the density of air ( $1.225 \text{ kg/m}^3$  under standard conditions),  $A$  is the projected area ( $\text{m}^2$ ) of the piece of ice,  $C_D$  is the drag coefficient of the ice and  $V_z$  is the velocity of the ice (m/s) in the  $z$  direction.

Acceleration is the derivative of the velocity, so we can rewrite the equation of motion for the vertical direction as follows:

$$\frac{dV_z}{dt} = \left( -W - \text{sign}(V_z) \frac{1}{2} C_D \rho A V_z^2 \right) / m \quad (32)$$

Where  $\text{sign}(\dots)$  indicates the direction of motion along the  $z$  axis. For the general case, the piece of ice may leave the blade with initial speed  $\Omega R$  at an arbitrary angle  $\theta$  with respect to the horizontal. Accordingly, there will be two components of the velocity, one in the  $z$  direction (as before)  $V_z$ , the other in the  $x$  direction,  $V_x$ . This assumes that the  $x$  axis is horizontal, is also in the plane of the rotor, and is positive in the direction of the tip of the blade at its apogee.

These velocities are initially:

$$V_{z,0} = \Omega R \sin(\theta) \tag{33}$$

$$V_{x,0} = \Omega R \cos(\theta) \tag{34}$$

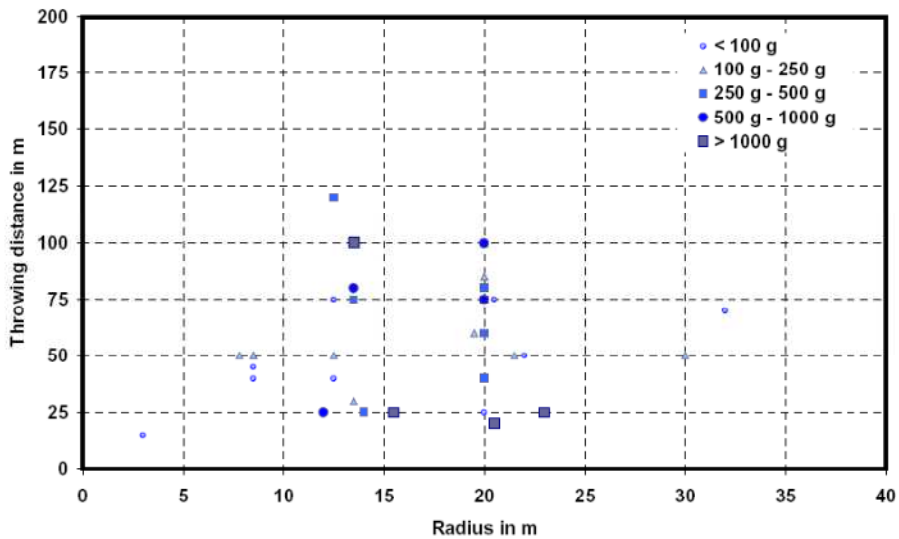
The equation of motion for the  $x$  direction is:

$$\frac{dV_x}{dt} = \left( -\text{sign}(V_z) \frac{1}{2} C_D \rho A V_x^2 \right) / m \tag{35}$$

The above equations are a bit difficult to solve analytically, but they can be solved numerically fairly easily. Similar equations may also be developed for the case of a particle of ice falling from a stationary turbine.

Some data from actual ice throw has been compiled by Seifert et al. (2003). Figure AC.1, taken from that report is shown below.

Figure AC.1: Observed throwing distance of ice (from Seifert et al., 2003)



As may be seen in the figure, the maximum distance that ice was observed to fall from a turbine with a diameter of 20 m during operation was approximately 100 m. Based on the observed data, Seifert et al. suggest the following simplified formula for the maximum throwing distance:

$$x_{\max,throw} = 1.5(2R + H) \quad (36)$$

Where  $x_{\max,throw}$  = maximum throwing distance (m),  $R$  = rotor diameter (m) and  $H$  = hub height (m).

By way of illustration, Equation 36 was used to predict the maximum throwing distance of a piece of ice from a turbine with a rotor radius of 20 m installed on a tower 50 m high. That distance was 135 m. The theoretical equations given previously were also used to calculate throwing distance. The following assumptions were made: spherically shaped piece of ice, drag coefficient of 1.2, air density of 1.225 kg/m<sup>3</sup>, ice density of 700 kg/m<sup>3</sup>, rotor speed of 40 rpm (corresponding to a tip speed ratio of 7 at a wind speed of 12 m/s), angle of release of 45°, and instantaneous release of the ice. The equations predict a maximum throwing distance of 226 m or somewhat less than twice that predicted from the empirical equation. The difference is deemed to be reasonable, especially considering the idealized shape of the particle. Real pieces of ice would actually be highly non-spherical in shape and experience considerably more drag. It may also be noted that it was reported in Cattin et al. (2007) that ice did not fall as far from a wind turbine in the Swiss Alps as would be predicted from Equation 36. In that case the maximum observed distance from a turbine with radius of 20 m and a tower height of 50 m was 92 m. As noted above, Equation 36 predicts 135 m.

Seifert et al. also considered data regarding ice thrown from stationary turbines. Based on the available data they proposed a simple equation for predicted ice fall. That equation is

$$x_{\max,fall} = U(R + H)/15 \quad (37)$$

Where  $U$  = wind speed at hub height in m/s,  $x_{\max,fall}$  = maximum falling distance (m),  $R$  = rotor radius (m),  $H$  = hub height (m).

Using Equation 37, the predicted maximum distance for a turbine with a radius of 20 m, a tower height of 50 m, and a wind speed of 20 m/s is 120 m. By way of comparison, the fall distance was predicted from the theoretical equations given above for the same situation. The

results are highly dependent on the size of the piece of ice and hence the surface to volume ratio. To take one example, a piece of ice that was assumed to be spherical and to have a weight of 10 g would land 110 m from the tower. In the examples discussed by Seifert et al., all the pieces of ice landed less than 100 m from the tower.

### **AC.2 Summary of Ice Throw Discussion**

As noted above, there are two plausible scenarios in which ice may fall from a wind turbine and may land at some distance from the tower. In the first scenario, ice that falls from a stationary turbine is blown some distance from the tower. In the second scenario, ice is thrown from the blade of an operating turbine during a failure of the control system. In the first case, ice may land 100 m or more from the tower in high winds, depending on the wind speed, the height from which the ice falls, and the dimensions of the ice. In the second case, the ice could land even further from the turbine. Just how far would depend on the actual speed of the rotor when the ice was shed, the height of the tower, the length of the blade, the angular position of the blade when the ice was released, and the size and shape of the ice. In general, it appears that ice is unlikely to land farther from the turbine than its maximum vertical extent (tower height plus the radius.)



## Appendix D

### Wind Turbine – Noise Introduction

Noise is defined simply as unwanted sound. Sound is defined as the sensation produced by stimulation of the organs of hearing by vibrations transmitted through the air or other medium. In air, the transmission is due to a repeating cycle of compressed and expanded air. The frequency of the sound is the number of times per second, Hertz (Hz), that the cycle repeats. Sound at a single frequency is called a tone while sound that is a combination of many frequencies is called broadband.

The human ear is capable of responding over a frequency range from approximately 20 Hz to 20 kHz (Hz: Hertz = 1 cycle/second; Middle C on a piano is a frequency of 262 Hz).

#### AD.1 Sound Pressure Level

Sound is characterized by both its frequency and its amplitude. Sound pressure is measured in micro Pascals ( $\mu\text{Pa}$ ). Because sound pressure can vary over a wide range of magnitudes a logarithmic scale is used to convert micro Pascals to decibels. Thus sound pressure level (SPL) is defined by  $\text{SPL} = 10 \log_{10} [p^2/p_{\text{ref}}^2] = 20 \log_{10}(p/p_{\text{ref}})$  with the resulting number having the units of decibels (dB). The reference pressure  $p_{\text{ref}}$  for airborne sound is  $20 \times 10^{-6}$  Pa (i.e.,  $20\mu\text{Pa}$  or 20 micro Pascals). This means that SPL of 0 dB corresponds to a sound wave with amplitude  $20\mu\text{Pa}$ . 140 dB is considered the threshold of pain and corresponds to 20,000,000  $\mu\text{Pa}$ . Doubling the amplitude of the sound wave increases the SPL by 6 dB.

Therefore, a  $40\mu\text{Pa}$  amplitude sound wave would have an SPL of about 6 dB.

When it is stated that there is a large frequency range over which humans can hear, it is also noted that the ear does not hear each frequency similarly. In fact, there is a frequency-dependent threshold of hearing (lower limit) and threshold of pain (higher limit). Experiments have been performed to determine these thresholds. The threshold of hearing curves show that one can hear a tone at 3 kHz (3000 Hz) with an SPL < 0 dB while at 100 Hz one does not hear the tone until its SPL is about 30 dB. Curves showing the thresholds can be easily found in textbooks and online (one online example is at

[http://www.santafevisions.com/csf/html/lectures/007\\_hearing\\_II.htm](http://www.santafevisions.com/csf/html/lectures/007_hearing_II.htm)). Experiments have also been conducted to determine equal loudness level contours. These contours indicate when two tones of dissimilar frequencies appear to be equally loud.

Some characteristics of human response to sound include:

- Changes in sound level <1 dB cannot be perceived
- Doubling the magnitude of the acoustic pressure leads to a 6 dB increase in SPL
- A 5 dB SPL change will result in a noticeable community response
- A 10 dB SPL change is subjectively heard as an approximate doubling in loudness

## **AD.2 Frequency Bands**

Most sounds in our environment contain multiple frequencies and are variable in that successive identical experiments cannot result in the exact same plot or tabulation of pressure vs. time. Therefore, it is common to use averages that measure approximately the amplitude of the sound and its frequency content. Common averaging methods rely on the principle of octaves, such as 1/10, 1/3, and single octave bands. This means that the entire frequency range is broken into chunks such that the relation between the starting and ending frequencies of each chunk,  $f_1$  and  $f_2$  respectively, are related by  $f_2 = 2^{1/N}f_1$  where  $N = 1$  for a single octave band and 3 for a 1/3 octave band. Because the bands can be constructed based on any starting frequency, a standardized set of bands have been specified. They are usually described by the center frequency of each band. The standard octave-bands are given in Table AD.1 (measured in Hz):

Table AD.1:

Octave bands. Values given in Hz.

<b>Center Frequency</b>	<b>Lower Band limit</b>	<b>Upper Band Limit</b>
16	11	22
31.5	22	44
63	44	88
125	88	177
250	177	355
500	355	710
1000	710	1420
2000	1420	2840
4000	2840	5680
8000	5680	11360
16000	11360	22720

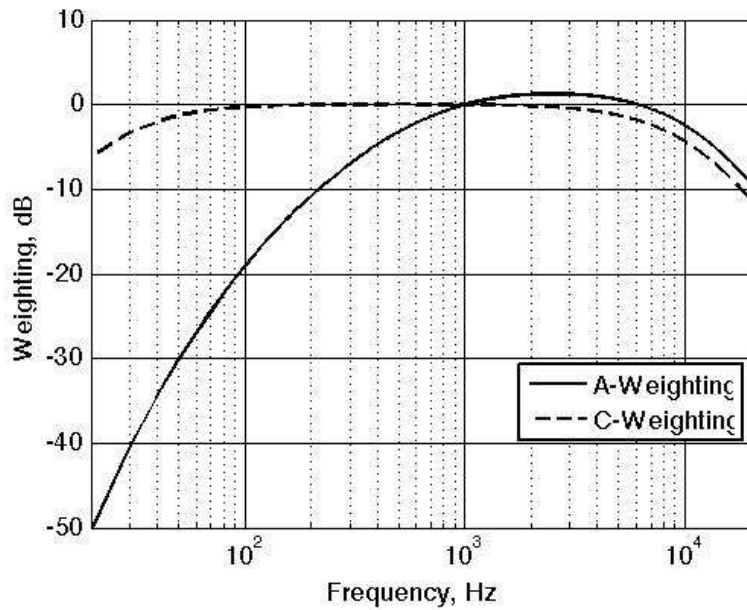
A similar set of bands can be written for the 1/3 octaves. For each octave band there are 3-1/3 octave bands. Many text and online resources specify the 1/3 octave bands such as ([http://www.engineeringtoolbox.com/octave-bands-frequency-limits-d\\_1602.html](http://www.engineeringtoolbox.com/octave-bands-frequency-limits-d_1602.html)). The 1/10 octave band is a narrow-band filter and is used when the sound contains important tones.

### **AD.3 Weightings**

Noise data are often presented as 1/3 octave band measurements. Again, this means that the sound in each frequency band has been averaged over that frequency range. Noise levels are also often reported as weighted values. The most common weighting is A weighting. It was originally intended to be such that sounds of different frequencies giving the same decibel reading with A weighting would be equally loud. The weighting of the octave band centered at 31.5 Hz requires one to subtract 39.4 dB from the actual SPL. The octave bands with centers from 1000 to 8000 where human hearing is most sensitive are corrected by only about +/- 1 dB. When considered together with the threshold of hearing, it is clear that the A-weighting is most

applicable for sounds of small amplitude. C-weighting on the other hand subtracts only a few dB from the very highest and very lowest frequency bands. It is therefore more applicable for higher levels of sound. The figure below shows these two weightings. When weighted, the sound pressure level is reported as dBA or dBC respectively.

Figure AD.1: Weighting values for reporting sound pressure levels



Noise levels change several times per day. To account for these differences other environmental noise measures are often used as shown in Table AD1.

Table AD 2:

A set of visual examples for these measures can be found at  
[http://www.epd.gov.hk/epd/noise\\_education/web/ENG\\_EPd\\_HTML/m2/types\\_3.html](http://www.epd.gov.hk/epd/noise_education/web/ENG_EPd_HTML/m2/types_3.html)

<b>Indicator</b>	<b>Meaning</b>
$L_{\max}$	The maximum A-weighted sound level measured
$L_{10}, L_{50}, L_{90}$	The A-weighted sound level that is exceeded n%, of the time, where n is 10, 50, and 90 respectively. During the measurement period $L_{90}$ is generally taken as the background sound level.
$L_{\text{eq}}$	Equivalent sound level. The average A-weighted sound pressure level, which gives the same total energy as the varying sound level during the measurement period of time.
$L_{\text{dn}}$	Day-night level. The average A-weighted sound level during a 24-hour day after addition of 10 dB to levels measured in the night between 10 p.m. and 7 a.m.

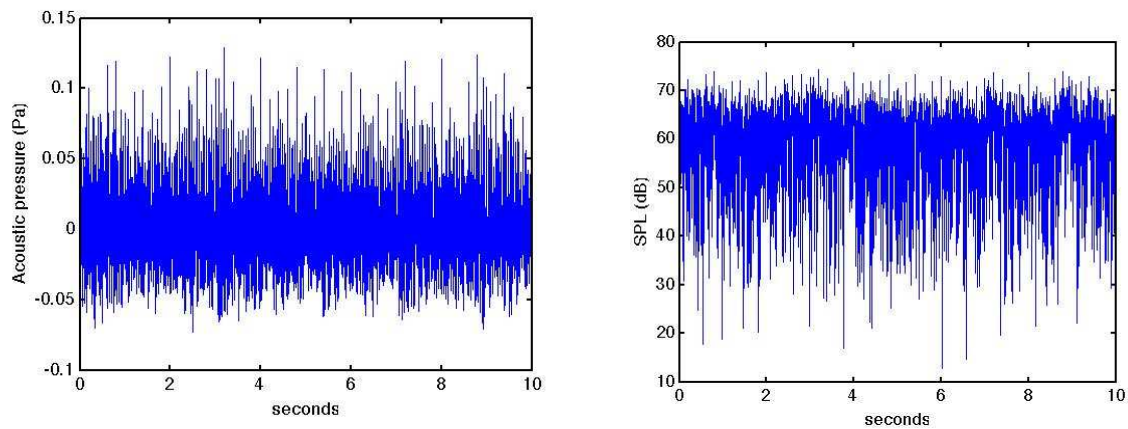
#### **AD.4 Sound Power**

Sound intensity and sound power are also often reported. Sound intensity is a measure of the energy transported per unit area and time in a certain direction. It can be shown that the intensity ( $I$ ) perpendicular to the direction of sound propagation is related to the amplitude of the pressure wave squared, the density of the air ( $\rho$ ), and the speed of sound ( $c$ ),  $I \sim p^2/\rho c$ . The sound power,  $P$ , is the total intensity passing through a surface around a sound source. Intensity has units of Watts per square meter ( $\text{W}/\text{m}^2$ ) and Power is measured in Watts ( $\text{W}$ ). Both of these quantities are normally reported in dB where the intensity level is calculated as  $L_I = 10 \log_{10} (|I|/I_{\text{ref}})$  and the power level is calculated as  $L_W = 10 \log_{10}(P/P_{\text{ref}})$ . The reference intensity level is related to the threshold of hearing at 1000 Hz such that  $I_{\text{ref}} = 10^{-12} \text{ W}/\text{m}^2$ . The reference power value is  $P_{\text{ref}} = 10^{-12} \text{ W}$  (1 picowatt). Here a doubling of the power leads to a 3 dB increase in the sound power level (PWL).

### AD.5 Example Data Analysis

This is an example of the type of analysis done on sound measurements from a wind turbine. First, the actual signal might look something like what is shown in Figure AD.2.

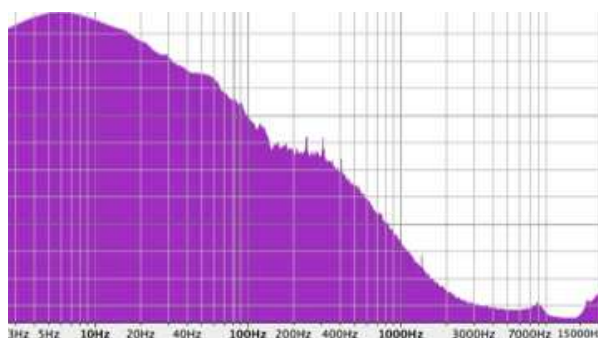
Figure AD.2: Pressure signal from a wind turbine



. (From(van den Berg, 2011), related to Rheine wind turbine farm). Left in Pascals, right as SPL in dB.

In Figure AD.2, just the acoustic pressure is shown, which means that atmospheric pressure, which is about 103,000 Pa, has been subtracted and the fluctuations then appear around 0 Pa. These data can easily be presented as SPL by transforming the pressure from Pa to dB. In order to analyze the pressure signal for low frequency content, a much longer time signal must be obtained. The frequency content of a long time signal is analyzed by performing a Fourier Transform. A typical transform of data from a wind turbine is shown in Figure AD.3.

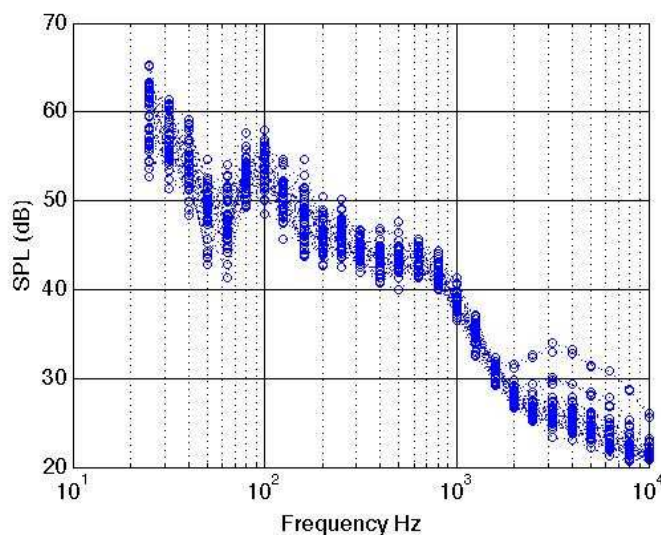
Figure AD.3: Frequency content of typical wind turbine measurement. (from Palmer ASA paper.)



(This figure does not correspond to the Rheine data for which the writer is not able to produce the full frequency domain plot.)

In order to better assess the broadband nature of wind turbine sound, the results are presented in 1/3-octave band form. The averages that are taken in each 1/3-octave band can be done on fast or slow time intervals. For instance, the data in Figure 3 could be averaged on 1/3-octave bands to come up with the overall SPL in the bands. Or, as a measurement is being taken, the instrumentation can provide 1/3-octave band averages on short time scales. For the Rheine data a fast average on 0.05 seconds was recorded. A few of the 1/3-octave band results are shown in Figure AD.4.

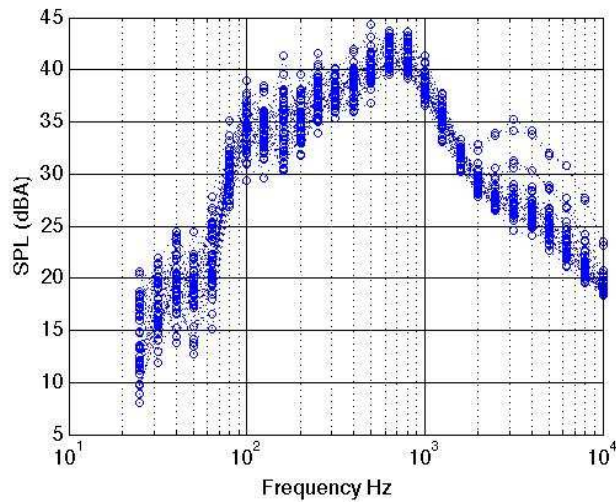
Figure AD.4: Fast averages for 1/3-octave band analysis.



*Shown results for 0–0.05, 5–0.05, 10–10.05, ..., 200–200.05 seconds.*

From these a final overall spectrum emerges. If these were presented as A-weighted spectrum, then Figure AD.5 is what is presented.

Figure AD.5: Fast averages for 1/3-octave band A-weighted analysis.



*Shown results for 0–0.05, 5–0.05, 10–10.05, ..., 200–200.05 seconds.*

### AD.6 Wind Turbine Noise from Some Turbines

What is known about aerodynamically generated noise from wind turbines is that it nominally increases with increasing wind speed until the max power is obtained, and it increases with increasing rotor tip speed. A report out of the Netherlands by (van den Berg et al., 2008) reports a vast amount of noise data related to wind turbines. The tables in Appendices B and C from the report clearly show these trends. Some of the data are reproduced here. Only measurements that were made by third parties (not specified by the wind turbine company) are reproduced here.



## WIND TURBINE HEALTH IMPACT STUDY

Table AD.3:

Sound power level in dB(A) from various wind turbines. (van den Berg et al., 2008).

<b>Manufacturer Make and model</b>	<b>Power kW</b>	<b>Hub Height m</b>	<b>Diameter m</b>	<b>rpm</b>	<b>4 m/s</b>	<b>5m/s</b>	<b>7m/s</b>	<b>8m/s</b>	<b>10m/s</b>
Enron TW1.5s	1500	80	70	11	100	100	100	100	
Enron TW1.5s	1500	81	70	22		102	102	103	104
NegMicon NM52	900	70	52	15	93	93			
NegMicon NM52	900	70	52	22		98	100	101	103
NegMicon NM54	950	46	54	15		95.6			
NegMicon NM54	950	46	54	22		101.6			
Vesta V66	1650	70	66	15	97	97	98	98	
Vesta V66	1650	70	66	19		101	101	102	102

It must be noted here that what has been reported are the sound power levels, which represents the total sound energy that propagates away from the wind turbine (i.e., the sound energy at the center of the blades, which propagates outward at the height of the hub). The sound level measured at a single position at the base of the turbine can easily be 50 dB lower (Lawrence rep.).

### **AD.7 Definition of Infrasound**

Discussion of the aerodynamic source of sound known as thickness noise or self-noise requires one to define low frequency sound and infrasound. By definition, infrasound is a pressure wave that is not audible. Nominally this means waves with frequency less than 20 Hz. It is noted though that waves with high enough amplitude below 20 Hz may still be audible. Low frequency sound is characterized as having a frequency between 20 and 200 Hz. As mentioned earlier, some mechanical noise sources contribute to the low frequency range, and clearly some of the aerodynamic sources of broadband sound will contribute to noise in the low frequency range. Thickness noise, if present, would have an associated frequency equal to the

blade passing frequency. Hence, a turbine with 3-bladed rotor turning at 20 rpm might generate thickness noise at a frequency of 1 Hz, which is clearly in the infrasonic range. Downwind rotors produce slightly stronger infrasound at the blade passing frequency because the blades interact directly with the wake behind the tower. The levels of the thickness noise generated by modern upwind turbines are not perceptible by the human auditory system. Any impulsive noise that is audible, which seems to have a frequency equivalent to the blade passing frequency, is actually the broadband noise generated by the other mechanisms being modified by differences in the flow that occur on a once-per-rev basis as discussed above. The frequencies of this pulsating sound are all in the audible range, and thus this sound is not infrasound.

## Appendix E

### Wind Turbine – Sound Power Level Estimates and Noise Propagation

#### AE.1 Approximate Wind Turbine Sound Power Level Prediction Models

The following are some approximate equations that are sometimes used to estimate the A-weighted sound power level,  $L_{WA}$ , from a typical wind turbine. The first equation gives the estimate in terms of the rated power of the turbine,  $P_{WT}$  (W). The second gives the estimate in terms of the diameter,  $D$  (m). The third gives it in terms of both the tip speed,  $V_{Tip}$  (m/s), and diameter. These equations should only be used when test data is not available.

$$L_{WA} = 10(\log_{10} P_{WT}) + 50 \quad (38)$$

$$L_{WA} = 22(\log_{10} D) + 72 \quad (39)$$

$$L_{WA} = 50(\log_{10} V_{Tip}) + 10(\log_{10} D) - 4 \quad (40)$$

#### AE.2 Sound Power Levels due to Multiple Wind Turbines

When multiple wind turbines are located close to each other, the total sound power can be estimated by applying logarithmic relations. For example, for two turbines with sound power levels  $L_{W1}$  and  $L_{W2}$ , the total sound power is:

$$L_{total} = 10 \log_{10} (10^{L_1/10} + 10^{L_2/10}) \quad (41)$$

For  $N$  turbines, the corresponding relation is:

$$L_{total} = 10 \log_{10} \sum_{i=1}^N 10^{L_i/10} \quad (42)$$

where  $L_{wi}$  is the sound power level of the  $i^{th}$  turbine. For turbines that are some distance away from each other the mathematics is more complicated, and the relations of interest (actually the sound pressure level) take into account the relative position of the turbines and the location of the observer as described below.

### AE.3 Noise Propagation from Wind Turbines

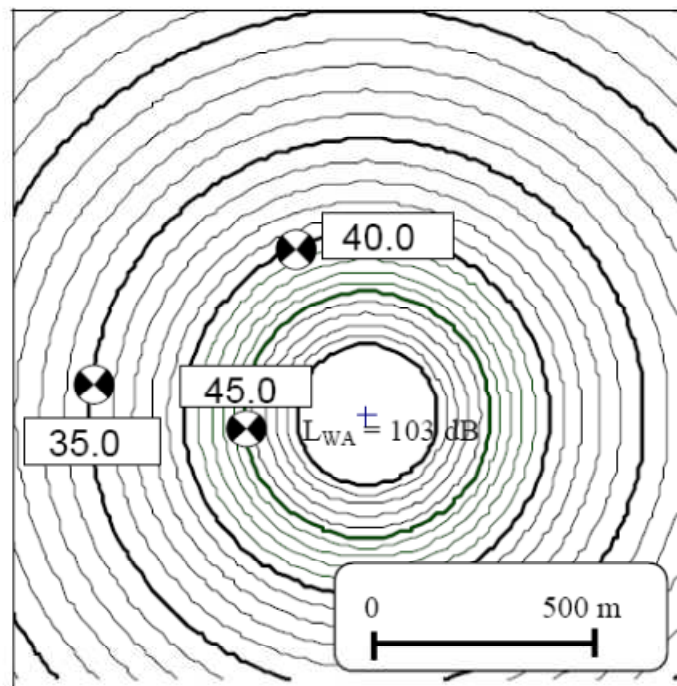
The sound pressure level will decrease with distance from a turbine. For estimation purposes, a simple model based on hemispherical noise propagation over a reflective surface, including air absorption, is given as:

$$L_p = L_w - 10 \log_{10}(2\pi R^2) - \alpha R \quad (43)$$

where  $L_p$  is the sound pressure level (dB) a distance  $R$  from a noise source radiating at a power level  $L_w$  (dB) and  $\alpha$  is the frequency-dependent sound absorption coefficient. For broadband estimates the absorption coefficient is often approximated by a constant value of 0.005 dB(A)/m.

Figure AE.1 (from Materialien 63) indicates the sound pressure level as a function of distance from a single wind turbine with a sound power level of 103 dB(A).

Figure AE.1: Typical sound pressure level vs. distance from a single wind turbine (From Materialien 63)



The results are summarized in Table AE-1.

Table AE-1  
Sound pressure level vs. distance

Sound Pressure, dB(A)	Distance, m
45	280
40	410
35	620

It may be seen that Equation 43, using the broadband absorption coefficient, predicts results close to those in the table (270 m, 435 m, and 675 m respectively).

#### AE.4 Noise Propagation from Multiple Wind Turbines

The sound perceived at a distance from multiple wind turbines is a function of the sound power level from each wind turbine and the distance to that turbine. The perceived value can be approximated by the following equation:

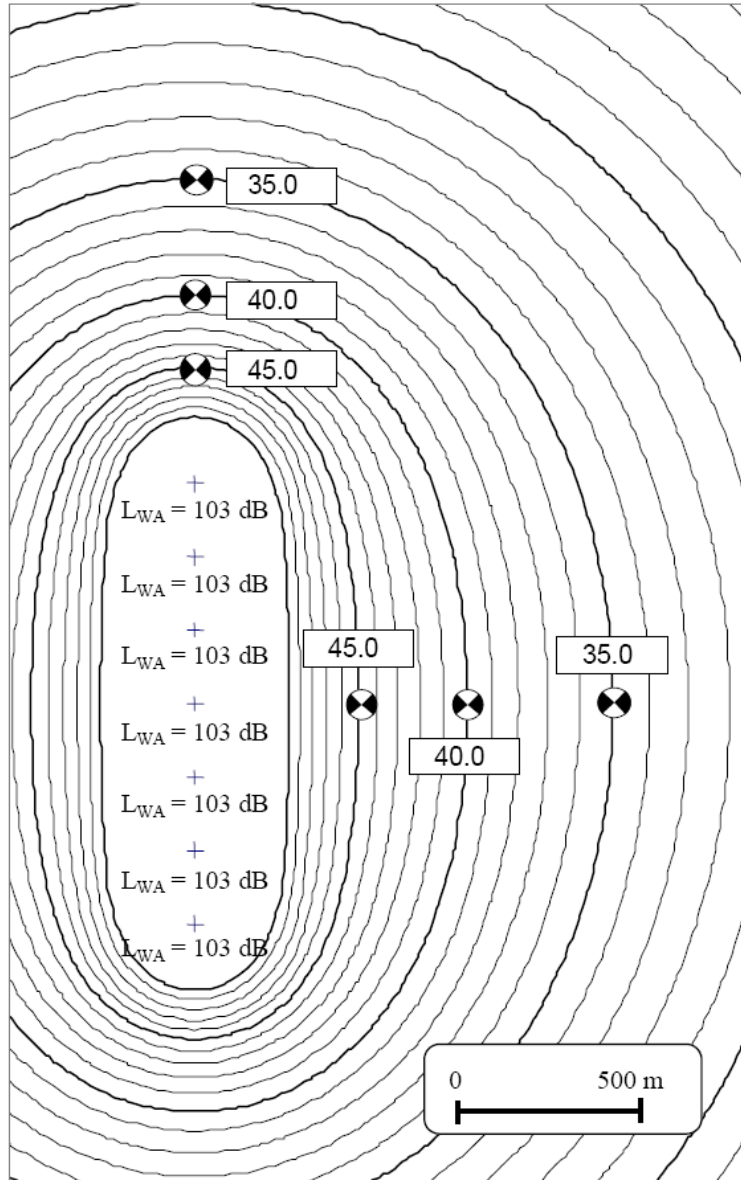
$$L_p = 10 \log_{10} \left[ \sum_{i=1}^N \frac{10^{(L_{w,i}/10 - \alpha R_i/10)}}{2\pi R_i^2} \right] \quad (44)$$

Where  $R_i$  is the distance to the  $i^{\text{th}}$  turbine.

Figure AE-2 illustrates the sound pressure level at various distances and directions from a line of seven wind turbines, each of which is operating at a sound power level of 103 dB(A).

WIND TURBINE HEALTH IMPACT STUDY

Figure AE.2: Sound pressure level due to a line of seven wind turbines, each operating at a sound power level of 103 dB(A) (from Materialien 63)



WIND TURBINE HEALTH IMPACT STUDY

The results are summarized in the Table AE-2.

Table AE 2:

The distances shown are in the direction perpendicular to the line of the turbines

<b>Sound Pressure, dB(A)</b>	<b>Distance</b>
45	440
40	740
35	1100

## Appendix F

### Wind Turbine – Stall vs. Pitch Control Noise Issues

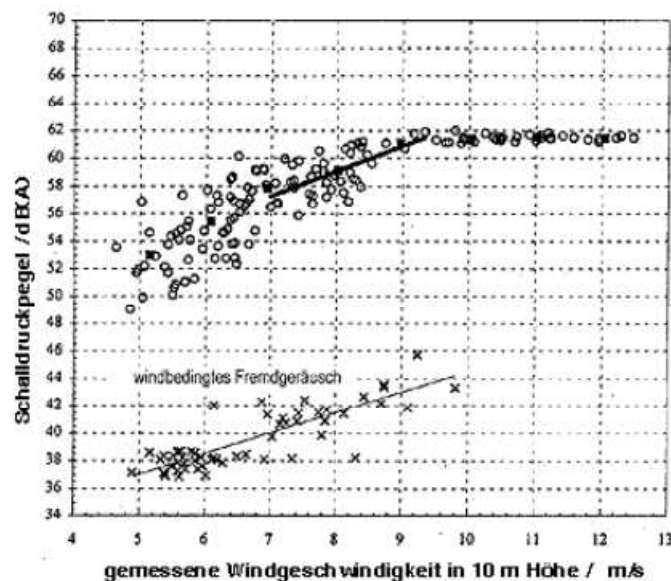
As noted in Appendix A, pitch regulated turbines are quieter than those with stall control. This is particularly the case at higher wind speeds. This appendix illustrates the difference, based on one source.

#### AF.1 Typical Noise from Pitch Regulated Wind Turbine

The figure below illustrates sound pressure level as a function of wind speed from a pitch regulated wind turbine (The data was taken at an unspecified distance from the turbine).

As can be seen, the noise level increases with wind speed up to a certain wind speed, here 9 m/s. After that wind speed is reached the blade pitch regulates the power and the noise level remains constant.

Figure AF.1: Sound pressure vs. wind speed from a pitch regulated wind turbine (from Materialien 63)



y-axis: sound pressure level, dB(A)

x- axis measured wind speed at 10 m height, m/s

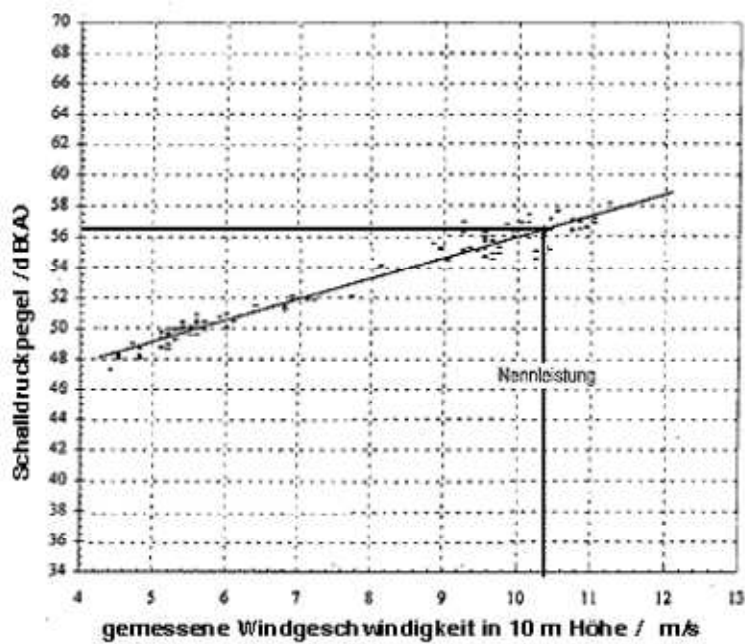
lower line: wind-induced background noise



### AF.2 Noise from a Stall Regulated Wind Turbine

The figure below illustrates sound pressure level as a function of wind speed from a stall controlled wind turbine (The data was taken at an unspecified distance from the turbine).

Figure AF.2: from Materialien 63



y-axis: sound pressure level, dB(A)

x- axis measured wind speed at 10 m height, m/s

The rated wind speed of this turbine is 10.4 m/s

As can be seen, the noise level increases approximately linearly with wind speed and does not level off.

## Appendix G

### Summary of Lab Animal Infrasound and Low Frequency Noise (IFLN) Studies

Table AG.1

Summary of Lab Animal Infrasound and Low Frequency Noise (IFLN) Studies

Study #	Animal Model	Endpoint	"Dose"	Timing	Measured Effects	Notes	Citation
1	Male Sprague-Dawley rats; 32 rat, 10 wks	Cardiac: ultrastructure observations, Ca2+, SERCA2 expression	5 Hz at 130 dB 5 Hz at 130 dB 5 Hz at 130 dB	2 hrs - 1 day 2 hrs - 7 days 2 hrs - 14 days	inc in [Ca2+]; sig inc. SERCA2 inc in [Ca2+]; Sig decr. In SERCA2 compared with control & 1 day inc in [Ca2+]; Sig decr SERCA2 compared with control and 7 day group	No noted observation of frank toxicity. Responses increased across groups; heart rates increased in 1 day group, not in others; left ventricular pressures increased with dose chamber; Animal dose is at or slightly below 5 Hz/130 dB; Pentobarb anesthesia	Pei et al., 2007
2	Male Adult Sprague-Dawley rats	Cardiac: whole-cell L-type Ca2+ currents (WLCC) in rat ventricular myocytes	5 Hz at 130 dB	2 hrs - 1 day; examined 1, 7 or 14 days post-exposure	Inc in [Ca2+](I) levels, LCC & SERCA2	No noted observation of frank toxicity. [Ca2+](I) levels as well as expression of LCC and SERCA2 may contribute to the infrasound exposure-elicited cardiac response; cannot concur with micrograph data	Pei et al., 2009
3	Male Sprague-Dawley rats	Neuronal release of stress-induced hormones	16 Hz at 130 dB	2 hrs - single exposure	activation of microglial cells and upregulation of Corticotrophin releasing hormone receptor (CRH R1); also upregulation expression is blocked by antalarmin	No noted observation of frank toxicity. Measured in the hypothalamic paraventricular neurons. Antalarmin is a non-peptide drug that blocks the CRF-1 receptor, and, as a consequence, reduces the release of ACTH in response to chronic stress	Du et al., 2010
4	Male Sprague-Dawley rats	Neurogenesis	16 Hz at 130 dB	2 hrs/day - 7 days (sacrificed at 3, 6, 10, 14 & 18 days post-exposure)	Measured early migration and differentiation in newly generated progenitor cells by examining BUdR uptake in cells in the hippocampus (dentate gyrus)	No noted observation of frank toxicity. Authors conclude infrasound inhibits cell proliferation and that effects on proliferation appear to be reversible in the 18 days post exposure groupbackground - 40 dB; authors report reversibility, but the data don't support this - also, comparisons are with the "normal" group (in chamber, but no infrasound) but no comparison with control.	Liu et al., 2010
5	Male Albino Wistar Rats	Neural: Behavioral Performance - vestibular function	16 Hz at 72-105 dB		Rota-rod Treadmill evaluation	No noted observation of frank toxicity. Rats selected for superior performance were unaffected, but inferior rats were less able to perform for as long at same exposures.	Yamamura & Kishi, 1980
6	Male Wistar rats	Neurological - biochemical	2 Hz at 105 dB 7 Hz at 122 dB 26 Hz at 124 dB	1 hr & then sac'd 1 hr & then sac'd 1 hr & then sac'd	Measured brain neuropeptide levels Measured brain neuropeptide levels Measured brain neuropeptide levels	No noted observation of frank toxicity. No control to determine whether Norepi levels were due to experimental design - not well controlled.	Spyraki et al., 1978
7	Female rats - no strain given	Neural	2 Hz at 105 dB 7 Hz at 122 dB 16 Hz at 124 dB		Observations made about rats' activity	Decreased time to sleep and decreased activity. Chamber and set-up is somewhat archaic and confirmatory measures are not made.	Spyraki et al., 1978
8	adult male Sprague-Dawley rats	Neural: hippocampus - dependent spatial learning and memory	16 Hz at 130 dB	14 days	Observations made using Morris water maze, measured expression and protein levels of brain-derived neurotrophic factor-tyrosine kinase receptor B.	No noted observation of frank toxicity. Calibration of sound chamber not discussed.	Yuan et al., 2009

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## WIND TURBINE HEALTH IMPACT STUDY

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*The views and opinions expressed in this report are solely those of the original authors, the expert panelists whose research focused on the topic of the potential health impacts associated with wind turbines. These views and opinions do not necessarily represent the views and opinions of the University of Massachusetts or the UMass Donahue Institute.*