

New York State Energy Research and Development Authority

Wind Turbine-Related Noise: Current Knowledge and Research Needs

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Wind Turbine Noise: Current Knowledge and Research Needs

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Acronyms and Abbreviations List

dB	decibel
dBA	decibel level on A weighted sound pressure scale
dB(C)	decibel level on C weighted sound pressure scale
dB(G)	decibel level on G weighted sound pressure scale
DEC	New York State Department of Environmental Conservation
DOH	New York State Department of Health
EPA	United States Environmental Protection Agency
ft	feet
hr	hour
Hz	hertz
km	kilometer
L _{dn}	A-weighted sound level average over 24 hr with 10 dB penalty added to nighttime levels
L _{eq}	long-term equivalent A-weighted sound level
m	meters
mph	miles per hour
MW	megawatts
m/s	meters per second
NASA	National Aeronautics and Space Administration
NYSERDA	New York State Energy Research and Development Authority
OSHA	Occupation Safety and Health Administration
WHO	World Health Organization

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Introduction

Wind energy is a growing renewable energy source in New York State. Wind turbine energy is considered a green, domestic source of energy. During operation, wind energy generation results in zero gaseous and particulate air pollutant emissions, and will help with New York State's goal of energy independence.

According to the New York State Energy Research and Development Authority (NYSERDA), New York State has approximately 5,000 megawatts (MW) of land-based wind potential¹ – enough to supply 10 percent of New York State's electricity needs. As of November 2011, 39 wind power projects were under way or proposed in New York State, according to the New York State Department of Environmental Conservation (DEC). In the spring of 2012, wind power from 18 projects made up approximately 2 percent of the electric power available to New York State (or more than 1,400 MW of capacity, potentially powering nearly 300,000 homes²).

Although wind is a source of clean, renewable, domestic power, it does present some challenges. Residents living near recently built wind farms and wind parks have expressed concerns about visual (shadow flicker), aesthetic (industrial-like view), ice throw, and noise issues. Residents have also questioned the potential impact on real estate values for homes located near wind turbines. Most noise-related complaints have focused on vibrations or a “whooshing” sound that results in annoyance and/or sleep disturbance. For this reason, most health effects research has addressed low-frequency sound emitted by wind turbines.

Literature reviewed for this report included more than 40 documents related to sound and noise. The sound literature included health assessments, epidemiology studies, laboratory studies, case studies, and literature reviews. The noise literature included general as well as wind turbine-specific issues. Most of the literature identified was community epidemiological or case studies that include sound (noise) measurements and subjective health data (such as questionnaires and interviews). The second most common type of reports involved community sound measurements without health data. Few of the studies reviewed included sound measurements both inside homes and outside homes. Literature reports including objective health data (measurable health conditions or outcomes) were essentially absent from the wind turbine literature.

¹ NYSERDA. “Large Wind Farm Developments.” Available from: <http://www.nyserda.ny.gov/Renewables/Large-Wind.aspx>

²S DEC. “Wind Power.” Available from: <http://www.dec.ny.gov/energy/40966.html>



Marble River Wind Farm

Figure 1 Key Points

Key Points

- Noise (unwanted sound) from wind turbines can include aerodynamic sound (such as “whooshing”) from the turbine blades moving through the air and mechanical sound from internal gears.
- Health symptoms most often reported in connection with wind turbine noise include annoyance and sleep disturbance.
- Researchers have identified a “worst case scenario” for wind turbine noise consisting of nighttime conditions, a stable atmosphere and low wind speeds.
- Research correlating health effects with wind turbine noise is limited; future research, including more extensive, well-targeted sound measurements and objective health data, is needed to better understand the issue.

1 What is Sound and How Is It Measured?

Sound is created by fluctuations in air pressure that move in waves through the air. People perceive these pressure variations as an auditory sensation—as sound. If the sound is unwanted, harmful or inappropriate in the environment, it is considered noise.

1.1 Sound Pressure

Humans perceive the relative strength of sound waves that reach the ear (sound pressure) as loudness or volume. In general, sound pressure levels are measured in decibels (dB). The threshold of human hearing is 0 dB, and the threshold of pain from sound occurs around 120-140dB. The decibel scale is logarithmic, so that a small change in the decibel level means a large change in loudness. For example, a 10 dB increase in sound pressure is perceived as a twice as loud as the original sound. Below are some examples of noise levels expressed as dBA; The “A” designation refers to measures that have been weighted to characterize audible noise.

Table 1. Examples of dBA sound levels ³

Airplane	130-150 dBA
Inside a car	70-90 dBA
Office Setting	55-75 dBA
Wind Turbine	40-50 dBA
Bedroom	30-35 dBA
Whisper	BA

1.2 Frequency

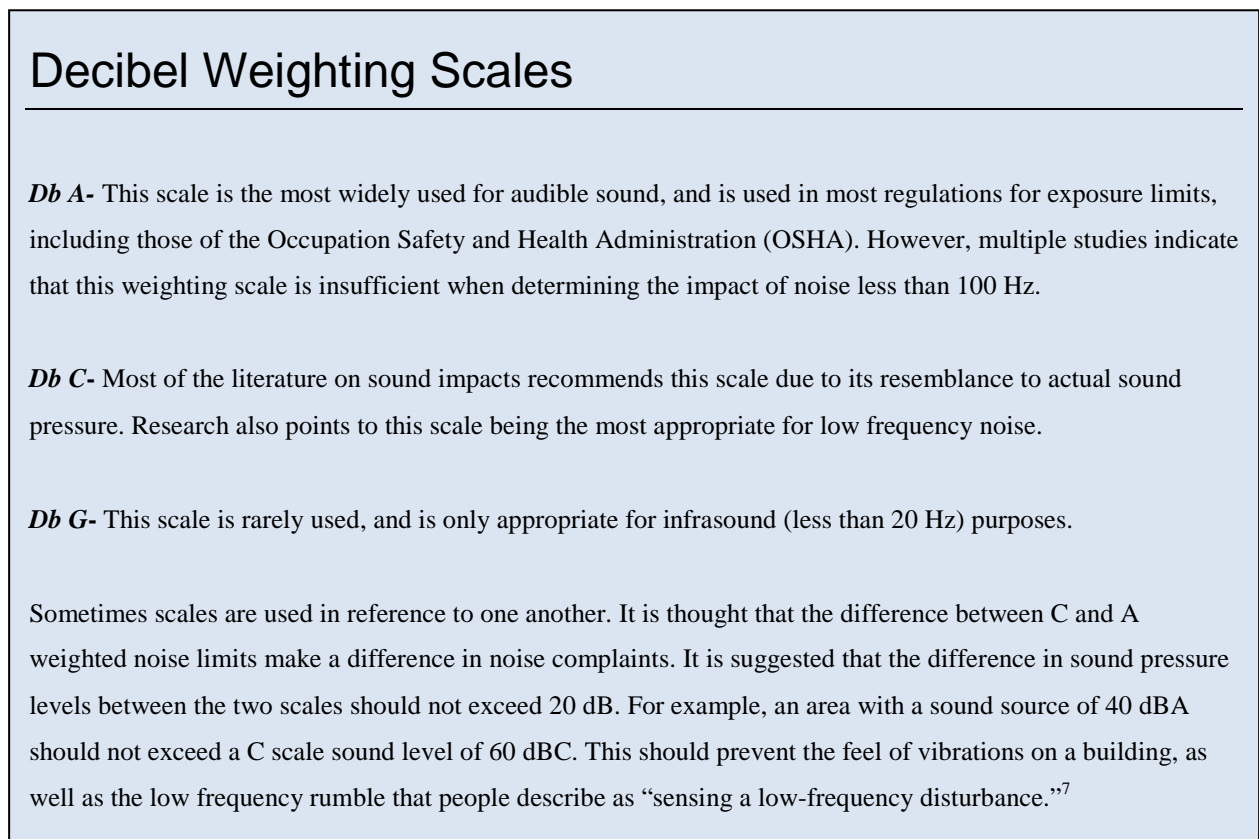
The frequency of sound refers to how many times per second the air in a sound wave expands and contracts, and is measured in Hertz (Hz). A higher frequency means that the air pressure fluctuates more quickly. Humans hear this increased fluctuation as a higher pitch. When there are fewer fluctuations per second, the pitch is lower. The definitions of different frequency ranges that are referred to in sound literature are:

- Audible Sound—sound that humans hear, which generally falls within the 20-20,000 Hz frequency range.
- High Frequency Sound—also known as ultrasound and consists of frequency levels above the human audible range (higher than 20,000 Hz). Although most humans cannot hear in this range, some animals can detect high frequency sound. Dogs can hear up to 45,000 Hz, and dolphins can hear up to 200,000 Hz. Thus, humans will not hear some sounds regardless of the decibel level, due to the frequency of the sound. High frequency sounds tend not to travel as far as lower frequency sounds.

³ American Wind Energy Association. http://www.windpoweringamerica.gov/newengland/issues_sound.asp?&print

- Low Frequency Sound—sounds with frequency levels in the 20-200 Hz range. These sounds are entirely within the audible sound range of humans. Low frequency sound is dangerous at very high dB levels. A frequency of 196 Hz at 160 dB is reportedly able to cause internal organ irritation after five minutes of exposure.⁴
- Infrasound- sound with frequency levels below 20 Hz and is not audible by most humans. Infrasound occurs naturally, and is produced by volcanic eruptions, ocean waves, wind and everything that produces sound by causing the air to oscillate slowly. It tends to travel much greater distances than higher frequencies sounds. Higher decibel levels of infrasound are associated with people reporting a sense of unsteadiness, or “a disturbance in the environment.” According to the Massachusetts Wind Turbine Health Impact Study, vibrations below 100–110 dB are not felt; infrasound at amplitudes over 100–110 dB can be heard and felt.⁵ Studies prepared for the National Aeronautics and Space Administration (NASA) suggest no significant effects from infrasound until the level exceeds 125 dB.⁶ Infrasound can cause body vibrations at very high decibel levels.

Figure 2. Decibel Weighting Scales



⁴ Leventhall, 2005

⁵ Massachusetts Department of Environmental Protection 2012

⁶ Howe Gastmeier Chapnik Limited 2006

⁷ Alberts, 2006

1.3 Sound Propagation

In addition to sound pressure levels and frequency, another factor relevant to wind turbine noise is how sound travels, also known as sound propagation. Many factors contribute to how sound propagates, including:

- Distance – The decibel level of a sound attenuates (lessens) with distance. There is a 6 dB decrease for every doubling of distance from a stationary source as seen in Figure 3.⁸ In addition, as shown in Figure 4, sounds with different frequencies will attenuate differently with distance. A sound with a frequency of 8,000 Hz will decrease by nearly 50 dB over about 1,000 meters, whereas a sound of 125 Hz will decrease only about 15 dB over more than 20,000 meters.

Figure 3. Attenuation by Distance

Bruel & Kjaer Sound & Vibration Measurement A/S⁹

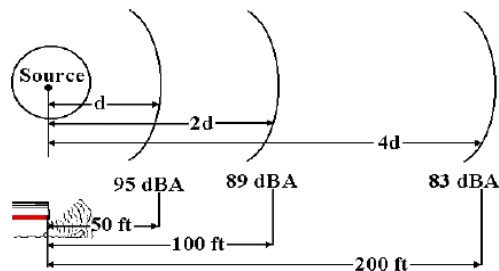
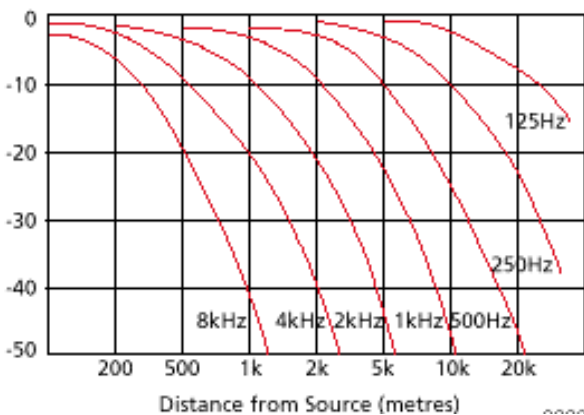


Figure 4. Frequency Attenuation

Bruel & Kjaer Sound & Vibration Measurement A/S¹⁰



Wethersfield Wind Farm

⁸ Bruel & Kjaer 2000

⁹ Bruel & Kjaer 2000

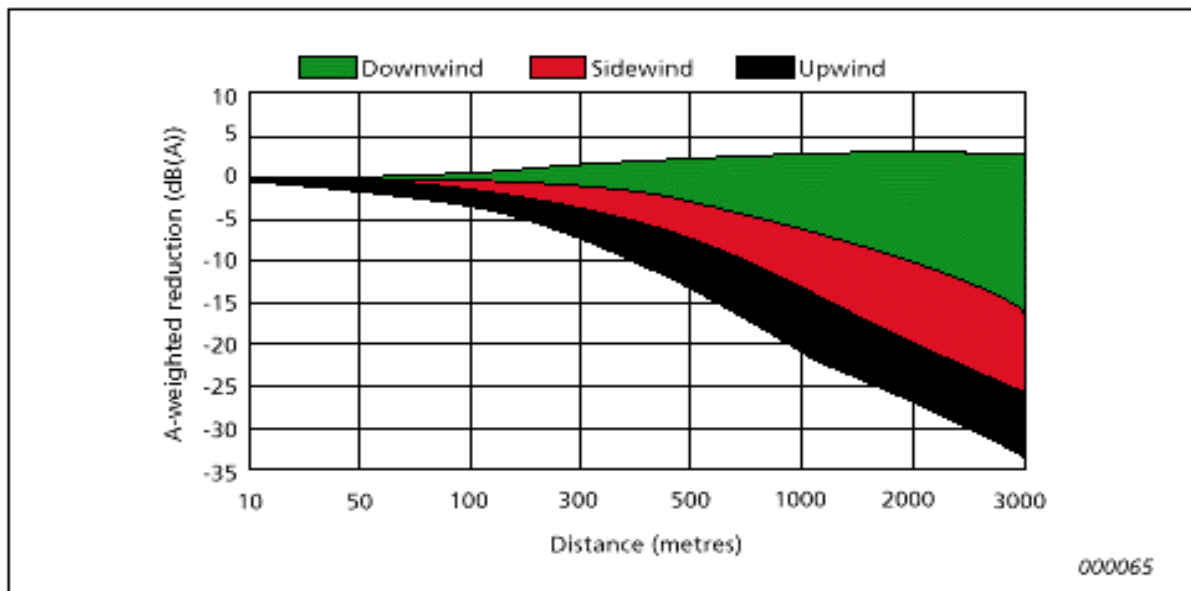
¹⁰ Bruel & Kjaer 2000

- Wind Direction – As seen in Figure 5 below, being located downwind of a source (such as a wind turbine), sound will remain relatively constant over a greater distance from the source than being located upwind of a source. Sound waves going downwind will bend down toward the ground. The following quote comes from a report by Daniel Alberts, senior member of the Society for Technical Communication.¹¹ In his report, he states:

Within 900 ft of a sound source, the wind direction does not seem to influence the sound. But after about 900 ft., the wind direction becomes a major factor in sound propagation. Downwind (meaning the wind is moving from the noise source towards the receiver) of the source, sound volume will increase for a time before decreasing. Upwind (the wind is moving from the receiver to the noise source), sound volumes decrease very quickly.

Figure 5. Wind Attenuation of Sound

Bruel & Kjaer Sound & Vibration Measurement A/S¹²



- Building Materials – General home construction materials may reduce noise, depending on the sound frequency range. In cold climates, homes have been estimated to attenuate 27 dB of noise; however, this estimate is based on traffic noise. Wind turbine noise, especially at lower wind and blade speeds, contains more low frequency sound than traffic noise, and lightweight building structures will not attenuate lower frequency noise as well as higher frequency noise.¹³ A report¹⁴ written for policy makers in Alberta, Canada, states that:
 - Low frequency noise is very difficult to suppress. Closing doors and windows in an attempt to diminish the effects sometimes makes it worse because of the propagation characteristics and the low-pass filtering effect of structures.
 - Heavy (dense) materials such as brick or stone walls serve well against low frequencies, but doors and windows permit the low frequencies to enter the home. Insulation solutions might be considered to increase energy efficiency while mitigating against lower and higher frequency sound.

¹¹ Alberts 2006

¹² Bruel & Kjaer 2000

¹³ Alberts 2006

¹⁴ DeGagne and Lapka 2008

- Topography of the Land- Sound located in a valley will stay trapped when there is an atmospheric inversion (see Worst-Case Scenario section). Flat terrain will attenuate sound as shown in Figure 3. In a terrain with more hills, however, sound waves will be both reflected and refracted if the source of the sound is near the base of the hill.
- Background Environmental Noise- Other sounds in the same location can affect sound propagation and sound levels. If two sounds are traveling to the same destination, there is an additive effect observed by the receiver of the sound (a louder perceived sound level than the individual sounds added together). This is true for tonal and repetitive sounds (such as wind turbines), but not for broad-band sounds or different types of sound.



Fenner Wind Farm

2 Current Research on Sound from Wind Turbines

2.1 What Types of Sounds Do Wind Turbines Emit?

Wind turbines make two types of sound: aerodynamic and mechanical. Aerodynamic sound is created by the wind turbine blades as they interact with the wind. The power of aerodynamic sound is related to “the ratio of the blade tip speed to wind speed.”¹⁵ Aerodynamic sound may be perceived as oscillating, whooshing or pulsing.

The aerodynamic sound from turbine blades can be “amplitude modulated”—that is, its volume can rise and fall as the blades rotate. When modulation occurs, the noise coming from the wind turbine can create an impulsive swishing or a whooshing sound. The United Kingdom Department of Trade and Industry found that most noise complaints were caused by this modulation, especially in the evenings.¹⁶ Another United Kingdom study found that amplitude modulation conditions existed between 7 percent and 25 percent of the time.¹⁷

Mechanical sound is created from the internal gears of a wind turbine. This type of noise can create distinct, perceptible, fairly consistent tones (in contrast to the whooshing blades), which potentially could be irritating. This kind of sound is a problem for wind turbine towers that are not adequately insulated. Improved insulation and other changes in the nacelle can be expected to lead to a decrease in mechanical noise being emitted from newer turbines.

2.2 What Sound Levels Have Been Measured From Wind Turbines?

2.2.1 Audible Sound Levels from Wind Farms

A number of studies describe audible sound levels measured from wind turbines:

- Several studies report audible sound measurements (20-20,000 Hz) for multiple wind farms recorded at distances more than 500 meters (approximately 1,640 feet) from the turbines during daytime hours. The highest recorded sound levels in these studies were in the range of 20-50 dBA, which is similar to sound levels ranging from a whisper to sound levels you would find inside a home.^{18,19,20}
- For two different types of wind turbines at Horse Hollow Wind Farm in Texas, researchers found that at 1,000 ft (approximately 300 m) the average noise level was 49.6 dBA for the Siemens 2.3 MW turbine, and 50.7 dBA for the General Electric 1.5 MW turbine.²¹
- According to monitoring done at the Maple Ridge Wind Farm in New York State, wind speeds of 12 m/s or less at distances of 340-640 m (1,115-2,100 ft) from the turbines, sound levels ranged between 40 and 50 dBA.²²

¹⁵ Alberts 2006

¹⁶ Hayes McKenzie Partnership Ltd 2006

¹⁷ Moorhouse 2007

¹⁸ Shepard 2011

¹⁹ Massachusetts Department of Environmental Protection 2012

²⁰ Katsaprakakis 2012

²¹ Epsilon Associates, Inc 2009

²² Schneider 2008

One case study was initiated by residents' complaints about noise in Cape Vincent, New York. The wind farm, located on Wolfe's Island, Ontario, consisted of 86 (2.3 MW) turbines, across the St. Lawrence River from Cape Vincent. The closest distance to a residence was 3.1 kilometer (km). Measurements were made preconstruction and during operation at very low wind speeds. The preconstruction average sound level was a relatively quiet 28.9 dBA, and rose to 32.8 dBA during operation.²³ Although DEC noise guidelines state that a difference in sound levels of less than 5 dBA is considered to be "noticeable to tolerable," the Cape Vincent residents expressed complaints about noise.

2.2.2 Infrasound and Low Frequency Sound Levels from Wind Turbines

Infrasound (less than 20Hz) and low frequency (20-200 Hz) noise measurements from wind turbines are also described in the literature:

- Wind turbines emit low frequency sound (approximately 25-50 dB) when there are unusually turbulent inflow conditions.²⁴
- In one wind turbine study of low frequency sound, average measurements at a distance from the turbines of 300 m with low wind speeds were 49.4 dBA and 63.5 dBC outdoors at 10 pm. Indoor measurements taken at 7:30am showed a much quieter average of 33.8 dBA and 54.7 dBC.²⁵ (Most complaints are about noise at night—see Worst Case Scenario section). Unfortunately, measurements indoors and outdoors were not taken simultaneously.
- A study at Pubnico Point Wind Farm in Nova Scotia, Canada found that upwind turbines can create pulses that contain infrasound (0-20Hz) with decibel levels less than 81 dBG. This study had trouble distinguishing the infrasound produced by the wind, the turbines and waves from the Atlantic Ocean.²⁶
- Infrasound is not associated with the "whooshing" sounds that can be characteristic of wind turbines; rather, such sounds are thought to be created by amplitude modulation. A "shhh" sound is associated with very low frequencies.

The literature reviewed suggests that there are no low frequency or infrasound effects at distances from turbines greater than approximately 1 km, and that infrasound at these distances and sometimes closer are comparable to natural infrasound sources in the environment.

²³ Schneider 2010

²⁴ Leventhall 2006

²⁵ Epsilon Associates, Inc. 2009

²⁶ Howe Gastmeier Chapnik Limited 2006

Figure 6. Considerations when measuring and reporting sound levels.

Considerations When Measuring and Reporting Sound Levels

- Sound measurements will vary from location to location due to the different variables related to sound propagation.
- Measurement equipment such as microphones can pick up extraneous noise when trying to measure noise coming directly from a specific source such as a wind turbine.
- Using modeling or calculations to estimate residential sound levels, rather than taking actual sound measurements, will lead to error unless all variables involved in sound propagation are accounted for.

2.2.3 Worst-Case Scenario

Several publications describe how a particular time of day, wind speed, and meteorological condition together contribute to what is known as the worst case scenario. This scenario consists of nighttime conditions, a stable/calm atmosphere and low wind speeds. At night, the land cools down, which can create calm conditions at ground level. Meanwhile, at the height of the turbine hub (approximately 80 m) winds are blowing more strongly than at ground level. A stable atmosphere inversion occurs, whereby the cool air near the ground's surface gets trapped underneath a warmer atmosphere above it, and vertical mixing ceases. As a result, sound also tends to get trapped in the low-lying areas (much like smoke and fog can).

Researchers have found that when wind speeds are less than 3 meters per second (6-7 miles per hour), turbines can still operate, and sound levels can be approximately 20 dBA above expected background levels, which according to the DEC can be "objectionable."²⁷ Over the course of a year, a stable atmosphere can potentially occur 43 percent of the time.²⁸ Most stable atmosphere measurements occur during nighttime hours. One study found that 72 percent of the nighttime noise measurements were higher than expected, and at very low wind speeds the sound measurements were more than twice as loud as expected.²⁹ Most measurements of wind turbine noise have been taken during daytime hours. However, this research suggests that a number of nighttime measurements under different weather conditions are also necessary, if the goal is to fully characterize nighttime noise.

²⁷ Schneider 2008

²⁸ Van den Berg 2008

²⁹ Van den Berg 2004

2.2.4 Sound in Outdoor versus Indoor Environments

Sound levels also vary in outdoor versus indoor environments. In one study that is not wind-related, sound measurements were made from 11 pm to 7 am both indoors and outdoors of homes near roadways. Outside the buildings, the average measurement was 61 dBA, which is comparable to a quiet office setting, with a maximum of 80 dBA, which compares to loudness of being inside a moving car). The sound inside the buildings averaged 41 dBA with a maximum of 61 dBA.³⁰ This goes back to the sound attenuation concepts that are discussed earlier on in the building materials section.

In addition, people in different parts of the same room indoors can experience different perceptions of sound. For example, a person standing next to a window or a door may experience different amounts of noise than standing in the center of the room. Sound measurements inside a room are higher or louder along the walls and doorways versus the middle of the room. In one study, sound in the center of the room was measured at 26 dBA, and next to the wall the sound measured 44 dBA.³¹ (Recall that a change of 10 dB is perceived as a doubling of loudness.) Many other room factors, such as height and width, influence how sound behaves in a room. Although the studies examining these factors address sources other than wind turbines, it is apparent that measuring multiple points in a room is important for sound measurement accuracy.

2.2.5 Number and Size of Turbines

Researchers report the following effects of turbine number and size:

- Having more turbines will lead to a synergistic effect on noise levels, causing them to sound louder because it is not a broadband sound that is produced.
- Larger turbines tend to emit more low frequency sounds than smaller turbines.³²



Wethersfield Wind Farm

³⁰ Pierrera 2011

³¹ Findeis and Peters 2004

³² DELTA 2008

3 Current State of Research on Health Effects from Wind Turbine Noise

The critical policy question is whether or not wind turbine noise is causing direct and/or indirect symptoms in local residents.

- Direct symptoms are symptoms that are caused from the noise exposure itself. These symptoms could include, but are not limited to, increased blood pressure, hearing loss, annoyance and sleep disturbance.
- Indirect symptoms are harder to correlate with noise because they are typically caused by an original direct symptom of the problem. One example is stress from annoyance (direct), which in turn could lead to effects on immune system function (indirect). Another example is lack of sleep or poor quality sleep (direct), which can negatively affect concentration and mood the following day (indirect).

The Occupational Safety and Health Administration (OSHA) has an 8-hour permissible noise exposure limit of 90 dBA. It has also set an impulsive (non-continuous) noise exposure limit of 140 dBA.³³ OSHA limits are based on short-term noise in an occupational setting, and generally deal with hearing loss. The population that is considered is working individuals who are assumed to be 18-55 years of age, and in relatively good health. Sensitive populations (e.g., older, younger, or health-impaired individuals) may be more easily bothered by much lower levels. As previously discussed, the highest dBA levels of wind turbine noise measured at nearby homes in the literature are in the 50 dBA range. When considering noise from wind turbines, researchers are looking at lower decibel level sounds on a longer time scale, and potential impacts on sleep disturbance and other health effects.

3.1 Annoyance

The most common direct symptom of wind turbines identified in the literature is annoyance. Annoyance is a mental state that can be experienced as a result of noise or other conditions. Depending on the person, annoyance can be experienced as anxiety, fear of the source/effects of the noise, type of sound (vibrations, tonal vs. broad-band, and different frequencies), belief that property values are depreciated, visual or aesthetic effects, or a belief that the noise could be avoided. Stress is additive, and can add to annoyance. This additive effect makes multiple stressors indistinguishable.³⁴ Here are a few examples:

- In one study, questionnaires were given out to residents living within 8 km of a group of wind turbines. The questionnaire asked about all areas of physical, environmental and health related quality of life. A comment section was available for reporting items of annoyance. Residents living within 2 km reported an overall lower quality of life and more often reported wind turbine noise annoyance in the comments section in comparison to those groups that were farther away.³⁵ Limitations of this study include a lack of sound measurements, and subjective health data (i.e., self-reported symptoms). Also, while the participants felt their annoyance and attributed it to the wind turbines, the self-reported quality of life numbers could not be directly attributed wind turbine noise exposure.

³³ OSHA 2008

³⁴ Colby 2009

³⁵ Shepherd 2011

- In multiple studies, calculated sound levels from within 2.5 km were compared to self-reported outdoor noise annoyance questionnaires from residents. Overall, less than 20 percent of residents were slightly annoyed, and less than 10 percent were very annoyed. For noise levels at a moderate level, such as a home or quiet office setting (greater than 40 dBA), the number of individuals who were very annoyed nearly quadrupled.^{36,37} Overall, few people were annoyed by the turbine noise, but the numbers increased as the sound level increased to more than 40 dBA. For indoor noise annoyance, less than 15 percent of participants reported any annoyance from wind turbines. Limitations of these studies include sound level calculations versus actual measurements inside the homes, subjective health data and low participation.
- A recent study conducted in the Wethersfield, NY wind park (126 MW) looked at A-weighted sound levels versus community responses to surveys. Monitoring was done at two background sites and five field sites, and short term measurements were also done inside and outside of resident's homes. The average sound measurements in the park locations were 44.8-51.6 dBA. At the resident's homes, the outdoor average sound level was 45 dBA, and indoors was 47 dBA (these sound measurements include other potential sources of noise as well). There were 62 participants in the surveys, and only 32 percent stated they were annoyed with the sound with varying severities. However, 91 percent of participants were satisfied with their living environment.³⁸

Annoyance can also be compounded by multiple sensory effects. For example, when someone is both visually and acoustically annoyed by wind turbines, it may be difficult to separate the two in an analysis. In the Cape Vincent, NY, study, local residents completed a questionnaire. Sound measurements were an average of 32.8 dBA (bedroom level sound). While 38 percent of participants were annoyed with the wind turbine sound at times, 88 percent of participants were annoyed with the new view of the turbines, and 92 percent were annoyed with the shadow flare effects and flickering lights.³⁹ Because annoyance can be compounded, it is possible the visual and sound annoyance impacts overlapped. Perhaps there is even an additive role as well.

It is also unclear whether larger or smaller turbines cause more annoyance. Large turbines emit more low frequency sound than do smaller turbines. However, one report suggested that lower frequencies were not found to be any more annoying than the higher frequencies that are created.⁴⁰

³⁶ Pedersen and Waye 2004

³⁷ Bakker 2012

³⁸ NYSERDA 2013

³⁹ Schneider 2010

⁴⁰ DELTA 2008

3.2 Sleep Disturbance

Sleep disturbance is the second most common complaint about wind turbine noise. Sleep disturbance can have many causes, and, over time, can lead to secondary health effects. These effects include but are not limited to stress, next day mood and performance issues and immunological effects. Extensive research shows a correlation between environmental noise and sleep disturbance. In addition, some research suggests that along with causing actual awakenings (sleep disturbance), environmental noise can affect the rate of change between the four stages of sleep, thereby affecting sleep quality.⁴¹ Sleep disturbance is thought to occur with sound levels of 50 dBA or louder, and subjective sleep quality to change at 40 dBA or louder.^{42, 43}

Sleep disturbance can vary between urban and rural areas due to different causes of sleep disturbance and different background noise levels. In one study, questionnaires were given to local residents in both urban and rural settings located near turbines. These questionnaires asked about both the frequency of sleep disturbance and the cause, if known. The study found that 6 percent of the rural community (no major roads and within 500 m of a wind turbine) and 4 percent of the urban community attributed sleep disturbance to the wind turbines.⁴⁴ Limitations of that study included self-reported sleep data and potentially non-objective questions.

3.3 Other Health Effects

In addition to annoyance and sleep disturbance, other symptoms related to noise in numerous environments have been reported. Cardiovascular effects and effects on performance are discussed extensively in the literature, whereas health effects from low frequency sound and infrasound and health effects specific to wind turbine noise are mentioned in a very limited number of studies.

- Cardiovascular effects. One area with extensive research in the field of noise is cardiovascular biomarkers and symptoms. These effects include blood pressure; heart rate variability; and symptoms such as hypertension, myocardial infarction, angina and cardiovascular disease. However, research is only extensive in the areas of occupational exposure, road traffic and airports. The high decibel levels for these sources of sound means that this research may not always be applicable to wind turbine noise. For road traffic noise, there is the suggestion of an increased risk of myocardial infarction and cardiovascular disease rate in people exposed to sound pressure levels greater than 60 dBA (office sound level) over time, increasing in a dose-response relationship.⁴⁵ Continuous occupational noise at more than 80 dBA (very loud) shows a moderate increased risk for coronary heart disease.⁴⁶ For general noise exposures, it has been shown that relative risk increases slightly for hypertension for every 5 dBA increase in sound pressure levels starting at a moderate sound level of 55 dBA, and a significant increase in relative risk for hypertension for sound levels exceeding a very loud 85 dBA.^{47, 48}

⁴¹ Stansfeld and Matheson 2003

⁴² Ohrstom, 1989

⁴³ Passchier-Vermeer 2000

⁴⁴ Bakker et al. 2012

⁴⁵ Babisch 2008

⁴⁶ Virkkunen, 2005

⁴⁷ Van Kempen 2002

⁴⁸ Passchier-Vermeer 2000



High Sheldon Wind Project

- Effects on performance. Changes in performance have also been linked to noise exposure. In school settings, it has been documented that outdoor exposures of 70 dBA or more can lead to changes in performance in school children. It is important to note that these levels are general measures of loudness, and the frequencies may vary among different settings.⁴⁹
- Health effects from low frequency sound and infrasound. A research group in Portugal has stated the existence of a collective group of symptoms labeled vibroacoustic disease. This phenomenon is said to be the result of biological effects of exposure to low frequency sound and infrasound. Symptoms occur in three stages according to exposure time and include, but are not limited to, abnormal collagen levels, pericardial thickening and genotoxicity.⁵⁰ Some limitations of this research include self-citing within the same research group and a lack of appreciable measurements. It is important to note that this research focused on aeronautical and train-related noises, not wind turbines.
- Health effects specific to wind turbine noise. In her book “Wind Turbine Syndrome,” pediatrician Nina Pierpont states that living in the vicinity of wind turbines can lead to a collection of symptoms including internal pulsation, quivering, nervousness, fear, compulsion, tightening of the chest, tachycardia, increased heart rate, headaches, vertigo, nausea, sleep deprivation and eye-related problems.⁵¹ This description is drawn from a small convenience sample study that has several limitations. The book is self-published and not peer-reviewed. The author included a small sample size (10 symptomatic families) with no control group, claims causation rather than a correlation, did not look into the medical histories of the participants, did not include measurements of sound, and used non-objective questions (e.g., “Did the wind turbine noise give you headaches?”) in her interviews with participants.

⁴⁹ Ohrstom 1989

⁵⁰ Alves-Pereira 2007

⁵¹ Pierpont 2010

4 Policy Relevant Noise Assessments

4.1 International Assessment of Environmental Noise Health Effects

The World Health Organization (WHO) published a literature review in 2011 that focuses on overall environmental noise, including but not limited to road, rail, airports and industrial sites.⁵² The symptoms addressed were cardiovascular disease, cognitive impairment, sleep disturbance, annoyance, and tinnitus (inability to perceive silence and ringing in the ears). This literature review synthesized research on the relationship of environmental noise and these symptoms, and presents dose-response relationships for some sound pressure levels:

- Hearing impairment and tinnitus: The WHO found that hearing impairment does not typically occur with exposure to sound pressure levels less than 70 dBA (mid-range of office sound) for extended periods of time, up to a lifetime exposure.
- Annoyance: The report states that for air, rail and road traffic noise, less than 3 percent of the population experiences annoyance for exposures less than 55 dBA (lower range of office level sound). Annoyance prevalence rises as sound pressure level increases.
- Sleep disturbance: The report presents ranges of sound pressure level exposures at night based on a weight of evidence. According to the WHO literature review, for 40-55 dBA at night, “adverse health effects are observed among the exposed population. Many people have to adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.”

The WHO report does not include wind turbine studies or measurements. Although its analysis of sound pressure levels may provide some guidance for future research in the area, it may not apply directly to the tones and frequencies that wind turbines may produce, which are different from other environmental noise sources.

4.2 US EPA’s Environmental Noise Levels Document

One of U.S. Environmental Protection Agency’s (EPA) most well known reports on noise was created to protect people against hearing impairment, as well as try to mitigate some annoyance that was reported through surveys. The researchers used two forms of noise measuring metrics to create adequate levels for the public. The first is known as Leq (long-term equivalent A-weighted sound level), and the second is Ldn (A-weighted sound level was averaged over 24 hours with a 10 dB penalty added to nighttime sound levels).⁵³

For outdoor levels in residential areas, the recommended L_{eq} and L_{dn} is less than 55 dB. For indoor levels, the recommended L_{eq} and L_{dn} is less than 45 dB. The goal of these recommendations is to receive only sporadic complaints or less from communities.

⁵² World Health Organization 2011

⁵³ U.S. Environmental Protection Agency 1974

EPA also addresses an important concept of normalization of sound levels based on different circumstances. For a quiet rural neighborhood, 10 dB needs to be added to the sound source level. If the community is brand new to the noise source, then an additional 5 dB must be added to the sound calculation. If the sound is impulsive, another 5 dB must be added to the sound calculation. So if wind turbines are installed in a community similar to the circumstances described, 20 dB would need to be added to the sound source level from the reception point to adequately normalize the noise level. A wind turbine should then hypothetically not be higher than 35 dB at any resident's location to insure that the level stays below 55 dB. Setback distances of turbines to residences should ensure these sound levels before operation.

4.3 Massachusetts Health Impact Assessment Review

A Massachusetts Department of Environmental Protection health impact assessment provided sound measurements associated with wind turbines and a discussion of health effects. However, the results of this study may not be universal because the different variables that influence sound propagation will cause different experiences for different areas and residents. Given those caveats, this study found that the sound level for a “typical modern utility scale” wind turbine at its site is 103 dBA, which is similar to the loudness of a lawn mower or motorcycle.⁵⁴ On average, at distances greater than 400 m from the turbines, the sound level dropped to less than 40 dBA (library level sound). The report recommends that for residential areas, setback distances should be selected to assume that a 37-dBA threshold is not exceeded at receptors. The highest infrasound measurements found in this assessment near a turbine was 90 dB at 5 Hz (with distances of less than or equal to 100 m).

In regard to health effects, the report concludes that there is insufficient evidence for a correlation between wind turbine noise and health problems or disease (excluding annoyance and sleep disturbance). This study also comes to the same conclusion about visual and noise annoyance overlap.

⁵⁴ Massachusetts Department of Environmental Protection 2012

5 Limitations of Current Research

Overall, the current research does provide some understanding about research related to general noise exposures and health, but is limited in relation to wind turbines. Some of the limitations found in this literature review include the following:

- A lack of indoor measurements makes it difficult to get accurate sound levels to understand public health implications, as on average a majority of people's exposure time occurs indoors.
- Topography and meteorology varies greatly from location to location. Generic sound standards and setback limits (based on another location) may not always be appropriate due to sound propagation and attenuation by site specific circumstances.
- Lack of objective health data makes it difficult to determine whether wind turbine noise is a public health issue, and the magnitude of the health issue (e.g. severity, prevalence).
- The inability to distinguish annoyance from sound, visual, and/or or aesthetic effects makes annoyance attribution rates difficult to quantify.
- Only a few studies show a correlation between sleep disturbance and wind turbine noise. There is a lack of measurable objective sleep disturbance data, as most of these studies are based on questionnaires.
- There is insufficient evidence at this time to correlate wind turbine noise with any health symptoms other than sleep disturbance and annoyance.
- Given the limited number of wind turbine facilities, and that individuals reside in close proximity to these machines, acquiring a research sample size that is sufficient to identify correlations and trends may be difficult.



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6 Future Research Needs

This review points to key comparisons, limitations and the state-of-the-science on potential impacts of sound produced by wind turbines. Although this review of the current literature finds very limited evidence to corroborate indirect symptoms of wind turbine noise, it does not conclude that such symptoms do not exist. More research is needed to definitively determine whether or not short-term or long-term exposure to wind turbine noise can lead to direct or indirect symptoms.

Future research needs on wind turbine noise include the following:

- Conduct indoor sound measurements to better characterize noise impacts when siting a wind turbine project. These measurements must evaluate impacts at multiple points in a room as low frequency sound levels are not uniform across a room.
- Design experiments to determine if visual perception and noise effects are independent or synergistic with respect to annoyance. Areas where visual impacts are diminished could serve as a point of comparison with projects with greater visual impact. Topographical differences that may alter visual and noise impacts must also be assessed.
- Design a study to evaluate if there is a correlation between objectively measured sleep disturbance and wind turbine noise at night in rural communities. Although background ambient night sound levels in urban settings may be comparable to turbine noise, background night ambient sound levels in rural communities have different characteristics. In addition, the expectation for nighttime quiet may differ in urban and rural populations.
- Collect and synthesize data to determine if the mapping and modeling scenarios are used in determining setback distances are adequate for all nighttime, meteorological, topographical and ground level wind speeds.
- Determine if there are identifiable sensitive populations that should be considered when permitting the siting of wind turbines.



Hardscrabble Wind Project

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Wind Turbine-Related Noise: Current Knowledge and Research Needs

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