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ORION WIND RESOURCES, LLC

PRONGHORN FLATS WIND FARM SOUND MODELING

Report | June 10, 2020

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1.0 EXECUTIVE SUMMARY

The Pronghorn Flats Wind Farm project (the “Project”) is an approximately 120 MW nameplate capacity wind power generation facility proposed for Banner and Kimball Counties, Nebraska.

The Project is subject to a Kimball County noise standard of 50 dBA measured at the dwelling. There are no noise standards in Banner County nor at the state or federal levels that apply to this project. However, for those homes in Banner County, we have established a Project design goal of 45 dBA L_{1h}. This guideline was established by reviewing relevant research and recommendations made with respect to wind turbine sound.

To assess the noise impacts of the project, RSG has conducted sound propagation modeling of the planned turbine layout. We used the internationally accepted methodology, ISO 9613-2, with parameters specific to wind turbines.

The modeling results show that project sound levels at all homes are at or below 37 dBA L_{1h} in Kimball County and 44 dBA L_{1h} in Banner County. Of the 17 homes between 40 dBA and 44 dBA, nine are on land leased for the Project.

2.0 INTRODUCTION

The Pronghorn Flats Wind Farm project (the “Project”) is an approximately 120 MW nameplate capacity wind power generation facility proposed for Banner and Kimball Counties, Nebraska. As part of the project’s Environmental Assessment (EA), RSG conducted sound propagation modeling for the proposed turbine array to assess compliance with the Kimball County noise standard of 50 dBA (metric not stated) and a self-imposed 45 dBA L_{1h} noise design goal in Banner County.

Included in this report are:

1. A project description,
2. An overview of ordinances and standards that apply to the project,
3. The establishment of a noise design goal based on relevant research and recommendations,
4. A description of sound propagation modeling procedures,
5. Sound propagation modeling results, and,
6. Conclusions.

A primer on acoustical terminology is provided in Appendix A.

Acoustical issues specific to wind turbine noise are described in Appendix B.

3.0 PROJECT DESCRIPTION

As noted above, the Pronghorn Flats Wind Farm project (the “Project”) is a proposed approximately 120 MW wind power generation facility located in the southwestern portion of Banner County and northwest corner of Kimball County, Nebraska (Figure 1: Pronghorn Flats Wind Farm – Project Area Map). The western boundary of the Project is the Wyoming state line. The northern, eastern, and southern extent of the project lands are bounded by Rd 14, Rd 19, and Rd 52 N, respectively. Land within the project area is rural and is primarily used for agriculture with some residences interspersed. The terrain is relatively flat.

The Project is modeled using General Electric (GE) 3.03 MW turbines with 140-meter rotor diameters, 98-meter hub heights, and low-noise trailing edges (LNTE). Other turbine models are also being considered. Two turbines are currently being proposed for Kimball County and 41 are being proposed for Banner County.

A single transformer at the collector substation connects the turbine array to the electric grid.

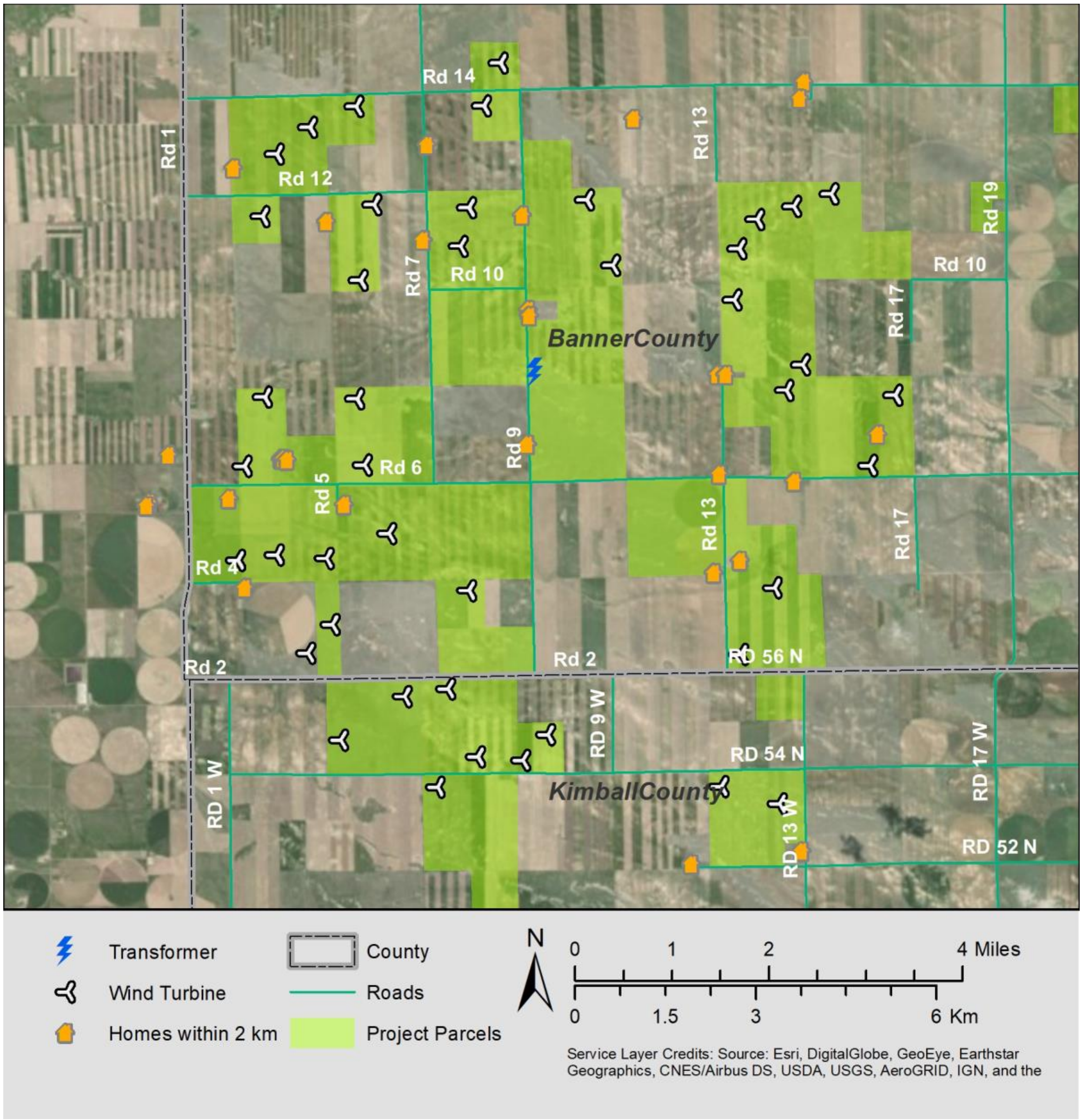

FIGURE 1: PRONGHORN FLATS WIND FARM – PROJECT AREA MAP

4.0 NOISE STANDARDS & GUIDELINES

There are no federal or state noise regulations applicable to the Project.

Kimball County has a wind energy ordinance in Section 18.03(7) of its Zoning and Subdivision Regulations. Paragraph "A" states that "No commercial WES shall exceed 50 dBA at the nearest occupied dwelling." However, this standard has no metric no averaging time and is thus ambiguous.

Section 18.03(9)(A) paragraph 11 of the Kimball County Zoning and Subdivision Regulations requires that "An Acoustical analysis that certifies that the noise requirements within this regulation can be met." This noise study is intended as that certification. The study was prepared by Mr. Kenneth Kaliski, who is Board Certified through the Institute of Noise Control Engineering (INCE). His stamp is affixed at the end of this document.

Banner County has no zoning ordinance or any other ordinance that limits the noise from wind turbines. Since there are no regulatory noise standards that apply to this project there, we have investigated several guidelines from other organizations that could be used to set a project-specific noise design goal. In particular, we have reviewed the guidelines of the U.S. EPA and Bureau of Land Management, as well as research into the effects of wind turbine sound on people. This review is detailed in Appendix C.

Given the scientific evidence regarding sleep disturbance and other impacts, the project is being designed to not exceed 45 dBA L_{1h} outside any Banner County residence. This would not apply to areas that have transient uses such as camps, driveways, trails, farm fields, barns, sheds, and parking areas. This level is more stringent than the BLM federal guidelines for wind turbines and is below the level that can cause hearing impairment, sleep disturbance, and speech interference. Note that at this sound level, the wind turbines may be audible at times, but that most people do not find this level of wind turbine sound to be highly annoying.

To protect against moderately perceptible noise-induced vibration and rattle, we are using a design goal of 65 dBZ in the 31.5 Hz, and 63 Hz low-frequency octave bands. This is consistent with ANSI S12.9 Part 4 Annex D and is conservative as it assumes no transmission loss from outside to inside the structure, even though some would be expected.[1]

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[1] RSG, et al. "Massachusetts study on wind turbine acoustics." Prepared for MassCEC and MassDEP, February 2016.

5.0 SOUND PROPAGATION MODELING

5.1 PROCEDURES

Modeling for the Project was performed in accordance with the standard ISO 9613-2, “Acoustics – Attenuation of sound during propagation outdoors, Part 2: General Method of Calculation.” The ISO standard states,

> This part of ISO 9613 specifies an engineering method for calculating the attenuation of sound during propagation outdoors in order to predict the levels of environmental noise at a distance from a variety of sources. The method predicts the equivalent continuous A-weighted sound pressure level … under meteorological conditions favorable to propagation from sources of known sound emissions. These conditions are for downwind propagation … or, equivalently, propagation under a well-developed moderate ground-based temperature inversion, such as commonly occurs at night.

The model takes into account source sound power levels, surface reflection and absorption, atmospheric absorption, geometric divergence, meteorological conditions, walls, barriers, berms, and terrain. The acoustical modeling software used here was CadnaA® Version 2020 from Datakustik GmbH. CadnaA® is a widely accepted acoustical propagation modeling tool, used by many noise control professionals in the United States and internationally.

ISO 9613-2 also assumes downwind sound propagation between every source and every receiver. Consequently, all wind directions, including the prevailing wind directions, are taken into account. The project area was modeled with hard ground (G=0). Otherwise, no reflections (such as due to buildings) were considered. Foliage attenuation was not modeled. Atmospheric absorption was based on 10˚C and 70% relative humidity and source contributions were considered up to 10,000 meters (6.2 miles) from each receiver.

Turbines were modeled with the manufacturer specified apparent sound power. All turbine data used is the most recent available from the manufacturer.

A 20-meter by 20-meter grid of 4 meter (13.1 feet) high receivers was set up in the model, covering approximately 1,078 sq. km. (416 sq. mi.) in and around the project area. The model was laid over the USGS Digital Terrain Model to give accurate elevations throughout.

A total of 30 discrete receivers, representing all homes within 2 km (1.2 mi.) of any wind turbine, were included in the model at a 4-meter (13 foot) height. Locations of these receivers are shown in Appendix E.

Results calculated with these parameters represent the highest one-hour equivalent sound level (L_{1h}) that will be emitted by the Project. The parameters used in this model combine to take into account wind turbine sound power and modeling uncertainty. As such, the results are likely to overestimate the measured sound levels.

5.2 SOUND SOURCES

Wind Turbines

The 43 preliminary wind turbine locations shown in Figure 1: Pronghorn Flats Wind Farm – Project Area Map were included in the sound propagation model. The wind turbine assumed was the GE 3.03-140 LNTE, although other models are currently being considered. If a different wind turbine is selected, revised sound modeling will be produced for that model. Details of the wind turbine modeled are found in Appendix D.

Project Transformer

The proposed 34.5 kV to 115 kV 130 MVA collector substation transformer will be located in the center of the project area (see Figure 1: Pronghorn Flats Wind Farm – Project Area Map).

The sound emissions data used for modeling is from the NEMA TR 1 standard (“Transformers, Step Voltage Regulators, and Reactors, NEMA TR 1-2013”), with spectral information taken from a transformer test performed by RSG for a similarly sized transformer. The transformer will be specified to have the highest sound level 5 dB below the NEMA TR-1 standard.

The transformer will have cooling fans. Cooling fan operation is usually a function of electric load and ambient air temperature. As a conservative assumption, we model the transformer with fans on. The fans-off cooling mode is specified by NEMA TR 1 as having sound pressure levels that are 3 dB lower.

5.3 RESULTS

Modeling results are shown in Figure 2. In this figure, the Banner County 45 dBA design goal is shown as a thick orange line. All homes are modeled to be below that project design goal. Detailed information for each receiver is provided in Appendix D.

TABLE 1: MAXIMUM PROJECT SOUND LEVELS AT ANY HOME (L_{1H})

		Octave Band	
	Overall	**31.5 Hz**	**63 Hz**
Design goal	45 dBA	65 dBZ	65 dBZ
Maximum Modeled Sound Level	44 dBA	59 dBZ	55 dBZ

In Kimball County, the maximum modeled sound level is 37 dBA L_{1h}. As noted above, the Kimball County noise standard does not have a metric or averaging time, and thus is ambiguous. We modeled for the L_{1h}, as it is commonly used for environmental noise and can be modeled and measured with a high degree of reliability. The worst-case interpretation of the standard would be some type of instantaneous maximum. In that case, the highest sound level could be up to 10 dB higher than the L_{1h}.[2] However, even with this extreme interpretation of the standard, the highest Project sound level at any Kimball County dwelling would by 47 dBA L_{max}, and would still meet the noise standard.

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[2] This is the potential difference from the maximum L_{max} over a year. The different between the Lmax and L_{1h} for a given wind power project is dependent on a variety of factors which are difficult to impossible to determine at this stage. Measurements of short-term metrics such as the L_{max} can also be unreliable.

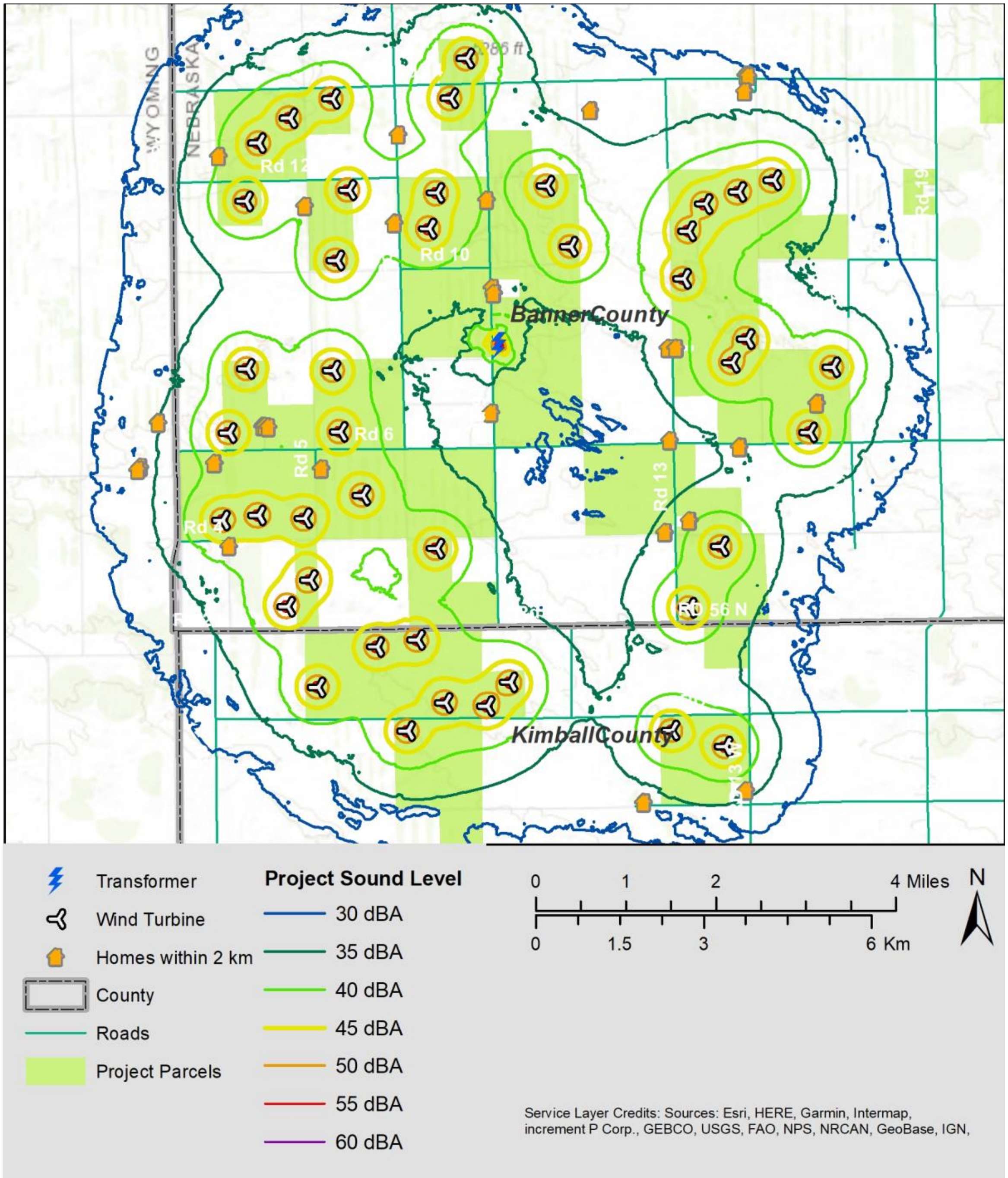

FIGURE 2: SOUND PROPAGATION MODELING RESULTS

Tonality

Figure 3 shows the tonal prominence of the GE 3.03-140 LNTE turbine compared with the ANSI S12.9 Part 4 tonality criteria. This indicates that sound power spectrum of the wind turbine does not have a tonal prominence.

The transformer in the Project substation has the potential to generate prominent discrete tones, especially at 120 Hz and its first few harmonics. Tones are always generated by a transformer but are often masked when cooling fans are operating. In addition, as one moves away from the substation, the sound is further masked by background sound (including the wind turbines).

Under ANSI S12.9 Part 4, if tonal sounds are present, 5 dB is added to the tonal sound as a penalty. In this case, the maximum sound level from the transformer is 39 dBA. Assuming it is tonal sound and not masked, adding 5 dB would bring the transformer sound to 44 dB. Thus, even with a tonal penalty, the substation sound would meet the Project design goal.

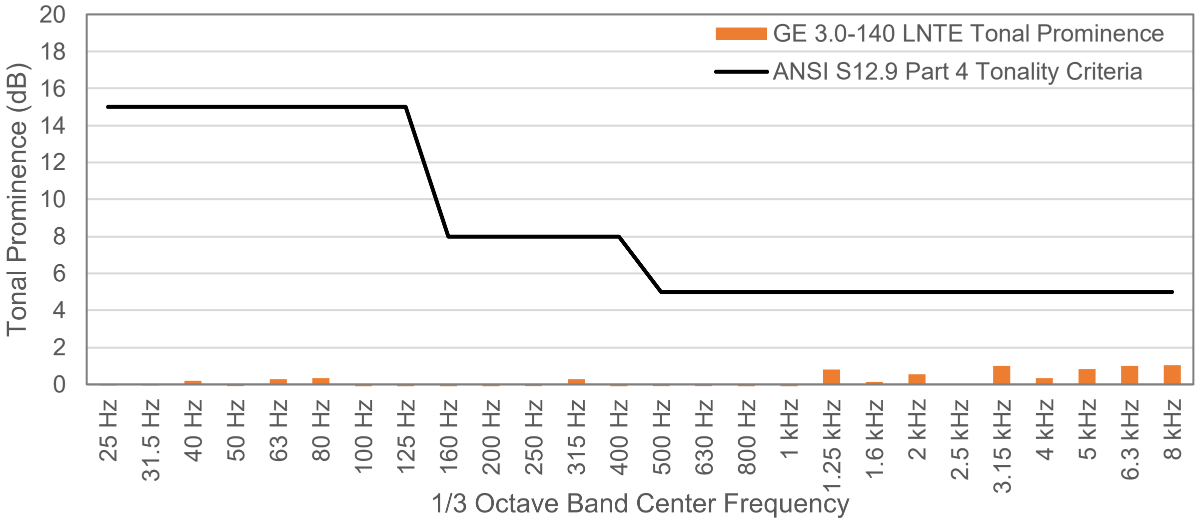

FIGURE 3: REPORTED 1/3 OCTAVE BAND TONAL PROMINENCE COMPARED TO ANSI S12.9 PART 4 TONALITY CRITERIA

6.0 CONCLUSIONS

RSG performed sound propagation modeling of the proposed Pronghorn Flats Wind Farm project as part of an Environmental Assessment. The project will be capable of generating approximately 120 MW. The modeled array consists of 43 GE3.03-140 LNTE wind turbines on a 98-meter tower, though other hub heights and turbine models are being be considered.

The Project is subject to a Kimball County 50 dBA (no metric) noise standard and a self-imposed Banner County noise design goal of 45 dBA L_{1h}, 65 dBZ L_{1h} at 31.5 Hz, and 65 dBZ L_{1h} at 63 Hz at any dwelling.

Sound propagation modeling was performed ISO 9613-2, implemented in the Cadna/A modeling package. The project model used parameters have been shown to represent conservatively accurate L_{1h} sound levels.

The results of the modeling show that all homes in the Project area, including those on Project lands, will be at 37 dBA L_{1h} or lower in Kimball County and 44 dBA L_{1h} or lower in Banner County.

As a result, no undue adverse noise impact is expected to occur, and the Kimball County noise standard and Banner County project noise design goals are modeled to be met.

Institute of Noise Control Engineering of the United States of America

Kenneth Kaliski
4002
January 31, 2022

APPENDIX A. PRIMER ON SOUND

Expressing Sound in Decibel Levels

Normal human hearing is sensitive to sound fluctuations over an enormous range of pressures, from about 20 micropascals (the “threshold of audibility”) to about 20 pascals (the “threshold of pain”).[3] This factor of one million in sound pressure difference is challenging to convey in engineering units. Instead, sound pressure is converted to sound “levels” in units of “decibels” (dB, named after Alexander Graham Bell). Once a measured sound is converted to dB, it is denoted as a level with the letter “L” (such as “L_{eq}”).

The conversion from sound pressure in pascals to sound level in dB is a four-step process. First, the sound wave’s measured amplitude is squared and the mean is taken. Second, a ratio is taken between the mean square sound pressure and the square of the threshold of audibility (20 micropascals) at 1 kHz. Third, using the logarithm function, the ratio is converted to factors of 10. The final result is multiplied by 10 to give the decibel level. By this decibel scale, sound levels range from 0 dB at the threshold of audibility to 120 dB at the threshold of pain.

Typical sound sources, and their sound pressure levels, are listed on the scale in Figure 4. Typical ambient nighttime sound levels around wind turbine locations, in the absence of wind turbines, is shown in Figure 5.

Human Response to Sound Levels: Apparent Loudness

For every 20 dB increase in sound level, the sound pressure increases by a *factor* of 10; the sound *level* range from 0 dB to 120 dB covers 6 factors of 10, or one million, in sound *pressure*. However, for an increase of 10 dB in sound *level* as measured by a meter, humans perceive an approximate doubling of apparent loudness: to the human ear, a sound level of 70 dB sounds about “twice as loud” as a sound level of 60 dB. Smaller changes in sound level, less than 3 dB up or down, are generally not perceptible.

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[3] The pascal is a measure of pressure in the metric system. In Imperial units, they are themselves very small: one pascal is only 145 millionths of a pound per square inch (psi). The sound pressure at the threshold of audibility is only 3 one-billionths of one psi: at the threshold of pain, it is about 3 one-thousandths of one psi.

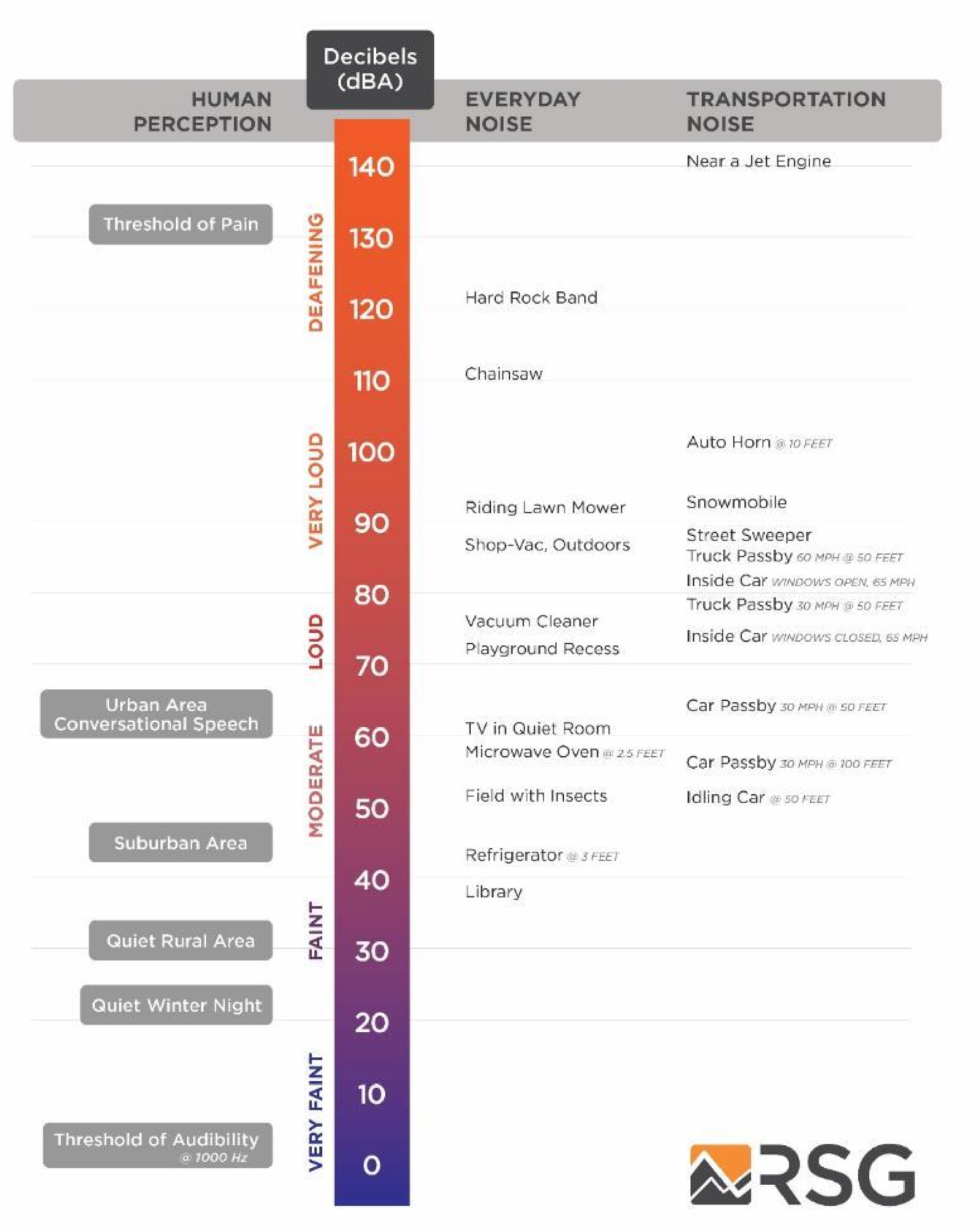

FIGURE 4: A SCALE OF SOUND PRESSURE LEVELS FOR TYPICAL SOUND SOURCES

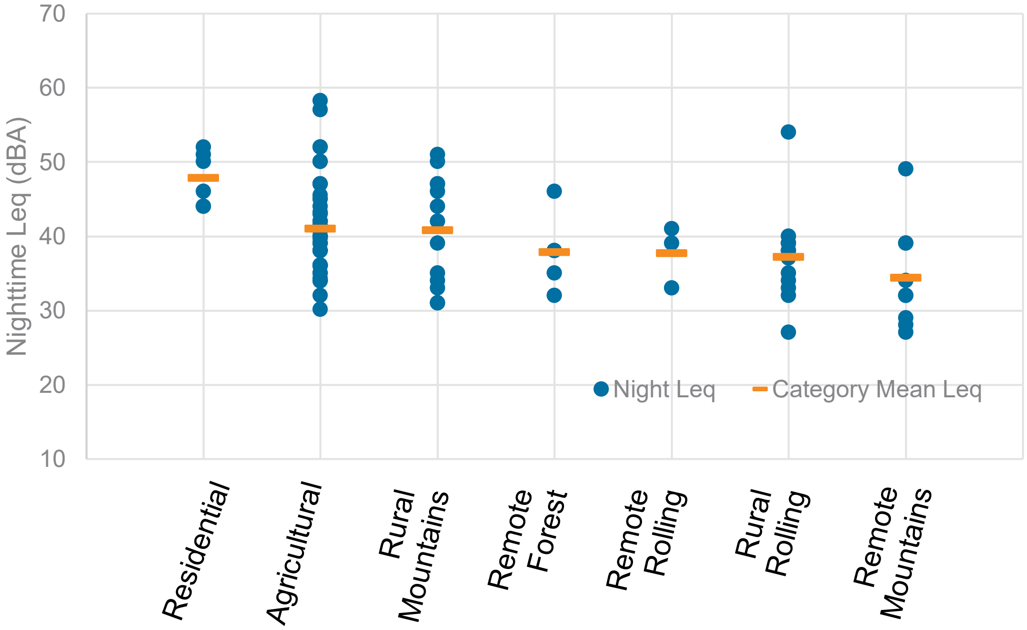

FIGURE 5: BACKGROUND NIGHTTIME L_{eq} AT 102 LOCATIONS AT POTENTIAL WIND TURBINE SITES ACROSS THE U.S. BY LAND USE CATEGORY[4]

Frequency Spectrum of Sound

The "frequency" of a sound is the rate at which it fluctuates in time, expressed in Hertz (Hz), or cycles per second. Very few sounds occur at only one frequency: most sound contains energy at many different frequencies, and it can be broken down into different frequency divisions, or bands. These bands are similar to musical pitches, from low tones to high tones. The most common division is the standard octave band. An octave is the range of frequencies whose upper frequency limit is twice its lower frequency limit, exactly like an octave in music. An octave band is identified by its center frequency: each successive band's center frequency is twice as high (one octave) as the previous band. For example, the 500 Hz octave band includes all sound whose frequencies range between 354 Hz (Hertz, or cycles per second) and 707 Hz. The next band is centered at 1,000 Hz with a range between 707 Hz and 1,414 Hz. The range of human hearing is divided into 10 standard octave bands: 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz, 4,000 Hz, 8,000 Hz, and 16,000 Hz. For analyses that require finer frequency detail, each octave-band can be subdivided. A commonly-used subdivision creates three smaller bands within each octave band, or so-called 1/3-octave bands.

Human Response to Frequency: Weighting of Sound Levels

The human ear is not equally sensitive to sounds of all frequencies. Sounds at some frequencies seem louder than others, despite having the same decibel level as measured by a sound level meter. In particular, human hearing is much more sensitive to medium pitches (from about 500 Hz to about 4,000 Hz) than to very low or very high pitches. For example, a tone measuring 80 dB at 500 Hz (a medium pitch) sounds quite a bit louder than a tone measuring

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[4] From Kaliski, K., Bastasch, M., and O'Neal, R., "Regulating and Predicting Wind Turbine Sound in the U.S.," Proceedings of InterNoise2018, Institute of Noise Control Engineering, 2018

80 dB at 60 Hz (a very low pitch). The frequency response of normal human hearing ranges from 20 Hz to 20,000 Hz. Below 20 Hz, pitch perception is greatly reduced and sound may be "felt" as much as "heard". Frequencies below 20 Hz are known as "infrasound". Likewise, above 20,000 Hz, sound can no longer be heard by humans; this is known as "ultrasound". As humans age, they tend to lose the ability to hear higher frequencies first; many adults do not hear very well above about 16,000 Hz. Most natural and man-made sound occurs in the range from about 40 Hz to about 4,000 Hz. Some insects and birdsongs reach to about 8,000 Hz.

To adjust measured sound pressure levels so that they mimic human hearing response, sound level meters apply filters, known as "frequency weightings", to the signals. There are several defined weighting scales, including "A", "B", "C", "D", "G", and "Z". The most common weighting scale used in environmental noise analysis and regulation is A-weighting. This weighting represents the sensitivity of the human ear to sounds of low to moderate level. It attenuates sounds with frequencies below 1000 Hz and above 4000 Hz; it amplifies very slightly sounds between 1000 Hz and 4000 Hz, where the human ear is particularly sensitive. The C-weighting scale is sometimes used to describe louder sounds. The B- and D- scales are seldom used. All of these frequency weighting scales are normalized to the average human hearing response at 1000 Hz: at this frequency, the filters neither attenuate nor amplify. G-weighting is a standardized weighting used to evaluate infrasound.

When a reported sound level has been filtered using a frequency weighting, the letter is appended to "dB". For example, sound with A-weighting is usually denoted "dBA" or "dB(A)". When no filtering is applied, the level is denoted "dB" or "dBZ". The letter is also appended as a subscript to the level indicator "L", for example "L_A" for A-weighted levels.

Time Response of Sound Level Meters

Because sound levels can vary greatly from one moment to the next, the time over which sound is measured can influence the value of the levels reported. Often, sound is measured in real time, as it fluctuates. In this case, acousticians apply a so-called "time response" to the sound level meter, and this time response is often part of regulations for measuring sound. If the sound level is varying slowly, over a few seconds, "Slow" time response is applied, with a time constant of one second. If the sound level is varying quickly (for example, if brief events are mixed into the overall sound), "Fast" time response can be applied, with a time constant of one-eighth of a second.[5] The time response setting for a sound level measurement is indicated with the subscript "S" for Slow and "F" for Fast: L_S or L_F. A sound level meter set to Fast time response will indicate higher sound levels than one set to Slow time response when brief events are mixed into the overall sound, because it can respond more quickly.

In some cases, the maximum sound level that can be generated by a source is of concern. Likewise, the minimum sound level occurring during a monitoring period may be required. To measure these, the sound level meter can be set to capture and hold the highest and lowest levels measured during a given monitoring period. This is represented by the subscript "max", denoted as "L_{max}". One can define a "max" level with Fast response L_{Fmax} (1/8-second time

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[5] There is a third time response defined by standards, the "Impulse" response. This response was defined to enable use of older, analog meters when measuring very brief sounds; it is no longer in common use.

constant), Slow time response L_{Smax} (1-second time constant), or Continuous Equivalent level over a specified time period $L_{1h\text{-}max}$ (maximum one-hour L_{eq}).

Accounting for Changes in Sound Over Time

A sound level meter's time response settings are useful for continuous monitoring. However, they are less useful in summarizing sound levels over longer periods. To do so, acousticians apply simple statistics to the measured sound levels, resulting in a set of defined types of sound level related to averages over time. An example is shown in Figure 6. The sound level at each instant of time is the grey trace going from left to right. Over the total time it was measured (1 hour in the figure), the sound energy spends certain fractions of time near various levels, ranging from the minimum (about 27 dB in the figure) to the maximum (about 65 dB in the figure). The simplest descriptor is the average sound level, known as the Equivalent Continuous Sound Level or L_{eq}. Statistical levels are used to determine for what percentage of time the sound is louder than any given level. These levels are described in the following sections.

Equivalent Continuous Sound Level - L_{eq}

One straightforward, common way of describing sound levels is in terms of the Continuous Equivalent Sound Level, or L_{eq}. The L_{eq} is the average sound pressure level over a defined period of time, such as one hour or one day. L_{eq} is the most commonly used descriptor in noise standards and regulations. L_{eq} is representative of the overall sound to which a person is exposed. Because of the logarithmic calculation of decibels, L_{EQ} tends to favor higher sound levels: loud and infrequent sources have a larger impact on the resulting average sound level than quieter but more frequent sounds. For example, in Figure 6, even though the sound levels spends most of the time near about 34 dBA, the L_{eq} is 41 dBA, having been "inflated" by the maximum level of 65 dBA and other occasional spikes over the course of the hour.

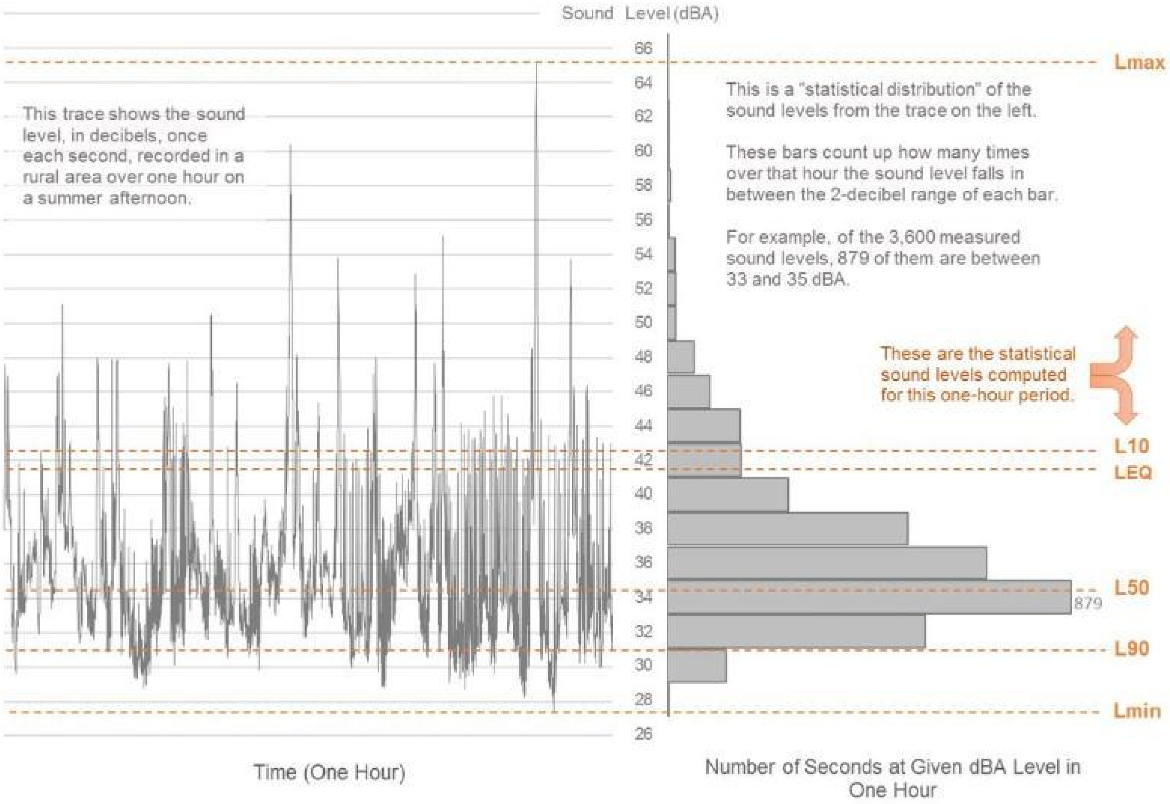

FIGURE 6: EXAMPLE OF DESCRIPTIVE TERMS OF SOUND MEASUREMENT OVER TIME

Percentile Sound Levels – L_n

Percentile sound levels describe the statistical distribution of sound levels over time. “L_n” is the level above which the sound spends “N” percent of the time. For example, L_{90} (sometimes called the “residual base level”) is the sound level exceeded 90% of the time: the sound is louder than L_{90} most of the time. L_{10} is the sound level that is exceeded only 10% of the time. (the “median level”) is exceeded 50% of the time: half.

L_{90} is often a good representation of the “ambient sound” in an area. This is the sound that persists for longer periods, and below which the overall sound level seldom falls. It tends to filter out other short-term environmental sounds that are not part of the source being investigated. L_{10} represents the higher, but less frequent, sound levels. These could include such events as barking dogs, vehicles driving by and aircraft flying overhead, gusts of wind, and work operations. L_{90} represents the background sound that is present when these event sounds are excluded.

Note that if one sound source is very constant and dominates the soundscape in an area, all of the descriptive sound levels mentioned here tend toward the same value. It is when the sound is varying widely from one moment to the next that the statistical descriptors are useful.

APPENDIX B. WIND TURBINE ACOUSTICS

Sources of Sound Generation by Wind Turbines

Wind turbines generate two principal types of noise: aerodynamic noise, produced from the flow of air around the blades, and mechanical noise, produced from mechanical and electrical components within the nacelle.

Aerodynamic noise is the primary source of noise associated with wind turbines. These acoustic emissions can be either tonal or broad band. Tonal noise occurs at discrete frequencies, whereas broadband noise is distributed with little peaking across the frequency spectrum.

While unusual, tonal noise can also originate from unstable air flows over holes, slits, or blunt trailing edges on blades. Most modern wind turbines have upwind rotors designed to prevent blade impulsive noise. Therefore, the majority of audible aerodynamic noise from wind turbines is broadband at the middle frequencies, roughly between 200 Hz and 1,000 Hz.

Wind turbines emit aerodynamic broadband noise as the spinning blades interact with atmospheric turbulence and as air flows along their surfaces. This produces a characteristic “whooshing” sound through several mechanisms (Figure 7):

- Inflow turbulence noise occurs when the rotor blades encounter atmospheric turbulence as they pass through the air. Uneven pressure on a rotor blade causes variations in the local angle of attack, which affects the lift and drag forces, causing aerodynamic loading fluctuations. This generates noise that varies across a wide range of frequencies but is most significant at frequencies below 500 Hz.
- Trailing edge noise is produced as boundary-layer turbulence as the air passes into the wake, or trailing edge, of the blade. This noise is distributed across a wide frequency range but is most notable at high frequencies between 700 Hz and 2 kHz.
- Tip vortex noise occurs when tip turbulence interacts with the surface of the blade tip. While this is audible near the turbine, it tends to be a small component of the overall noise further away.
- Stall or separation noise occurs due to the interaction of turbulence with the blade surface.

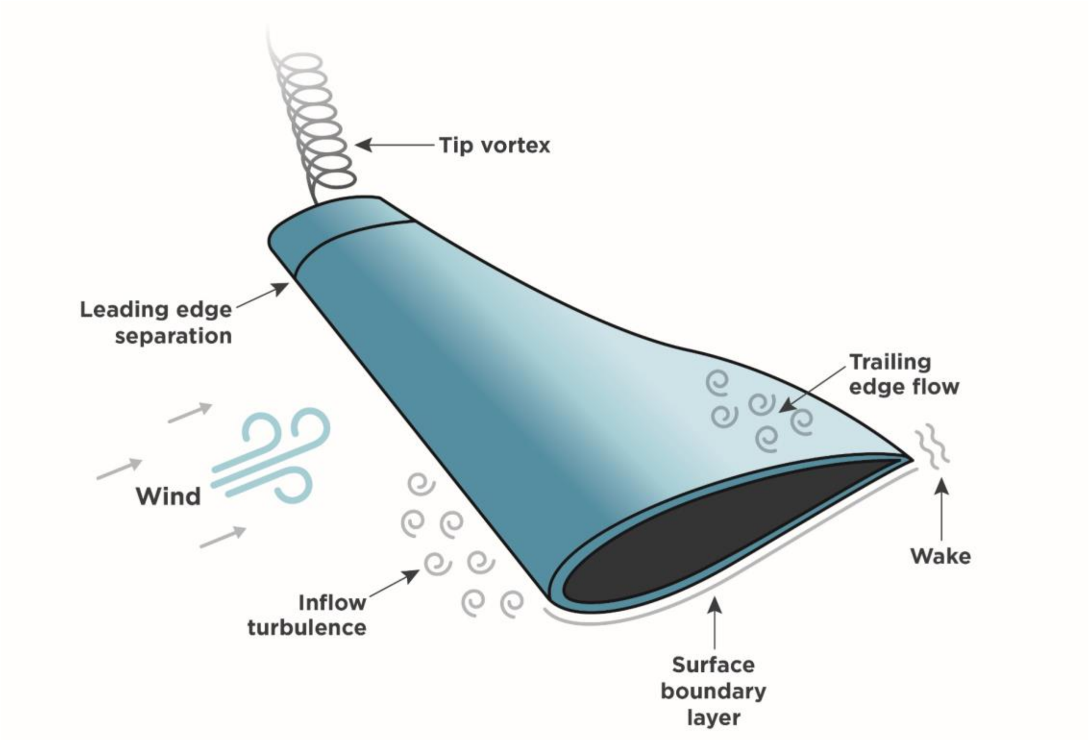

FIGURE 7: AIRFLOW AROUND A ROTOR BLADE

Mechanical sound from machinery inside the nacelle tends to be tonal in nature but can also have a broadband component. Potential sources of mechanical noise include the gearbox, generator, yaw drives, cooling fans, and auxiliary equipment. These components are housed within the nacelle, whose surfaces, if untreated, radiate the resulting noise. However modern wind turbines have nacelles that are designed to reduce internal noise, and rarely is the mechanical noise a significant portion of the total noise from a wind turbine.

Amplitude Modulation

Amplitude modulation (AM) is a fluctuation in sound level that occurs at the blade passage frequency. No consistent definition exists for how much of a sound level fluctuation is necessary for blade swish to be considered AM, however sound level fluctuations in A-weighted sound level can range up to 10 dB. Fluctuations in individual 1/3 octave bands are typically more and can exceed 15 dB. Fluctuations in individual 1/3 octave bands can sometimes synchronize and desynchronize over periods, leading to increases and decreases in magnitude of the A-weighted fluctuations. Similarly, in wind farms with multiple turbines, fluctuations can synchronize and desynchronize, leading to variations in AM depth.[6] Most amplitude modulation is in the mid frequencies and most overall A-weighted AM is less than 4.5 dB in depth.[7]

Many confirmed and hypothesized causes of AM exist, including: blade passage in front of the tower, blade tip sound emission directivity, wind shear, inflow turbulence, and turbine blade yaw

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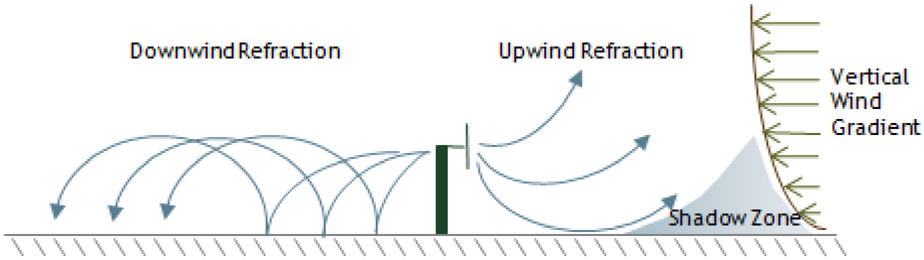
[6] McCunney, Robert, et al. “Wind Turbines and Health: A Critical Review of the Scientific Literature.” *Journal of Occupational and Environmental Medicine.* 56(11) November 2014: pp. e108-e130.

[7] RSG, et al., “Massachusetts Study on Wind Turbine Acoustics,” Massachusetts Clean Energy Center and Massachusetts Department of Environmental Protection, 2016

error. It has recently been noted that although wind shear can contribute to the extent of AM, wind shear does not contribute to the existence of AM in and of itself. Instead, there needs to be detachment of airflow from the blades for wind shear to contribute to AM.[8] While factors like the blade passing in front of the tower are intrinsic to wind turbine design, other factors vary between turbine designs, local meteorology, topography, and turbine layout. Mountainous areas, for example, are more likely to have turbulent airflow, less likely to have high wind shear, and less likely to have turbine layouts that allow for blade passage synchronization for multiple turbines. AM extent varies with the relative location of a receiver to the turbine. AM is usually experienced most when the receiver is between 45 and 60 degrees from the downwind or upwind position and is experienced least directly with the receiver directly upwind or downwind of the turbines.

Meteorology

Meteorological conditions can significantly affect sound propagation. The two most important conditions to consider are wind shear and temperature lapse. Wind shear is the difference in wind speeds by elevation and temperature lapse rate is the temperature gradient by elevation. In conditions with high wind shear (large wind speed gradient), sound levels upwind from the source tend to decrease and sound levels downwind tend to increase due to the refraction, or bending, of the sound (Figure 8).



Not to scale

FIGURE 8: SCHEMATIC OF THE REFRACTION OF SOUND DUE TO VERTICAL WIND GRADIENT (WIND SHEAR)

With temperature lapse, when ground surface temperatures are higher than those aloft, sound will tend to refract upwards, leading to lower sound levels near the ground. The opposite is true when ground temperatures are lower than those aloft (an inversion condition).

High winds and high solar radiation can create turbulence which tends to break up and dissipate sound energy. Highly stable atmospheres, which tend to occur on clear nights with low ground-level wind speeds, tend to minimize atmospheric turbulence and are generally more favorable to downwind propagation.

In general terms, sound propagates along the ground best under stable conditions with a strong temperature inversion. This tends to occur during the night and is characterized by low ground-level winds. As a result, worst-case conditions for wind turbines tend to occur downwind under

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[8] "Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect." *RenewableUK.* December 2013.

moderate nighttime temperature inversions. Therefore, this is the default condition for modeling wind turbine sound.

Masking

As mentioned above, sound levels from wind turbines are a function of wind speed. Background sound is also a function of wind speed, i.e., the stronger the winds, the louder the resulting background sound. This effect is amplified in areas covered by trees and other vegetation.

The sound from a wind turbine can often be masked by wind noise at downwind receivers because the frequency spectrum from wind is similar to the frequency spectrum from a wind turbine. Figure 9 compares the shape of the sound spectrum measured during a 5 m/s wind event to that of the GE 3.0-140 LNTE wind turbine. As shown, the shapes of the spectra are similar at lower frequencies. At higher frequencies, the sounds from the masking wind noise are higher than the wind turbine. As a result, the masking of turbine noise occurs at higher wind speeds for some meteorological conditions. Masking will occur most, when ground wind speeds are relatively high, creating wind-caused noise such as wind blowing through the trees and interaction of wind with structures.

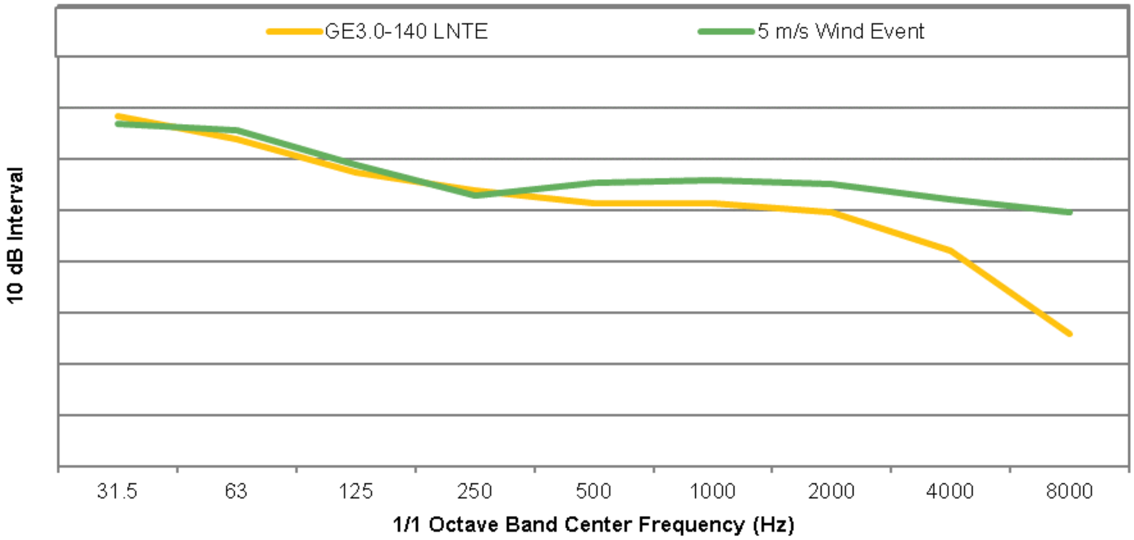

FIGURE 9: COMPARISON OF NORMALIZED FREQUENCY SPECTRA MEASURED FROM A 5 M/S WIND EVENT AND THE SOUND POWER SPECTRA FROM THE GE 3.0-140 LNTE[9]

It is important to note that while winds may be blowing at turbine height, there may be little to no wind at ground level. This is especially true during strong wind gradients (high wind shear), which mostly occur at night. This can also occur on the leeward side of ridges where the ridge blocks the wind.

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[9] The purpose of this Figure is to show the shapes to two spectra relative to one another and not the actual sound level of the two sources of sound. The level of each source was normalized independently.

APPENDIX C. NOISE DESIGN GOALS FOR WIND TURBINES

Federal Guidelines

Many federal agencies have adopted guidelines and standards that apply to other types of facilities. A summary of some of these standards is shown in Table 2. Note that these standards are in terms of L_{eq}, L_{dn}, or L_{10}. The L_{eq} is the pressure weighted average sound level, over a specified period of time. The L_{dn} is the A-weighted day-night L_{eq}, where a penalty of 10 dB is applied to nighttime sound. The L_{10} is the 10th percentile sound level. It is the level that is exceeded 10% of the time, and thus represents the higher sound levels over a period of time.

The United States Department of the Interior, Bureau of Land Management (BLM) has developed a Programmatic Environmental Impact Statement (PEIS) for Wind Energy Development on BLM Lands in the Western United States. Noise is addressed in several sections of the PEIS. Several relevant points made in the PEIS are listed below:

- From Section 4.5.1: “at many wind energy project sites on BLM-administered lands, large fluctuations in broadband noise are common, and even a 10-dB increase would be unlikely to cause an adverse community response. In addition, noise containing discrete tones (tonal noise) is much more noticeable and more annoying at the same relative loudness level than other types of noise, because it stands out against background noise.”
- From Section 4.5.2: “In general, background noise levels (i.e., noise from all sources not associated with a wind energy facility) are higher during the day than at night. For a typical rural environment, background noise is expected to be approximately 40 dB(A) during the day and 30 dB(A) at night (Harris 1979), or about 35 dB(A) as DNL (Miller 2002).”
- From Section 4.5.4: “The EPA guideline recommends an L_{dn} of 55 dB(A) to protect the public from the effect of broadband environmental noise in typically quiet outdoor and residential areas (EPA 1974). This level is not a regulatory goal but is ‘intentionally conservative to protect the most sensitive portion of the American population’ with ‘an additional margin of safety.’ For protection against hearing loss in the general population from non-impulsive noise, the EPA guideline recommends an L_{eq} of 70 dB(A) or less over a 40-year period.”

TABLE 2: SUMMARY OF FEDERAL GUIDELINES AND STANDARDS FOR EXTERIOR NOISE

Agency	**Applies to**	**Standard (dBA)**
Environmental Protection Agency	Guideline to protect public health and welfare with an adequate margin of safety	55 dB L_{dn}
Environmental Protection Agency	Level of intermittent noise identified to protect against hearing loss	70 dB L_{24h}
Environmental Protection Agency	100 percent speech intelligibility indoors and 99 percent speech intelligibility outdoors at 1 meter (3.3 feet)	55 dB L_{dn}
Occupational Safety and Health Administration	Maximum allowable sound level for an 8-hour work day	90 dB L_{8h}
Bureau of Land Management (BLM)	Guidelines for the development of wind turbines on federal lands managed by BLM	Refers to the EPA 55 dB L_{dn} guideline.
Federal Energy Regulatory Commission (FERC)	Compressor facilities under FERC jurisdiction	55 dB L_{dn}
Federal Highway Administration (FHWA)	Federally funded highway projects. For "Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential for the area to continue to serve its intended purpose."	57 dBA L_{eq} or 60 dBA L_{10} during peak traffic noise hour.
	For residential, active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools, television studios, trails, and trail crossings	67 dBA L_{eq} or 70 dBA L_{10} during the peak traffic noise hour
Federal Interagency Task Force	This Taskforce is set up to develop consistency of noise standards among federal agencies	55 to 65 dB L_{dn} for impacts on residential areas

- From Section 5.5.3.1: "aerodynamic noise is the dominant source from modern wind turbines (Fégeant 1999)."
- From Section 5.5.3.1: "Considering geometric spreading only, this results in a sound pressure level of 58 to 62 dB(A) at a distance of 50 m (164 ft.) from the turbine, which is about the same level as conversational speech at a 1 m (3 ft.) distance. At a receptor approximately 2,000 ft. (600 m) away, the equivalent sound pressure level would be 36

to 40 dB(A) when the wind is blowing from the turbine toward the receptor. This level is typical of background levels of a rural environment (Section 4.5.2). To estimate combined noise levels from multiple turbines, the sound pressure level from each turbine should be estimated and summed. Different arrangements of multiple wind turbines (e.g., in a line along a ridge versus in clusters) would result in different noise levels; however, the resultant noise levels would not vary by more than 10 dB."

- From Section 5.5.3.1: "In general, the effects of wind speed on noise propagation would generally dominate over those of temperature gradient."
- From Section 5.5.3.1: "Wind-generated noise would increase by about 2.5 dB(A) per each 3 ft./s (1 m/s) wind speed increase (Hau 2000); the noise level of a wind turbine, however, would increase only by about 1 dB(A) per 3 ft./s (1 m/s). In general, if the background noise level exceeds the calculated noise level of a wind turbine by about 6 dB(A), the latter no longer contributes to a perceptible increase of noise. At wind speed of about 33 ft./s (10 m/s), wind-generated noise is higher than aerodynamic noise. In addition, it is difficult to measure sound from modern wind turbines above a wind speed of 26 ft./s (8 m/s) because the background wind-generated noise masks the wind turbine noise at that speed (DWIA 2003)."
- From Section 6.4.1.6: "Noise generated by turbines, substations, transmission lines, and maintenance activities during the operational phase would approach typical background levels for rural areas at distances of 2,000 ft. (600 m) or less and, therefore, would not be expected to result in cumulative impacts to local residents."

These statements from the BLM's Wind Energy Development PEIS do not represent a regulatory standard itself, but they do provide some insight on how one federal agency is approaching noise generated from wind turbine projects.

The EPA discussed speech intelligibility relative to a day-night exterior sound level of 55 dBA (55 dBA L_{dn} is the EPA's guideline sound level to protect public health). 55 dBA L_{dn} is equivalent to a 45 dBA L_{eq} sound level at night and 55 dBA L_{eq} sound level during the day. Or alternatively a sound level of 48.6 dBA L_{eq} through the night and day. The EPA states that on average this will yield 100 percent speech intelligibility indoors, with a 5 dB margin of safety and 99 percent speech intelligibility at 1 meter (3.3 feet) outdoors.

World Health Organization Guidelines

The United Nation's World Health Organization (WHO) has published "Guidelines for Community Noise" (1999) which uses research on the health impacts of noise to develop guideline sound levels for communities. The foreword of the report states, "The scope of WHO's effort to derive guidelines for community noise is to consolidate actual scientific knowledge on the health impacts of community noise and to provide guidance to environmental health authorities and professionals trying to protect people from the harmful effects of noise in non-industrial environments."

Table 4.1 of the WHO's "Guidelines for Community Noise" (1999) provides guideline values for community noise in specific environments. The WHO guidelines suggest a daytime and nighttime protective noise level. During the day, the levels are 55 dBA $L_{eq(16)}$, that is, an average over a 16-hour day, to protect against serious annoyance and 50 dBA $L_{eq(16)}$ to protect against moderate annoyance.

During the night, the WHO recommends limits of 45 dBA L_{8h}[10] and an instantaneous maximum of 60 dBA L_{Fmax} (fast response maximum). These are to be measured outside the bedroom window. These guidelines are based on the assumption that sound levels indoors would be reduced by 15 dBA with windows partially open. That is, the sound level inside the bedroom that is protective of sleep is 30 dBA L_{8h}. So long as the sound levels outside of the house remains at or below 45 dBA, sound levels in the bedroom will generally remain below 30 dBA. Given the climate in this region, this is essentially a summertime standard, since residents are less likely to have their windows open during other times of the year. By closing windows, an additional ~10 dB of sound attenuation will result. In addition to protection against annoyance, these guidelines are intended to protect against speech intelligibility, sleep disturbance, and hearing impairment. Of these factors, protection against annoyance and sleep disturbance require the lowest limits.

The WHO suggest that full-sentence intelligibility requires a signal-to-noise ratio of about 15 dB. For speech volume of 50 dBA, this would indicate some speech interference as low as 35 dBA for “smaller rooms.” Although speech interference is influenced by the spectrum of the masking sound, no particular guidance is given to adjust the WHO’s guidelines for sound sources of different frequency content. Since speech may range from 100 Hz to 6 kHz, there will be overlap between the spectra of wind turbine noise and speech. This guideline is generally intended for classrooms and so includes corrections for the hearing impaired, reverberation, children, and lack of language proficiency. 50 dBA is also a low sound level for speech at close distances, with most normal speech being 60 dBA at close distances, as is stated in ANSI 12.65-2011 (Figure 10).

The WHO long-term guideline to protect against hearing impairment is 70 dBA L_{24h} over a lifetime exposure, and higher for occupational or recreational exposure.

The WHO indicates that sound sources with high levels of low-frequency sound can be more intrusive. The guidelines do not include specific limits and instead state:

> “When noise is continuous, the equivalent sound pressure level should not exceed 30 dB(A) indoors, if negative effects on sleep are to be avoided. For noise with a large portion of low-frequency sound a still lower guideline is recommended.”

No specific definition is given for what entails a “large portion” of low-frequency sound. The WHO recommends doing a frequency analysis if the difference between the C- and A-weighted sound levels exceeds 10 dB. As WHO indicates, this only gives “crude information” about low-frequency content, and is not an indicator in and of itself.

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[10] This is the equivalent average sound level, averaged over eight nighttime hours, measured outside the bedroom window.

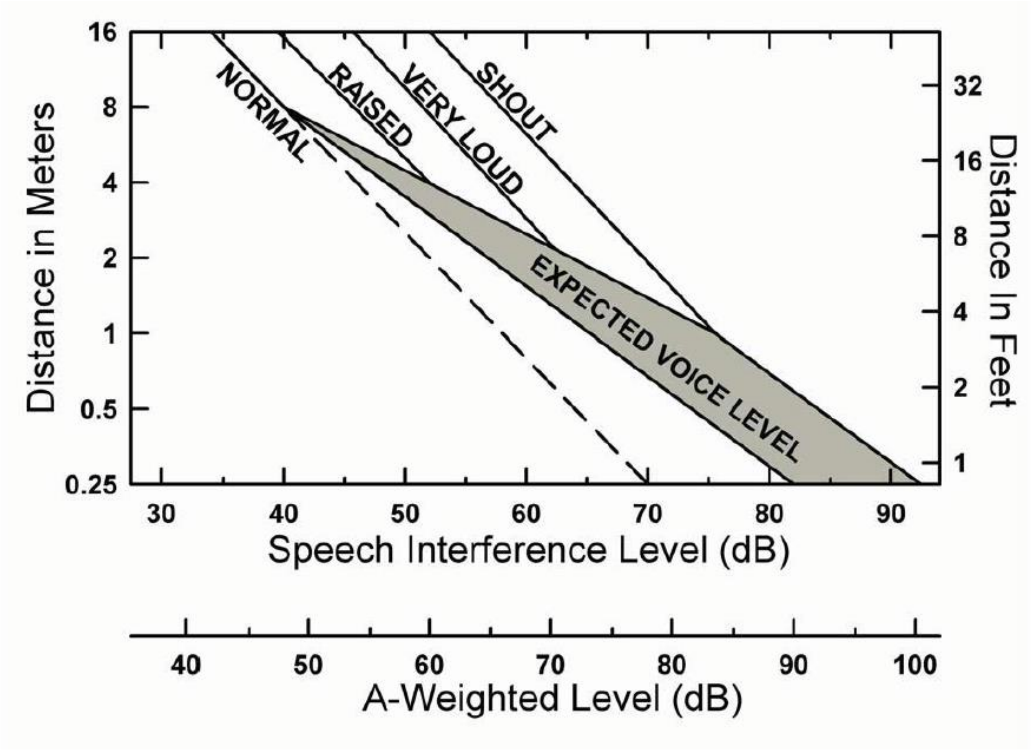

FIGURE 10: SOUND PRESSURE LEVEL OF SPEECH (FROM ANSI S12.65-2011)

Since the WHO guidelines were developed to protect human health, all suggested limits apply to sound levels at residences or areas where humans typically frequent. For example, the guidelines reflective of sleep disturbance are specified to be measured outside the bedroom window.

In October 2009, WHO Europe conducted an updated literature review and built upon WHO's guidelines for nighttime noise in Europe. They added an *annual average* nighttime guideline level to protect against adverse effects on sleep disturbance. This guideline is 40 dBA $L_{night, outside}$, measured outside the bedroom window.

Neither the 1999 nor 2009 guidelines were developed specifically for wind turbine noise.

In 2018, WHO Europe developed a "conditional" recommendation of 45 dB L_{den} (day evening night level)[11] limit for wind turbines. This recommendation was based on the exterior turbine-only sound level where 10 percent of a population is highly annoyed to wind turbine noise indoors. The 10% criterion is not based on any systemic health studies on wind turbine sound. Recent work of Hübner et al on a sample of U.S. residences around wind turbines found that "assessing annoyance alone is imprecise as it does not accurately reflect the small subset of residents who experience psychological and physical symptoms." The authors concluded that

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[11] The L_{den} is the annual average equivalent continuous sound level, with the evening weighted with +5 dB and night with +10 dB.

annoyance that leads to stress was not a function of wind turbine sound level, but rather due to a perception of a lack of fairness in the permitting process and other subjective factors.[12]

WHO Europe considers annoyance a “health endpoint”, which is not widely recognized in the U.S. That is, annoyance is not considered a disease. WHO Europe did not find evidence of the correlation of wind turbine noise with ischemic heart disease (IHD), hypertension, sleep disturbance, hearing impairment, and delayed learning in children. Each of these has been found in relation to excessive environmental noise from other sources such as highways and transit.

We do not recommend the WHO Europe guideline for wind turbine sound be used in a regulation or permit limit. The first issue is that the WHO considers the recommendation “conditional.” The term conditional means that:

> …recommendation requires a policy-making process with substantial debate and involvement of various stakeholders. There is less certainty of its efficacy owing to lower quality of evidence of a net benefit, opposing values and preferences of individuals and populations affected or the high resource implications of the recommendation, meaning there may be circumstances or settings in which it will not apply.

They label the guideline conditional because of the limited amount of evidence found and the fact that they considered this evidence to be poor (2018 WHO Guidelines at p. 78).

The guidelines do not include some of the more recent studies that have been performed on this subject, due to no studies being included after 2014. This includes the comprehensive Health Canada study (Michaud et al, 2015 and 2016) and the Danish Cancer Society study (Poulsen et al, 2018 and 2019). As a result, the literature review is already out-of-date. For example, both Health Canada and the Danish Cancer Society looked at sleep disturbance due to wind turbine noise and found no impacts at the levels considered as design goals in this report.

The WHO Europe guideline uses the L_{den} (annual average day-evening-night equivalent continuous sound level) metric. This is not a reasonable regulatory metric in the U.S. Given that it is an annual average, to assess compliance with the L_{den} metric would require measurement of turbine-only sound levels during all times of day and during all meteorological and operational conditions. Due to number of other sound sources present at most sites, this will be difficult, if not impossible as it would require constantly shutting off the wind power project to account for the contribution from the wind power project. The use of the L_{den} might be justifiable if it were proven to best predict human response to wind turbine noise, but as the WHO Europe guideline states, “Based on all these factors, it may be concluded that the acoustical description of wind turbine noise by means of L_{den} or L_{night} may be a poor characterization of wind turbine noise and may limit the ability to observe associations between wind turbine noise and health outcomes.” (2018 WHO Guidelines at p. 86) The reasoning for the WHO’s use of this metric is due to its specification in the European Noise Directive (END) for use in noise mapping (2018 WHO Guidelines at p. 86).

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[12] Hübener, G., Pohl, J., Hoen, B., Firestone, B., Rand, J., Elliott, D., Haac, R. “Monitoring annoyance and stress effects of wind turbines on enarby residents: A comparison of U.S. and European samples,” Environment International, V132, 105090, 2019.

Wind Turbine Community Complaint Potential

Many sound level standards and guidelines are based on research conducted for transportation noise. There have been some studies that conclude that wind turbine noise is more intrusive to some listeners than a transportation source of equivalent magnitude. Suggested reasons for increased annoyance include amplitude modulation, tonality, low-frequency content, and the newness of wind turbine noise as an environmental noise source.

The following subsection of this report reviews these studies that have been performed comparing human response to audible sound and infrasound from wind turbines.

Response in the Normal Hearing Range

Studies of human response to wind turbine sound were performed in Sweden (in 2000 and 2005) and The Netherlands (2007) by Eja Pederson and other authors (Waye, Lassman, etc.).[13,14,15,16] There have been several papers about these studies, including a summary written by Janssen et al (2011) that included a combined dose-response curve.[17] The Pederson studies were performed by sending self-reporting surveys to respondents living in and around wind farms and comparing responses from these surveys to modeled sound levels at those residences. A total of 1,830 people responded to these surveys.

The Janssen dose-response curve shows that for sound at 45 dBA L_{eq} (calculated outdoors), there is an annoyance rate of approximately 40 percent for residents outdoors and 21 percent for residents indoors. The highly annoyed rate is 23 percent outdoors and 11 percent indoors for this sound level. Note that some sound levels were calculated using the equations of the Swedish Environmental Protection Agency and assumes that receptors are always downwind of the source and others were calculated using ISO 9613-2; although, Janssen reported that the results between the two models were similar.[18]

A common finding among the various studies is that annoyance was lower among residents who benefited economically from the wind turbines. Annoyance also increases with age, visibility of the turbines from the residence, and noise sensitivity.

Health Canada studied health indicators among populations exposed to wind turbine sound.[19] Just as with Pedersen's studies, self-reporting surveys were distributed to participants (1,238 in

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[13] Pedersen, Eja and Waye, Kerstin. "Perception and annoyance due to wind turbine noise - a dose-response relation." Journal of the Acoustical Society of America. 116(6). pp. 3460-3470.

[14] Pedersen, Eja, et al. "Response to wind turbine noise in the Netherlands." Acoustics 2008. Paris, France.: 29 June – 4 July 2008.

[15] Pedersen, Eja and Persson Waye, Kerstin. "Wind turbines-low level noise sources interfering with restoration?" Environ. Res. Lett. 3 (January-March 2008). 11 January 2008.

[16] Pedersen, Eja and Larsman Pernilla. "The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines." Journal of Environmental Psychology. 28(2008). pp. 379-389.

[17] Janssen, Sabine, et al. "A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources." *J. Acoust. Soc. Am.* 130(6). December 2011. pp. 3746-3753.

[18] The values shown in Janssen et al are the L_{DEN} or day-evening-night sound level. The values shown in this paper have been adjusted to represent a median hourly value.

[19] Michaud, David. "Wind Turbine Noise and Health Study: Summary of Results." *6th International Meeting on Wind Turbine Noise.* Glasgow, Scotland: 20-23 April 2015.

total). Correlations were found between wind turbine modeled sound levels and annoyance toward noise, shadow-flicker, turbine visibility, blinking lights, and vibration. Although C-weighted sound levels were calculated for the study, A-weighted levels were primarily assessed, due to the high correlation between A-weighted and C-weighted levels (R^2=0.88). The rate of highly annoyed residents due to wind turbine noise was found to be approximately 18 percent at sound levels between 40 and 46 dBA L_{eq}. This sound level assumes wind turbines emissions at an 8 m/s wind speed measured at a height of 10 meters. Also note, that the Health Canada study assumed a ground absorption factor of G=0.7 with no uncertainty factor added to the wind turbine sound power, so levels modeled by Health Canada will be about 3 dB lower than the equivalent scenario modeled in this report. Therefore, the 18 percent highly annoyed would be equivalent to a range of 43 to 49 dBA, using the modeling parameters used in this report.

A Japanese study also looked at the relative annoyance of residents surrounding wind farms, compared with the $L_{eq,n}$, or average of the A-weighted 10-minute sound levels from each hour over the night with the wind turbine(s) at their rated capacity.[20] The $L_{eq,n}$ measured by the study is lower, on average, than the sound level downwind with the 10-meter wind speed at 8 m/s, due to the directionality of turbines. Due to differences in wind farm layouts (single turbine, grid layout, ridgeline layout, etc.), this difference was not readily determined. The authors estimated that, on average, the $L_{eq,n}$ will be about 6 dB less than the L_{dn}. Using this assumption, the authors found that wind turbine noise is between 6 and 9 dB more annoying than road traffic noise. The study found that between 41 and 45 dB $L_{eq,n}$ approximately 14 percent of respondents were extremely annoyed, and 19 percent were moderately annoyed.[21] Other findings included that visual disturbance was well correlated with wind turbine noise disturbance, and that insomnia, though low in incidence overall, was more prevalent near wind turbine sites. Insomnia was also found to be related to visual disturbance. Wind turbine noise was also found to have an effect on sleep disturbance, when audible, and particularly when sound levels were greater than 40 dB $L_{eq,n}$.

Old, et al. analyzed the modeling metrics used in the Janssen, Michaud, and Kuwano dose-response curves and found that they were not directly comparable.[22] That is, they used different metrics and/or averaging times. He normalized the dose-response curves of the three authors to a common median one-hour L_{eq}, with a mixed ground factor and four-meter receptor height. No uncertainty factor was added to the manufacturer mean sound power level.

Haac, et al. is the only dose response study done in the U.S. The study was sponsored by the U.S. Department of Energy and conducted through a contract with the Lawrence Berkley National Laboratory, RSG, and researchers at three universities. This study found that less than half of all respondents (41%) could hear the wind turbines inside their homes at sound levels between 40 and 45 dBA ($L_{1h\ max}$). About two thirds (69%) could hear the wind turbines outside their homes at the same level. Less than 20% of nonparticipants surveyed (19%) were highly

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[20] Kuwano, Sonoko, et al. “Social Survey on Wind Turbine Noise in Japan.” *Noise Control Engr. J. 62(6). November-December 2014. pp. 503-520.*

[21] Yano, Takashi, et al. “Dose-response relationships for wind turbine noise in Japan.” *Internoise 2013.* Innsbruck, Austria: 15-18 September 2013.

[22] Old, I., Kaliski, K., “Wind turbine noise dose response – Comparison of recent studies,” Proceedings of the 7th International Conference of Wind Turbine Noise, May 2017.

annoyed by sound levels between 40 and 45 dBA. The three most significant factors leading to annoyance were “like the look of the project”, “noise sensitive”, and “prior attitude”. The level of annoyance is lower when project participants are included.

The noise-annoyance dose-response curves for the studies mentioned above are shown in Figure 11.

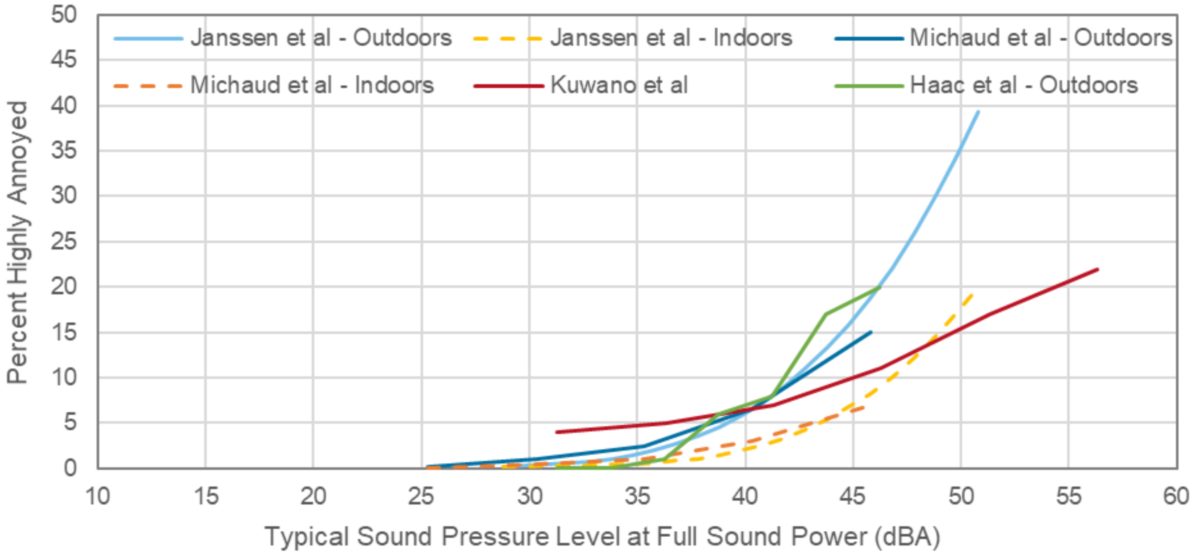

FIGURE 11: WIND TURBINE NOISE DOSE-RESPONSE CURVES FOR NONPARTICIPANTS NORMALIZED TO 1-HOUR L_{eq}, G=0.5+2 dB, 4-METER HEIGHT ADAPTED FROM OLD & KALISKI (2017) AND HAAC ET AL. (2019)

Hübner, et al. took a slightly different approach, using data from dose response studies in the United States, Germany, and Switzerland and then adding criteria, to better asses how many people, who actually hear wind turbine noise are highly annoyed, and how many of those experience some kind of stress related symptom or used some kind of strategy to mitigate symptoms.[23] Results found that a total of five-percent of the total people surrounding the wind power projects and ten-percent of those who were able to hear wind turbine noise found it strongly annoying. Annoyance was correlated with perceived fairness of the planning process and how the residents considered the wind power project in general.

Infrasound

Infrasound is generally defined as the portion of the frequency spectrum below 20 Hz which is nominally inaudible to humans. Low-frequency sound is in the lower portion of the audibility range and is generally considered in the frequency range from 20 Hz to 200 Hz.

Measurements of infrasound at distances from wind turbines typical of their nearest residential neighbors have consistently found that infrasound levels are below published audible human perception limits. O’Neal et al. measured sound from wind projects that used the GE 1.5 sle and Siemens SWT 2.3-93 model wind turbines. They found that at typical receptor distances away

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[23] Hübner, Gundula, et al. “Monitoring Annoyance and Stress Effects of Wind Turbines on Nearby Residents: A comparison of U.S. and European Samples.” *Environment International.* V132, 2019.

from a wind turbine, more than 1,000 feet away, wind turbine sound exceeds audibility thresholds starting at 50 Hz.[24]

Tachibana et al. measured sound levels from 34 wind projects around Japan over a three-year period.[25] They found that infrasound levels were "much lower than the criterion curve" proposed by Moorehouse et al.[26] RSG et al. studied infrasound levels at two wind turbine projects in the northeastern U.S. Both indoor and outdoor measurements were made.[27] Comparisons between turbine-on periods and adjacent turbine shutdown periods indicated the presence of wind-turbine-generated infrasound, but well below ISO 389-7[28] and Watanabe et al.[29] perception limits. In their review of several wind turbine measurement studies (including O'Neal and Tachibana), McCunney et al. did not find evidence of audible or perceptible infrasound levels at typical residential distances from wind projects.[30]

Authors Salt, Pierpont, and Schomer have theorized that infrasound from wind farms can be perceived by humans and cause adverse reactions, even when it is below measured audibility thresholds.[31,32,33] Some of these theories have focused on the human vestibular system, hypothesizing that subaudible infrasound could stimulate the vestibular system, upsetting the human body's manner of determining balance and causing symptoms such as dizziness, nausea, and headaches, along with disruptions in sleep. More recently Schomer has stated that the hypothesis that subaudible wind turbine infrasound causes adverse health effects can almost be ruled out, though he has not fully abandoned the hypothesis.[34] In response, McCunney et al. and Leventhall contend that there has been no demonstration that humans can perceive subaudible infrasound, citing the relative insensitivity of the inner ear (where the

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[24] O'Neal, R. et al. "Low frequency noise and infrasound from wind turbines." Noise Control Engineering J. 59 (2), 2011.

[25] Tachibana, et al. "Nationwide field measurements of wind turbine noise in Japan." Noise Control Engr. J. 62 (2) 2014.

[26] Moorehouse, A. T. "A procedure for the assessment of low frequency noise complaints." J. Acoust. Soc. Am. 126 (3) 2009.

[27] RSG, et al. "Massachusetts study on wind turbine acoustics." Prepared for MassCEC and MassDEP, February 2016.

[28] *Acoustics -- Reference zero for the calibration of audiometric equipment -- Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions,* International Standards Organization, ISO 389-7:2005, last reviewed 2013

[29] Watanabe, T., and Moller, H., "Low frequency hearing thresholds in pressure field and in free field," *J. Low Freq. Noise Vib., Vol. 9(3), 106-115.*

[30] McCunney, Robert, et al. "Wind Turbines and Health: A Critical Review of the Scientific Literature." *Journal of Occupational and Environmental Medicine.* 56(11). November 2014. pp. e108-e130.

[31] Salt, Alec and Hullar, Timothy. "Responses of the Ear to Low-Frequency Sounds, Infrasound, and Wind Turbines." *Hear Res.* 268(2010). pp. 12-21.

[32] Pierpont, Nina. "Wind Turbine Syndrome: A Report on a Natural Experiment." *K-Selected Books*: Santa Fe, New Mexico: 2009.

[33] Schomer, Paul, et al. "A Theory to Explain Some Physiological Effects of the Infrasonic Emissions at Some Wind Farm Sites." *J. Acoust. Soc. Am.* 137(3). March 2015. pp. 1357-1365.

[34] Hessler, George, et al. "Health Effects from Wind Turbine low Frequency noise and Infrasound- Do Wind Turbines Make People Sick? That is the Issue." *Sound and Vibration*. January 2017. pp. 34-44.

vestibular system is located) to airborne sound and the presence of other low to moderate magnitude infrasound sources in the body and the environment.[35,36]

Yokoyama et al. conducted laboratory experiments with subjects exposed to synthesized infrasound from wind turbines. In one experiment, synthesized wind turbine sound was filtered to eliminate high-frequency sound at 10 different cutoff frequencies from 10 Hz to 125 Hz.[37] The results indicate that when all sound above 20 Hz was filtered out, none of the respondents could hear or sense the wind turbine sound. In a second experiment correlating subject response of wind turbine sound to different frequency-weighting schemes, they found that the subjective loudness of wind turbine sound was best described by the A-weighted sound level rather than other weightings that focused on low-frequency sound or infrasound.[38]

Hansen et al. compared subjective response to infrasound and “sham” infrasound.[39] In one case, recordings of wind turbine noise, filtered to exclude sound above 53 Hz, were presented to subjects with the infrasonic content present, with only the infrasonic content present, and with the infrasonic content removed. Results showed that adverse response to the sound, was determined by the low frequency, not infrasonic content of the sound. A study by Walker, et al. found that feelings of nausea and annoyance were more correlated with audible frequency blade swish than infrasonic components.[40]

Research by Tonin, et al. found that response to infrasound was more determined by information the subject had received about the effects of infrasound than the presence of infrasound in a sound signal.[41]

Most recently, Maijala, et al. measured infrasound at two locations near wind power projects that had been the subject of infrasound complaints, did a survey of the prevalence of symptoms attributed to infrasound, and performed a infrasound detection and annoyance test on both those that did and those that did not attribute their symptoms to wind turbine infrasound. They found that under most conditions, infrasound was below perception thresholds, but it could approach previously measured perception thresholds under some conditions. Infrasound was at a similar level to average urban areas. During listening tests, no subjects could reliably differentiate between wind turbine sound recordings that did or did not include infrasound even at levels that approached perception thresholds. There was also no difference in annoyance between recordings that did and did not include infrasound and there were no differences in

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[35] McCunney, Robert, et al. “Wind Turbines and Health: A Critical Review of the Scientific Literature.” *Journal of Occupational and Environmental Medicine.* 56(11). November 2014. pp. e108-e130.

[36] Leventhall, Geoff. “Infrasound and the ear.” *Fifth International Conference on Wind Turbine Noise*. Denver, Colorado: 28-30 August 2013.

[37] Yokoyama S., et al. “Perception of low frequency components in wind turbine noise.” Noise Control Engr. J. 62(5) 2014.

[38] Yokoyama et al. “Loudness evaluation of general environmental noise containing low frequency components.” Proceedings of InterNoise2013, 2013

[39] Hansen, K, et al. “Perception and Annoyance of Low Frequency Noise Versus Infrasound in the Context of Wind Turbine Noise.” *6th International meeting on Wind Turbine Noise*. Glasgow, Scotland: 20-23 April 2015.

[40] Walker, Bruce and Celano, Joseph. “Progress Report on Synthesis of Wind Turbine Noise and Infrasound.” *6th International Meeting on Wind Turbine Noise*. Glasgow, Scotland: 20-23 April 2015.

[41] Tonin, Renzo and Brett, James. “Response to Simulated Wind Farm Infrasound Including Effect of Expectation.” *6th International Meeting on Wind Turbine Noise*. Glasgow, Scotland: 20-23 April 2015.

autonomic nervous system response (indicated through heart rate and skin electrical conductivity). Subjects that attributed health effects to wind turbine infrasound were not more able to detect infrasound. Some of those that previously attributed their symptoms to infrasound negatively reacted to clips that they were told would contain infrasound, but which actually did not. The study concludes that the symptoms specified by respondents could not have been caused by infrasound, but instead were due to either expectations of adverse health effects to wind turbine noise or were an attribution of conditions with other causes to wind turbine infrasound.[42]

While infrasound from wind farms has not been shown to be audible by humans, infrasound and low-frequency sound can create noise-induced vibration in lightweight structures. ANSI S12.2-2008 Table 3 lists low-frequency noise criteria to prevent "perceptible vibration and rattles in lightweight wall and ceiling structures."[43] These criteria are shown in Table 3. While these are interior levels, the equivalent exterior sound levels will be higher due to building noise reduction. [44, 45, 46] Outside to inside noise reduction is a function of sound frequency and whether windows are open or closed.

ANSI S12.9 Part 4 addresses the annoyance of sounds with strong low-frequency content. Table 4 shows the "Annex D" criteria for minimal annoyance. Annex D suggests that sounds at these frequencies are similar indoors and outdoors as any transmission loss of the walls and windows can be offset by modal resonance amplification in enclosed rooms.

For comparison, Moorehouse's proposed *interior* criteria for infrasound and low-frequency sound are 94 dB, 69 dB, and 52 dB for the 16 Hz, 31.5 Hz, and 63 Hz octave bands, respectively.[47]

TABLE 3: ANSI S12.2 SECTION 6 – INTERIOR SOUND LEVELS FOR PERCEPTIBLE VIBRATION AND RATTLES IN LIGHTWEIGHT WALL AND CEILING STRUCTURES

1/1 OCTAVE BAND CENTER FREQUENCY	16 HZ	31.5 HZ	63 HZ
Clearly perceptible vibration and rattles likely	75 dB	75 dB	80 dB
Moderately perceptible vibration and rattle likely	65 dB	65 dB	70 dB

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[42] Maijala, Panu, et al. "Infrasound and Health of Wind Turbines." (*Finnish) Government Policy Brief.* 2020. This study has only been released preliminarily and only in the Finnish language.
[43] "American National Standard Criteria for Evaluating Room Noise", American National Standards Institute ANSI/ASA S12.2-2008, Acoustical Society of America, (2008).
[44] O'Neal, R. et al. "Low frequency noise and infrasound from wind turbines." Noise Control Engineering J. 59 (2), 2011.
[45] RSG, et al. "Massachusetts study on wind turbine acoustics." Prepared for MassCEC and MassDEP, February 2016.
[46] Delta Electronics Light & Acoustics, *Low frequency noise from large wind turbines, Summary and conclusions on measurements and methods,* Danish Energy Authority, EFP-06 Project, 19 December 2008
[47] Moorehouse, A., et al. "Proposed criteria for the assessment of low frequency noise disturbance," Acoustics Research Centre, Salford University DEFRA NANR45, 2005.

TABLE 4: ANSI S12.9 PART 4 ANNEX D – LOW-FREQUENCY SOUND LEVELS BELOW WHICH ANNOYANCE IS MINIMAL

1/1 OCTAVE BAND CENTER FREQUENCY	16 HZ	31.5 HZ	63 HZ
Sound Level Below Which Annoyance is Minimal	65 dB	65 dB	65 dB

APPENDIX D. SOURCE INFORMATION

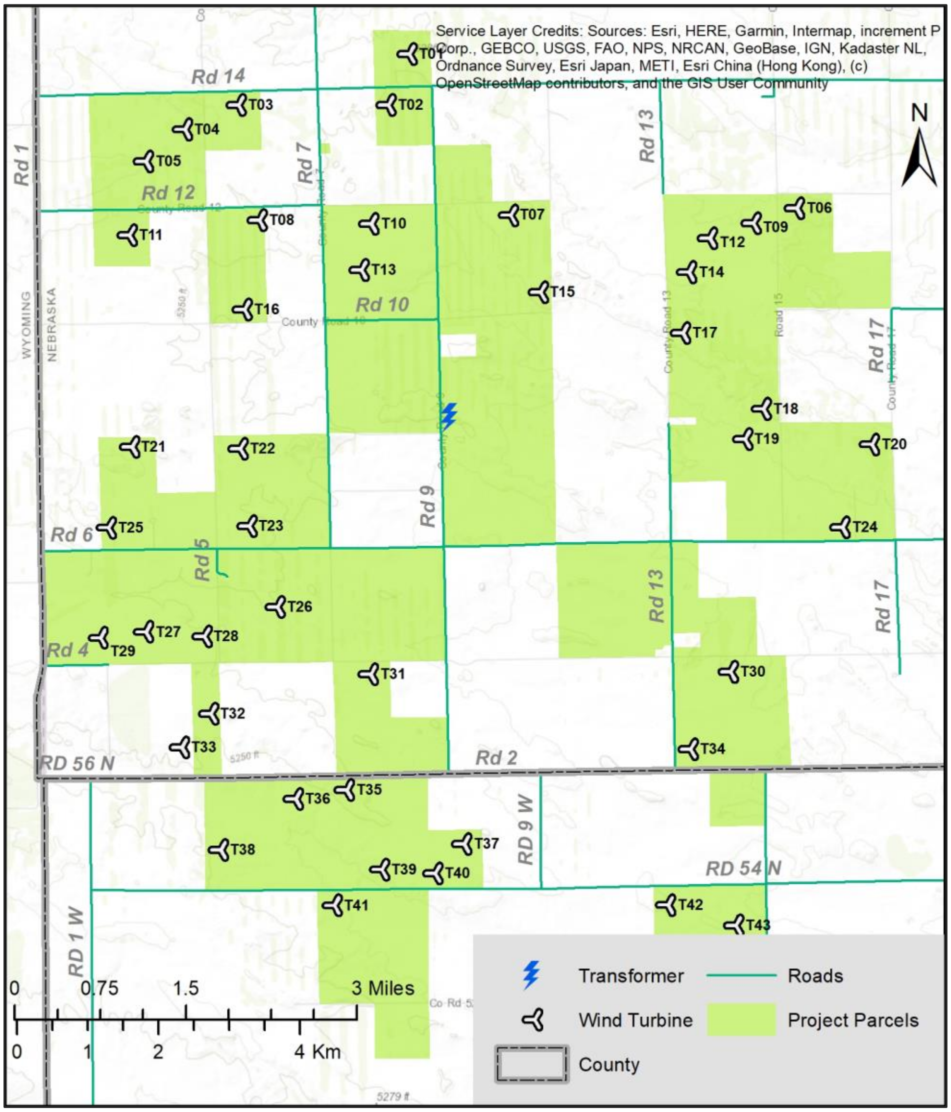


FIGURE 12: WIND TURBINE LOCATION MAP

TABLE 5: WIND TURBINE INFORMATION TABLE

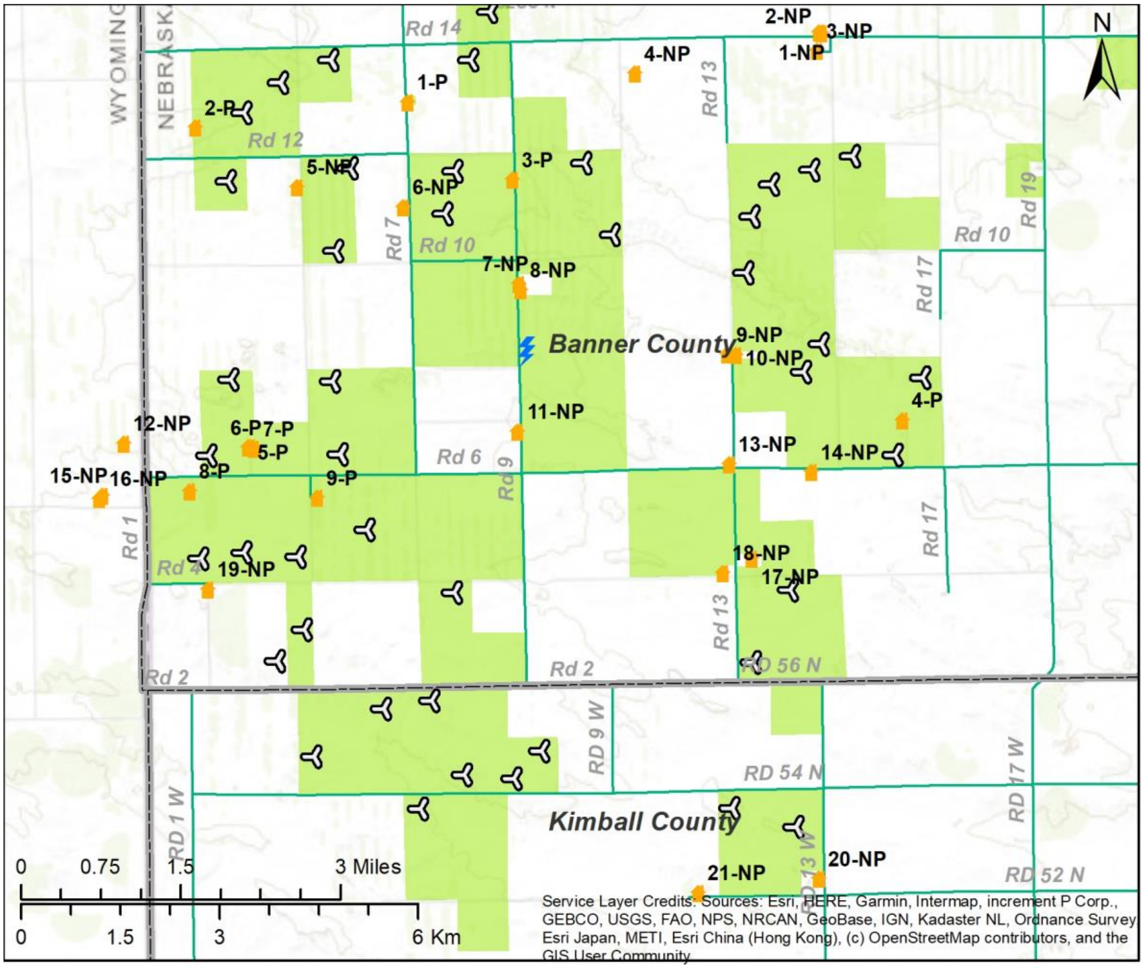
Turbine ID	Turbine Type	Hub Height (m)	Coordinates (UTM NAD83 Z13N)		
			X (m)	Y (m)	Z (m)
1	GE 3.0-140 LNTE	98	584,353	4,593,073	1,603
2	GE 3.0-140 LNTE	98	584,060	4,592,357	1,708
3	GE 3.0-140 LNTE	98	581,945	4,592,354	1,694
4	GE 3.0-140 LNTE	98	581,185	4,592,008	1,713
5	GE 3.0-140 LNTE	98	580,639	4,591,557	1,715
6	GE 3.0-140 LNTE	98	589,829	4,590,897	1,713
7	GE 3.0-140 LNTE	98	585,782	4,590,801	1,669
8	GE 3.0-140 LNTE	98	582,240	4,590,725	1,695
9	GE 3.0-140 LNTE	98	589,212	4,590,689	1,698
10	GE 3.0-140 LNTE	98	583,820	4,590,676	1,671
11	GE 3.0-140 LNTE	98	580,400	4,590,520	1,690
12	GE 3.0-140 LNTE	98	588,603	4,590,473	1,706
13	GE 3.0-140 LNTE	98	583,675	4,590,025	1,675
14	GE 3.0-140 LNTE	98	588,311	4,589,994	1,691
15	GE 3.0-140 LNTE	98	586,205	4,589,712	1,680
16	GE 3.0-140 LNTE	98	582,026	4,589,469	1,696
17	GE 3.0-140 LNTE	98	588,219	4,589,136	1,696
18	GE 3.0-140 LNTE	98	589,355	4,588,063	1,693
19	GE 3.0-140 LNTE	98	589,091	4,587,642	1,683
20	GE 3.0-140 LNTE	98	590,892	4,587,562	1,668
21	GE 3.0-140 LNTE	98	580,433	4,587,531	1,678
22	GE 3.0-140 LNTE	98	581,970	4,587,504	1,712
23	GE 3.0-140 LNTE	98	582,091	4,586,408	1,702
24	GE 3.0-140 LNTE	98	590,476	4,586,398	1,704
25	GE 3.0-140 LNTE	98	580,104	4,586,388	1,662
26	GE 3.0-140 LNTE	98	582,495	4,585,270	1,712
27	GE 3.0-140 LNTE	98	580,637	4,584,913	1,699
28	GE 3.0-140 LNTE	98	581,457	4,584,856	1,710
29	GE 3.0-140 LNTE	98	579,995	4,584,828	1,701
30	GE 3.0-140 LNTE	98	588,894	4,584,354	1,709
31	GE 3.0-140 LNTE	98	583,813	4,584,321	1,669
32	GE 3.0-140 LNTE	98	581,549	4,583,761	1,695
33	GE 3.0-140 LNTE	98	581,143	4,583,285	1,710
34	GE 3.0-140 LNTE	98	588,328	4,583,260	1,702
35	GE 3.0-140 LNTE	98	583,474	4,582,687	1,671
36	GE 3.0-140 LNTE	98	582,750	4,582,562	1,710
37	GE 3.0-140 LNTE	98	585,133	4,581,926	1,694
38	GE 3.0-140 LNTE	98	581,694	4,581,844	1,689
39	GE 3.0-140 LNTE	98	583,966	4,581,564	1,696

Turbine ID	Turbine Type	Hub Height (m)	Coordinates (UTM NAD83 Z13N)		
			X (m)	Y (m)	Z (m)
40	GE 3.0-140 LNTE	98	584,718	4,581,506	1,694
41	GE 3.0-140 LNTE	98	583,297	4,581,056	1,691
42	GE 3.0-140 LNTE	98	588,013	4,581,065	1,686
43	GE 3.0-140 LNTE	98	588,971	4,580,778	1,685

TABLE 6: TRANSFORMER INFORMATION TABLE

Source ID	**Modeled Sound Power (dBA)**	**Source Height (m)**	**Coordinates (UTM NAD83 Z16N)**		
			X (m)	**Y (m)**	**Z (m)**
Transformer (Fans On)	102	3	584,944	4,587,947	1,603

APPENDIX E. RECEIVER LEVEL RESULTS



Service Layer Credits: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

FIGURE 13: RECEIVER MAP

TABLE 7: RECEPTOR SOUND LEVEL RESULTS AND COORDINATES

	Sound Level Results			**Coordinates (UTM Zone 13N, NAD 83)**		
Receptor	Overall Level (dBA)	31.5 Hz Level (dBZ)	63 Hz Level (dBZ)	X (m)	Y (m)	Z (m)
1-NP	32	51	47	589,357	4,592,764	1,574
2-NP	31	50	47	589,396	4,592,754	1,573
3-NP	33	52	48	589,326	4,592,481	1,576
4-NP	34	53	49	586,575	4,592,140	1,583
5-NP	41	57	53	581,470	4,590,430	1,610
6-NP	42	58	54	583,071	4,590,125	1,602
7-NP	40	54	50	584,822	4,588,968	1,598
8-NP	40	53	49	584,844	4,588,871	1,599
9-NP	38	55	51	587,967	4,587,899	1,573
10-NP	38	56	52	588,099	4,587,891	1,573
11-NP	35	53	48	584,805	4,586,738	1,589
12-NP	35	53	49	578,853	4,586,557	1,622
13-NP	34	53	49	587,999	4,586,245	1,573
14-NP	36	54	50	589,242	4,586,129	1,569
15-NP	33	52	48	578,528	4,585,772	1,614
16-NP	34	53	49	578,486	4,585,724	1,616
17-NP	39	56	52	588,339	4,584,816	1,575
18-NP	36	55	50	587,902	4,584,603	1,578
19-NP	44	59	55	580,120	4,584,359	1,614
20-NP	37	53	49	589,353	4,579,990	1,582
21-NP	33	51	47	587,533	4,579,776	1,570
1-P	39	56	52	583,141	4,591,710	1,604
2-P	40	56	52	579,933	4,591,328	1,625
3-P	40	57	53	584,726	4,590,540	1,594
4-P	43	58	54	590,621	4,586,911	1,574
5-P	42	58	54	580,727	4,586,498	1,614
6-P	42	58	54	580,760	4,586,498	1,614
7-P	42	58	54	580,820	4,586,479	1,613
8-P	42	58	54	579,851	4,585,838	1,616
9-P	42	58	54	581,771	4,585,740	1,610

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