Appendix E – Crocker Wind Farm Sound Level Assessment

SOUND LEVEL ASSESSMENT

CROCKER WIND FARM

RSG
the science of insight

12.13.2017

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1.0 INTRODUCTION

Crocker Wind Farm, LLC is submitting a permit application to the South Dakota Public Utilities Commission (PUC) to build a Wind Energy System (WES) facility in Clark County, South Dakota. The facility will involve the construction of 120 wind turbines for a project rating of up to 400 MW. The turbines would be installed in an area northwest, west, southwest, south, and southeast of Crocker and is bisected by South Dakota Route 20 (SD 20). For the application, RSG has performed a sound level assessment of the project based on the current turbine layout. Included in this report are:

- A description of the project;
- A discussion of sound level standards;
- Background sound level monitoring procedure and results;
- Sound propagation modeling procedures and results; and
- Conclusions.

Appendix A includes a primer on the science of sound, including descriptions of some of the acoustical terms used in this report.

The information presented in this report leads us to conclude that the proposed Crocker Wind Farm can be constructed and operated in such a way as to comply with the Clark County and PUC noise limits for wind energy systems at all non-participating residences.

2.0 PROJECT DESCRIPTION

Crocker Wind Farm is proposed to be located in Clark County, South Dakota. The project area is generally to the northwest, west, southwest, south, and southeast of Crocker, just south of the Day/Clark County Line and 3 miles east of the Spink/Clark County Line. The southern extent of the project area is approximately 7 miles north of US Route 212 and the county seat, Clark. The roads and borders that envelope the project area are the Day/Clark County Line to the north, 415th Avenue to the west, 166th Street to the south, and 426th Avenue to the east.

The wind project is designed to include 120 turbines, with hub heights between 80 and 95 meters (262 and 312 feet), depending on the final turbine selection. A substation will be located in the middle of the project, just off of 419th Avenue. The proposed turbine model options are shown in Table 1.

The area around the project is composed primarily of agricultural land uses with farm residences and undeveloped lands. Terrain in the area is mostly flat with some rolling elevation variations of approximately 100 feet, and a typical overall elevation of 1,800 feet (550 meters) above sea level.

A map of the site including the turbine layout is provided in Figure 1.

TABLE 1: PROPOSED TURBINE MODELS

Turbine Make/Model	Turbine Output (MW)	Hub Height (m)
Vestas V136	3.45	82
Vestas V110 STE	2.0	95
GE 2.5-116 LNTE	2.5	90
Gamesa G126	2.625	84

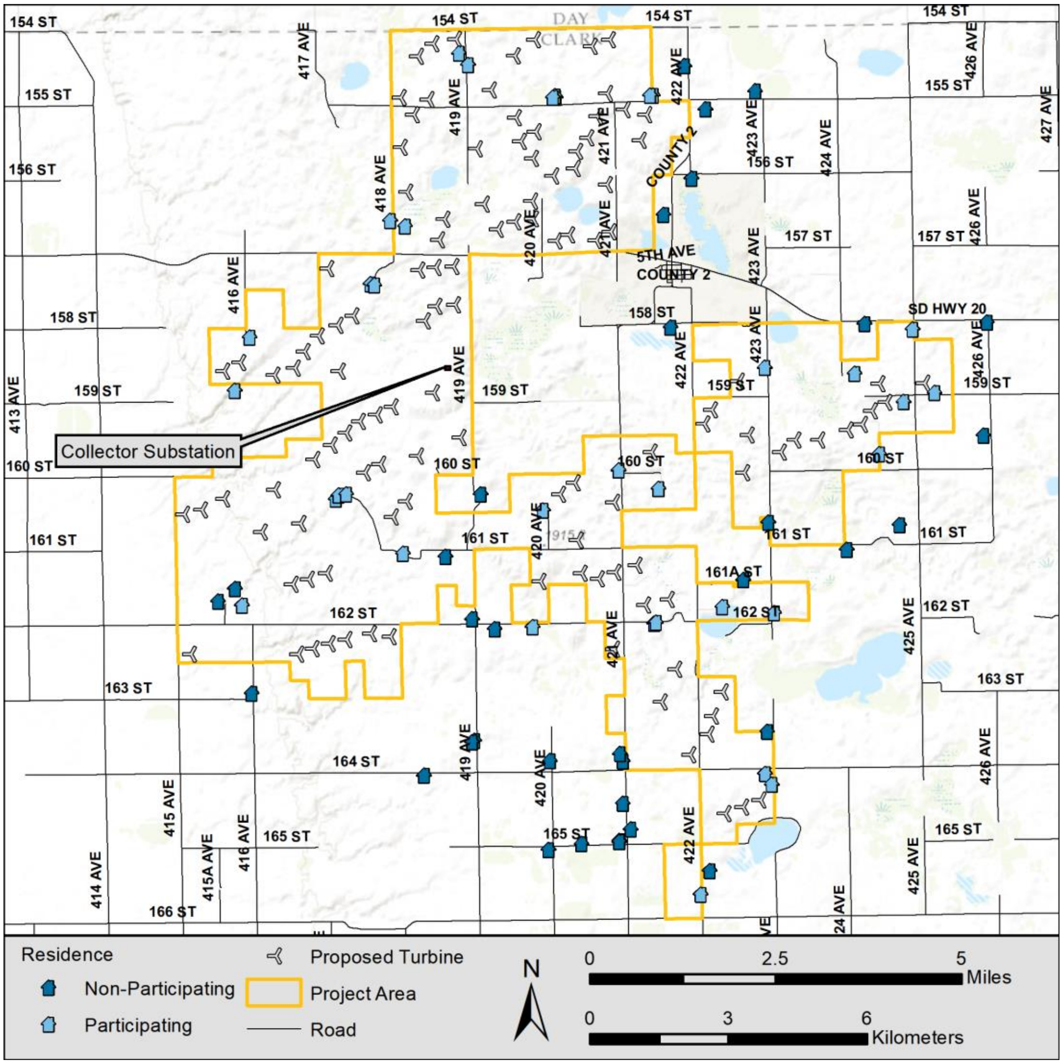

FIGURE 1: CROCKER WIND FARM AREA MAP

3.0 SOUND LEVEL STANDARDS & GUIDELINES

3.1 | LOCAL STANDARDS

Locally, the Clark County Zoning Ordinance regulates noise from wind energy systems in Section 4.21.03:

> “13. Noise. Noise shall not exceed 50 dBA, average A-weighted Sound pressure including constructive interference effects at the perimeter of the principal and accessory structures of existing off-site residences, businesses, and buildings owned and/or maintained by a governmental entity.”

3.2 | STATE STANDARDS

The South Dakota PUC does not have a quantified or codified standard or rule regarding noise from WES facilities. They have, however, developed a “Model Ordinance for Siting of Wind Energy Systems”[1] (Model Ordinance). The PUC encourages local governments to use the model ordinance for their specific needs. For large WES facilities the model ordinance states that noise, “[…] shall not exceed 55 dBA, average A-weighted sound pressure at the perimeter of occupied residences existing at the time the permit application is filed, unless a signed waiver or easement is obtained from the owner of the residence.”

It is our understanding that since developing the Model Ordinance, the PUC has reduced their recommended noise limit to 50 dBA at the perimeter of an existing occupied residence, unless a signed waiver or easement is obtained from the owner of the residence. This is consistent with the sound limits in the Clark County Zoning Ordinance.

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[1] SD PUC, “Draft Model Ordinance for Siting of Wind Energy Systems (WES)”, October 2008

4.0 SOUND LEVEL MONITORING PROCEDURES

Background sound level monitoring was conducted throughout the area to quantify the existing sound levels around the project.

Three locations were monitored to determine existing background sound levels, Monitors A, B, and C. A map of the monitor locations within the project area are shown in Figure 2.

Monitoring locations were selected to represent different areas and different soundscapes (i.e. unique sound characteristics) within the project.

Further information on the monitoring locations as well as a review of monitoring equipment and procedures is found in the following sections.

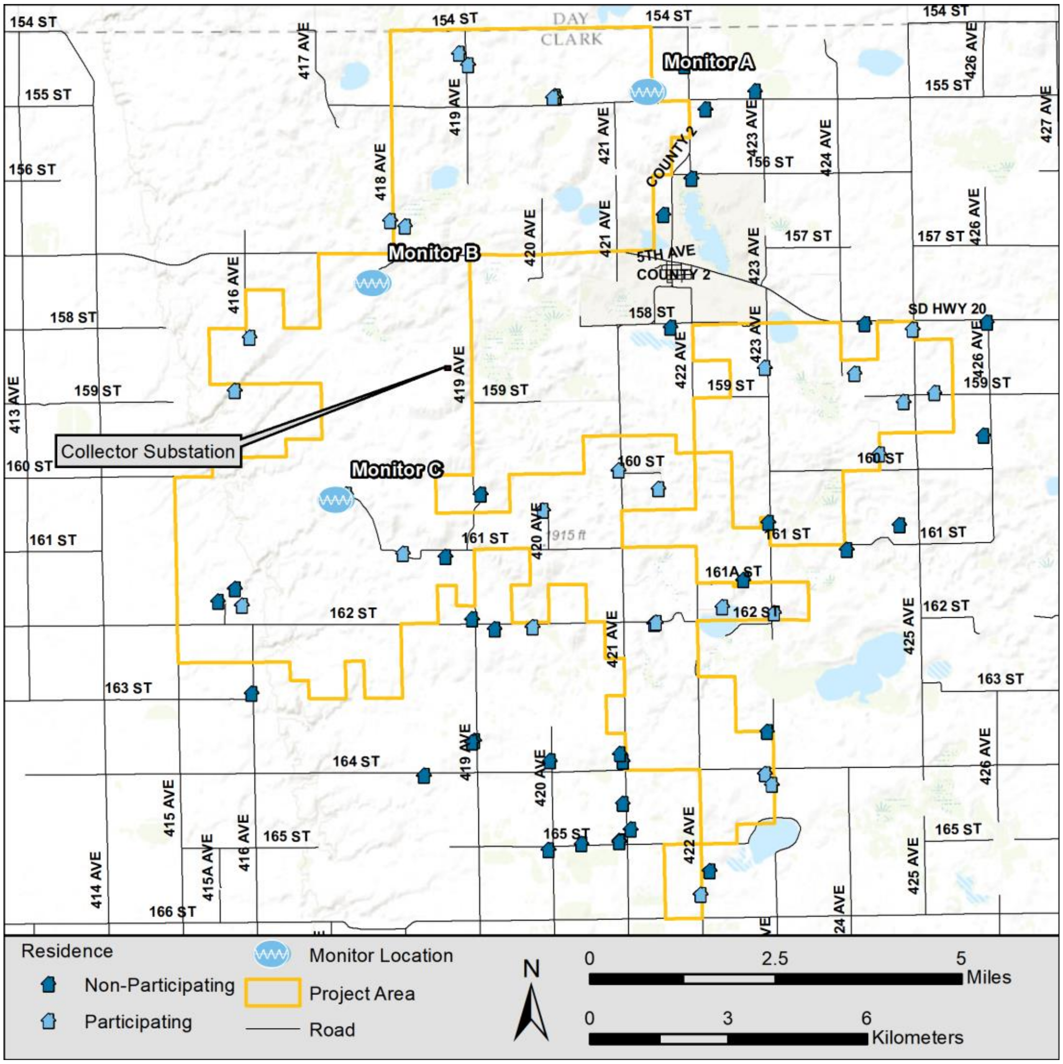

FIGURE 2: MONITORING LOCATION MAP

4.1 | EQUIPMENT

Background sound level monitoring was performed with ANSI/IEC Type 1 Svantek SV979 and ANSI/IEC Type 2 Rion NL22 sound level meters. The Svantek SV979 sound level meters were set to log, at a minimum, 1/3 octave band sound levels once each second for the entire measurement period and the Rion NL22 sound level meter was set to log A-weighted sound levels once each second for the entire measurement period. The Svanteks were set to record audio internally, and the Rion was attached to an external audio recorder. Sound level meter microphones were mounted on wooden stakes at a height of approximately 1.5 meters (5 feet) and covered with 180 mm (7 inch) windscreens to minimize the impact of wind distortion on measurements. Before and after the measurement periods, the meters were calibrated with either a Cesva CB-5 or Brüel and Kjær 4231 calibrator.

A list of the equipment used at each monitor is shown in Table 2. At each site, an ONSET anemometer was located at microphone height. Wind data was logged at a rate of once each minute. Precipitation and temperature data were obtained from the Weather Underground station located in Watertown, South Dakota.

TABLE 2: SOUND MONITOR SPECIFICATIONS BY SITE

Monitor Location	Sound Level Meter	Audio Recorder
A	Svantek SV979	Internal
B	Rion NL22	Edirol R-05
C	Svantek SV979	Internal

4.2 | DATA PROCESSING

After data collection, data was downloaded, processed, and summarized into 10-minute, overall day, overall night, and monitoring-period length periods. For each 10-minute period, equivalent average (Leq), upper 10th percentile (L10), median (L50), and lower 10th percentile (L90) sound levels were also calculated.

A second set of data was also generated with periods removed from the data that either contained anomalous sound events or periods with conditions that could lead to false sound level readings.

Periods that were removed from the sound level data included:

- Wind speeds above 11 mph (5 m/s);
- Precipitation and thunderstorm events;
- Anomalous events; or
- Equipment interaction either by RSG staff, other humans, or animals.

4.3 | MONITOR LOCATION DESCRIPTIONS

MONITOR A

Monitor A was located at an active farm which are common throughout the project area and is representative of that type of land use. A picture of the monitoring setup is shown in Figure 3, and a map of the monitoring location is shown in Figure 4.

Monitor A was situated in the northeastern part of the project area, approximately 3,700 meters (2.3 miles) north of the village of Crocker. County Road 42 was located approximately 180 meters (590 feet) to the south, with the intersection between County Road 42 and County Road 2 located approximately 930 meters (3,050 feet) to the southeast. The county boundary with Day County is approximately 1,600 meters (1 mile) to the north. The nextEra-owned Day County Wind Energy Center is located approximately 6,300 meters (3.9 miles) to the northwest.

The monitor was on the north side of barns that were part of a farm. Trees to the north of the monitor provided shelter. Farm buildings were located primarily to the south. A residence was located on another parcel to the southeast. The surrounding area is predominantly farmland, with scattered clumps of trees that surround homesteads and barns.

FIGURE 3: PHOTOGRAPH OF MONITOR A LOOKING EASTWARD

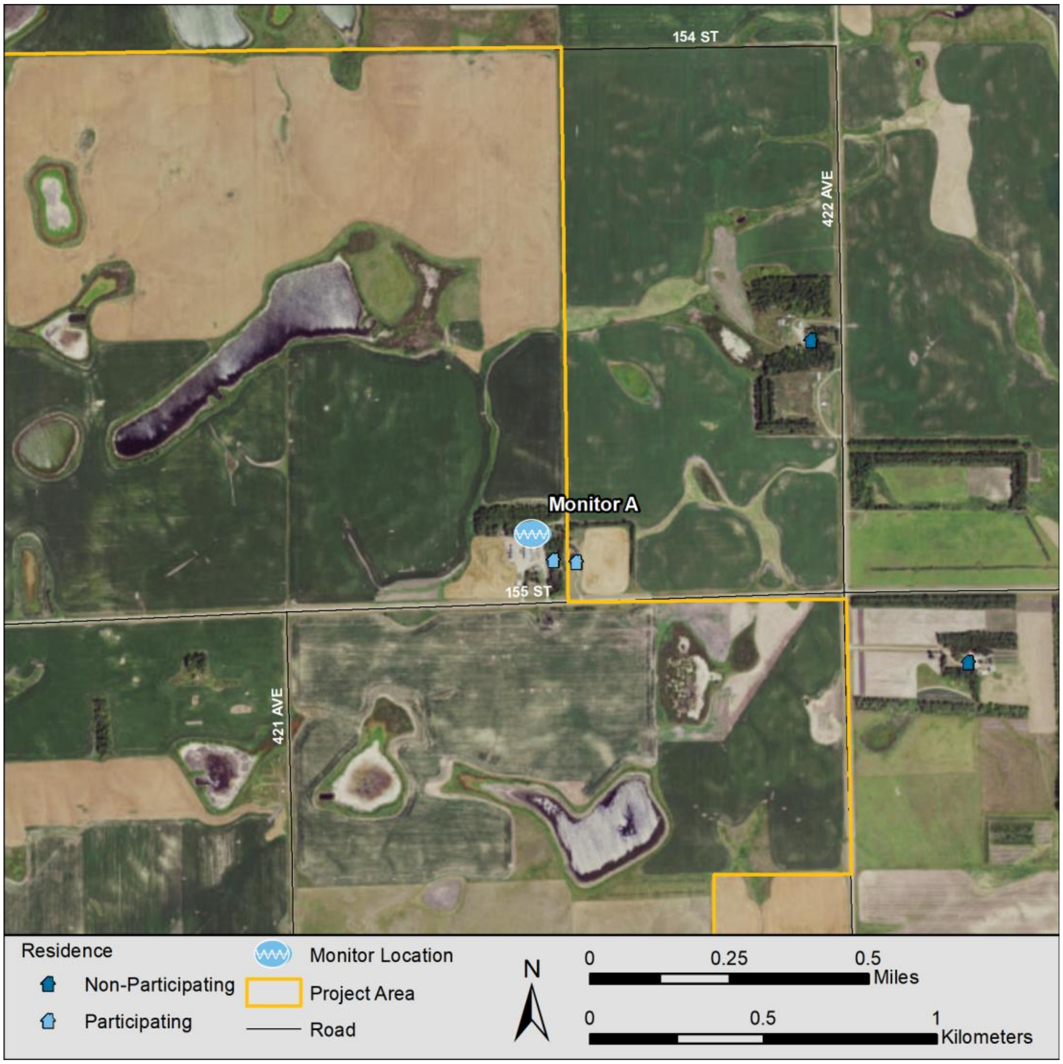

FIGURE 4: MONITOR A LOCATION AERIAL VIEW

MONITOR B

Monitor B was located at a homestead with less consistent sound sources than at Monitor A. It is representative of a rural residential farm in moderate proximity to a state highway. A picture of the monitor setup is shown in Figure 5, and a map of the monitoring location is shown in Figure 6.

Monitor B was situated in the western part of the proposed project area. South Dakota Highway 20 (SD 20) was the closest road, located approximately 640 meters (2,100 feet) to the north with the intersection between SD 20 and 418th Avenue located approximately 800 meters (2,600 feet) to the northeast. The village of Crocker was located approximately 6,500 meters (4.1 miles) to the east and the Day County Wind Energy Center was located approximately 6,400 meters (4 miles) to the north.

The monitor was located on a homestead, approximately northeast and slightly downhill of the residence, in an area with small trees, that surrounds a nearby residence. This general area is higher than the surrounding area. Cattle farming and haying take place in the fields surrounding the homestead, with ancillary barns located to the south, at a distance of approximately 90 meters (300 feet).

FIGURE 5: PHOTOGRAPH OF MONITOR B LOOKING EAST

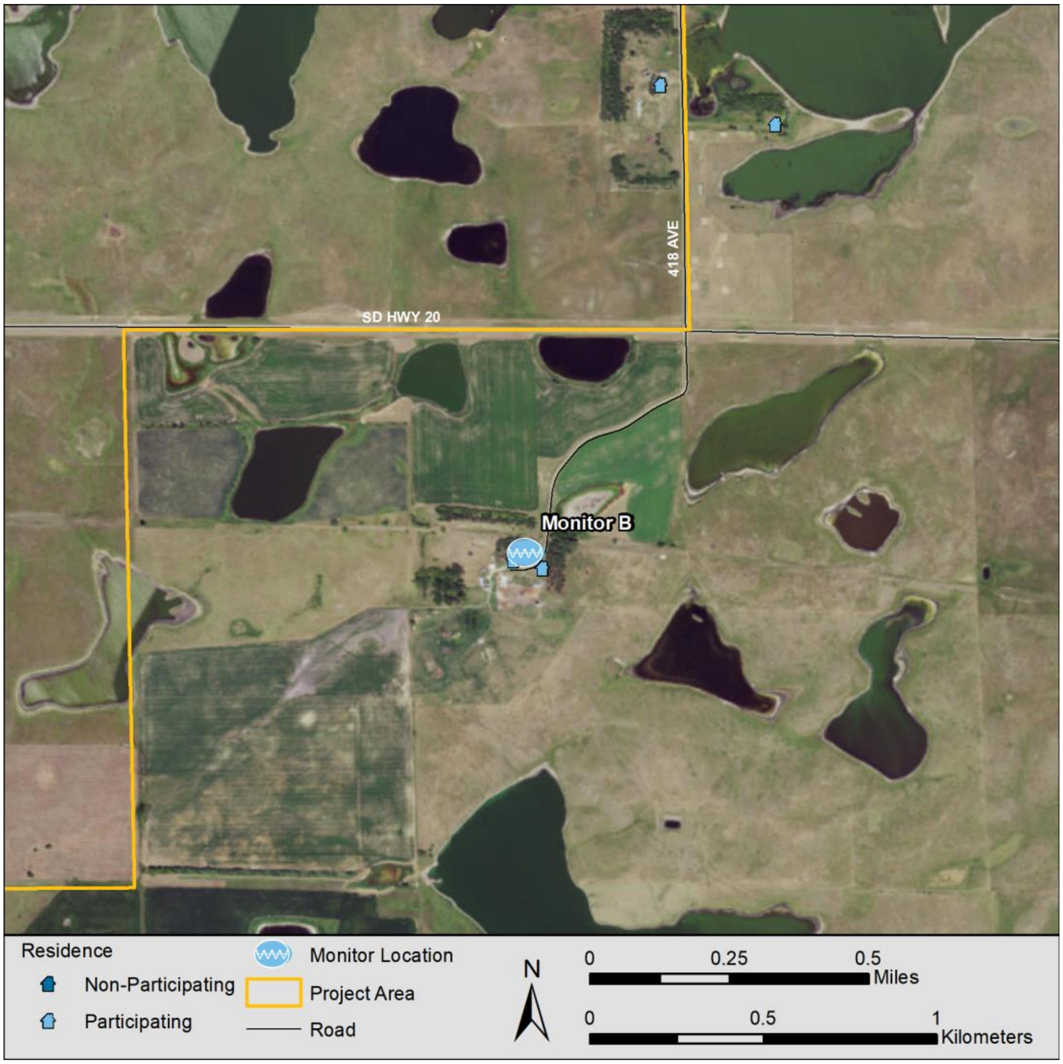

FIGURE 6: MONITOR B LOCATION AERIAL VIEW

MONITOR C

Monitor C was located just south of a residence, on a cattle-raising operation, and is representative of a rural residential farm that is not near any notable roadways. The residence was part of a series of three residences belonging to the family that owns the ranch. A picture of the monitoring setup is shown in Figure 7, and a map of the monitor location is shown in Figure 8. The area is in a low-lying area, with pasture and haying land covering the surrounding hills in all directions. While there were some trees near the monitor, the area was not consistently wooded.

The monitor was situated at the end of 161st Street, approximately 3,000 meters (1.9 miles) west of the intersection with 419th Avenue. The location is in the southwestern part of the project in a sparsely populated area, except for the immediately surrounding residences.

FIGURE 7: PHOTOGRAPH OF MONITOR C LOOKING NORTHEAST

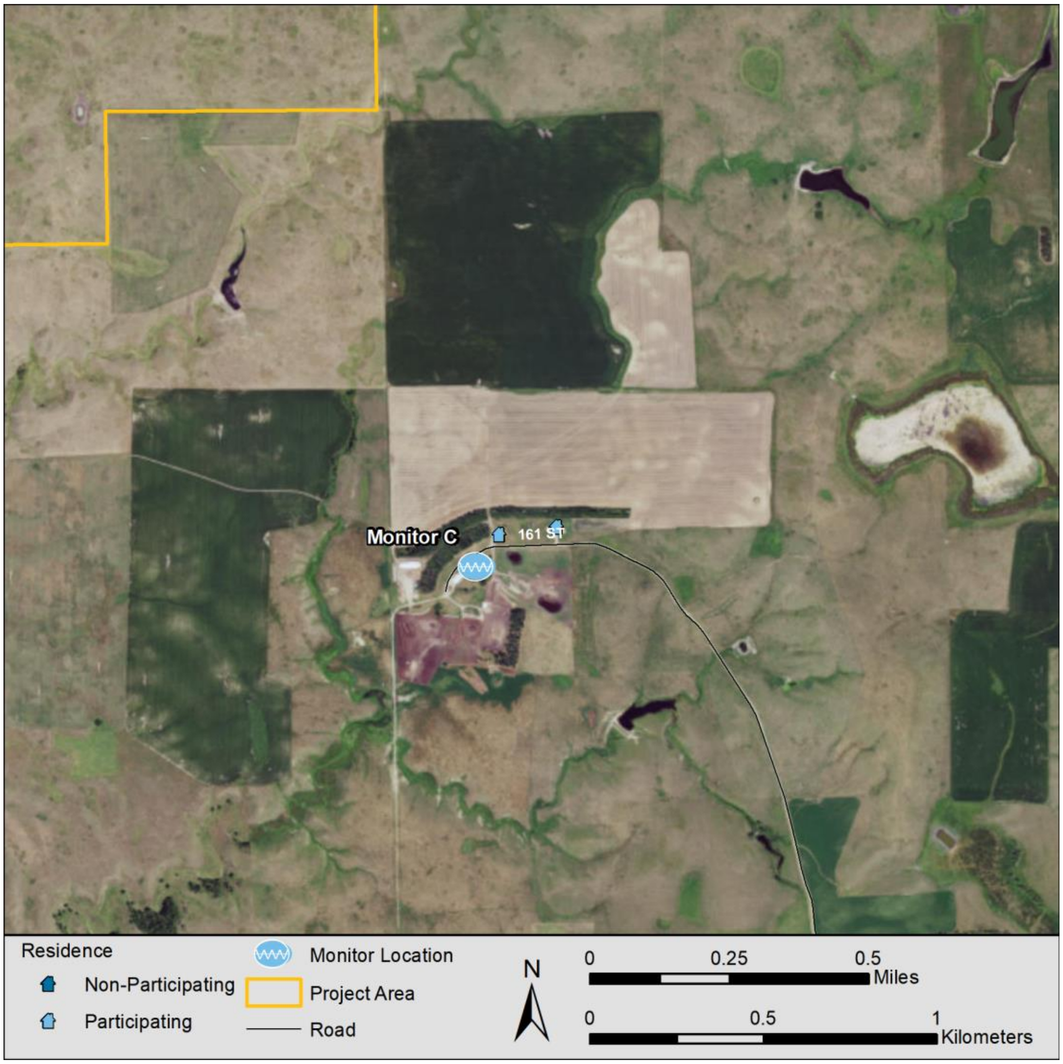

FIGURE 8: MONITOR C LOCATION AERIAL VIEW

5.0 SOUND LEVEL MONITORING RESULTS

For each monitor site, sound level monitoring results are presented this report section. Each chart contains 10-minute sound levels, gust wind speed measured adjacent to each microphone, the temperature obtained from a Weather Underground site in Watertown, SD, and indications of data exclusions. Points on the sound level graph represent data summarized for a single 10-minute interval. All portions of the chart exhibit day/night shading: night is defined as 22:00 to 07:00 and shaded in grey.

The specific sound level metrics reported are the L_{EQ} and L_{90}. Equivalent continuous sound levels (L_{EQ}) are the energy-average level over one hour. Tenth-percentile sound levels (L_{90}) are the statistical value above which 90% of the sound levels occurred during one hour. Data that were excluded from processing (e.g., due to high wind and rain periods) are included in the graphs but shown in lighter colors. Furthermore, square markers on the upper portion of the chart indicate periods for which data was excluded and designate if the period was eliminated as a result of rain, wind gusts over 11 mph, or anomalous events.

Sound level data and wind gust data presented in the charts are those measured at each corresponding site. Wind data from the monitoring location, measured at the microphone height of 1.5 meters (5 feet), are presented as the maximum gust speed occurring at any time over a 10-minute interval; they are not averaged.

5.1 | RESULTS SUMMARY

METEOROLOGY

Local meteorological data was collected from anemometers alongside the monitors and a Weather Underground site in Watertown, SD. According to the airport, local temperatures ranged from -1.7°C to 19.2°C over the duration of the monitoring period. There were no precipitation events.

A summary of the 1.5-meter (5-foot) wind speeds measured at each monitoring location is provided in Table 3. The table reveals that Monitors B and C had equal average wind speeds, with the highest gust measured at monitor C. Monitor A consistently had the lowest wind speeds.

TABLE 3: SUMMARY OF MEASURED 10-MINUTE 1.5-METER (5-FOOT) WIND SPEEDS

Monitor	10-min Wind Speed (mph)		10-min Gust Speed (mph)	
	Average	Maximum	Average	Maximum
A	3.1	11.2	6.8	20.3
B	4.8	17.3	8.5	25.9
C	4.8	21.4	8.2	30.4

EXCLUSION PERIODS

Periods were excluded at each monitor through both manual identification and automated processing. Manual processing included the review of spectrograms created from the measured one-second one-third octave band data, accompanied by audio recordings made through the sound level meter's microphone. For Monitor B, where the monitor did not log 1/3 octave band data, processing was performed by listening to the audio files of time periods where sound levels were atypical of the rest of the monitoring period. In this way, typical sources and anomalous events were identified.

There were no rainy periods during monitoring. Automated processing of wind speed permitted the identification of gusts above 11 mph on a one-minute basis. That is, if a gust within a specific one-minute period was measured above 11 mph, then that whole minute was eliminated.

A summary of each monitor's total runtime and the amount of time excluded from the reported sound levels for rain, wind, and anomalous events are shown in Table 4. The most time was excluded from Monitor B (2 days of data, or 29%) due to the effect of strong winds at microphone height.

TABLE 4: SUMMARY OF RUNTIME AND EXCLUSION PERIODS AT EACH MONITOR

Locations	Run-time	Exclusion Statistics							
		Rain		High Wind		Anomalies		Total	
	(hours)	(hours)	(%)	(hours)	(%)	(hours)	(%)	(hours)	(%)
A	165.8	0	0.0%	28.6	17.2%	0.4	0.2%	29.0	17.5%
B	166.5	0	0.0%	48.2	28.9%	0.0	0.0%	48.2	29.0%
C	166.2	0	0.0%	43.6	26.2%	1.85	1.1%	45.4	27.3%

BACKGROUND SOUND LEVELS

The measured background sound levels are listed for all seven sites in Table 5. The reported levels represent all valid periods, that is, all periods that were not excluded due to weather or anomalous activity, as discussed above.

Sound levels are less at night than during the day, except for at Monitor A. The large difference between L_{EQ} and 10th-percentile levels (L_{90}) indicates that the soundscapes at Monitors B and C are often dominated by transient or intermittent sounds (such as aircraft overflights, passing automobiles, or farming activity). Monitor A is dominated by equipment fan noise, which maintained a constant sound level and operated throughout the nighttime hours and much of the day.

TABLE 5: PRECONSTRUCTION MONITORING SUMMARY SOUND LEVELS (IN dBA)

Monitor Location	Overall				Day				Night			
	Leq	L90	L50	L10	Leq	L90	L50	L10	Leq	L90	L50	L10
A	51	34	51	53	50	32	50	52	52	50	51	53
B	39	21	31	41	41	21	32	43	36	20	29	39
C	42	17	31	43	44	20	33	45	36	15	26	38

5.2 | MONITORING RESULTS FOR MONITOR A

Background sound level monitoring results for Monitor A are shown in Figure 9 and Figure 10. Sound levels at this site were driven by the existence of fans at the agricultural barns located just to the south of the site. The fans typically operated all through the night, and a large portion of the day, dominating overall sound levels. As a result, there is no particular pattern to sound levels. Other sound sources included the ingress and egress of trucks and other farm equipment to the property. There were few audible biogenic sounds other than wind.

Daytime and nighttime equivalent average sound levels (L_{EQ}) were 50 and 52 dBA respectively. Daytime and nighttime lower 10th percentile sound levels (L_{90}) were 32 and 50 dBA respectively. The daytime lower 10th percentile sound levels were higher than the nighttime sound levels due to the continuous nighttime operation of the nearby equipment fans and more intermittent daytime operation.

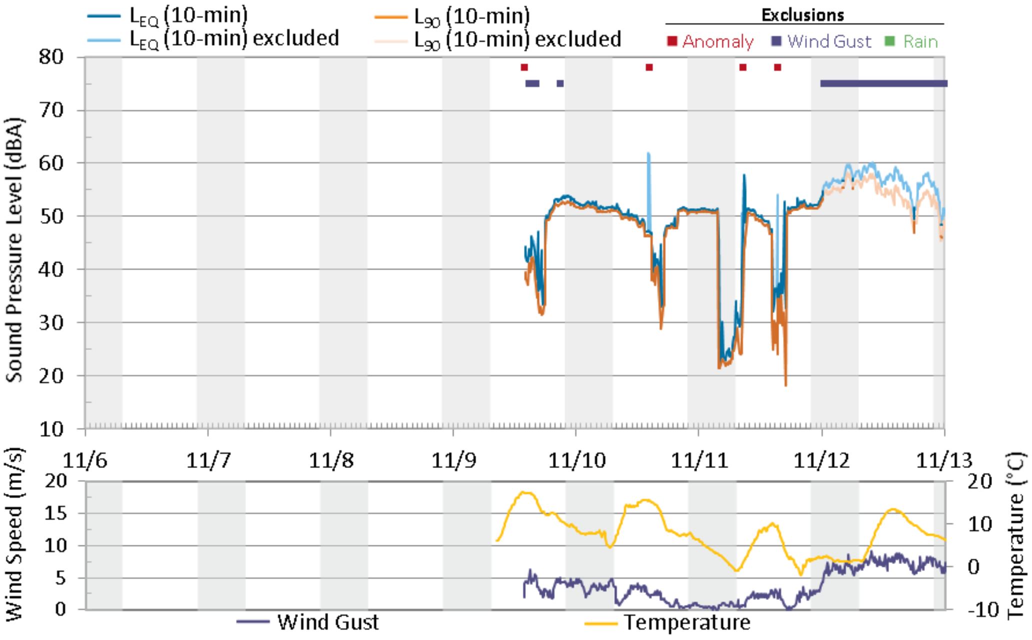

FIGURE 9: SOUND PRESSURE LEVELS OVER TIME - MONITOR A, N0VEMBER 9 TO NOVEMBER 13, 2016

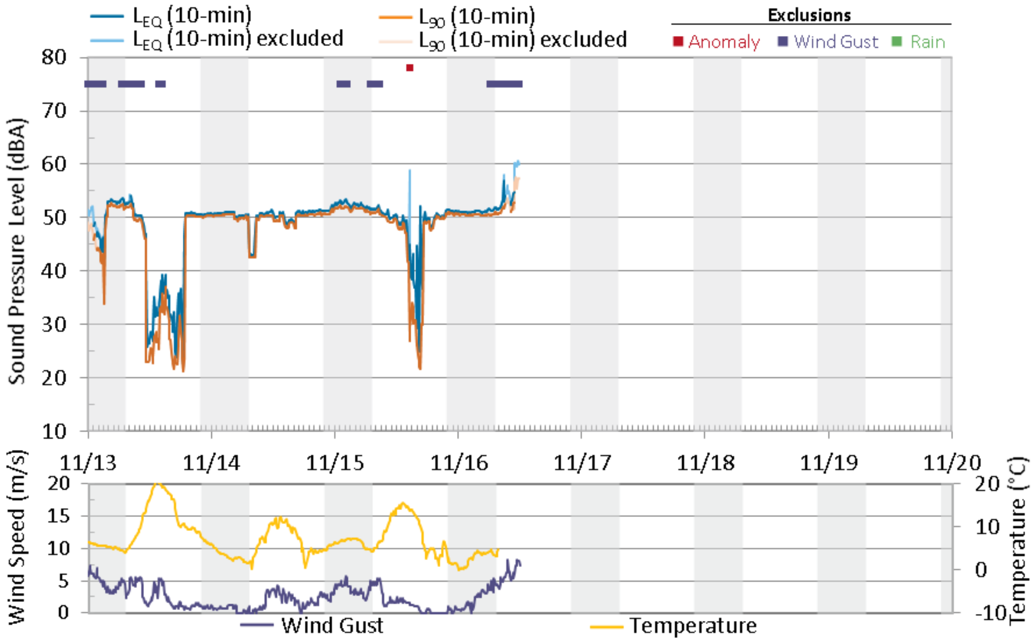

FIGURE 10: SOUND PRESSURE LEVELS OVER TIME - MONITOR A, NOVEMBER 13 TO NOVEMBER 16, 2016

5.3 | MONITORING RESULTS FOR MONITOR B

Background sound level monitoring results for Monitor B are shown in Figure 11 and Figure 12. Sound sources at the site include farming equipment, farm animals, domestic animals, occasional coyotes, and distant car passbys from South Dakota Highway 20. Sound levels exhibit a diurnal pattern, though not in overall sound level. Instead, sound levels become more constant at night, as is demonstrated by convergence of the equivalent average and lower 10th percentile sound levels. This is caused by a nighttime reduction in anthropogenic sound sources.

Equivalent average sound levels were 41 dBA during the day and 36 dBA at night and lower 10th percentile sound levels (L_{90}) were 21 dBA during the day and 20 dBA at night. Lower 10th percentile sound levels are quite low overall, demonstrating the rural nature of the site, with few consistent sound sources.

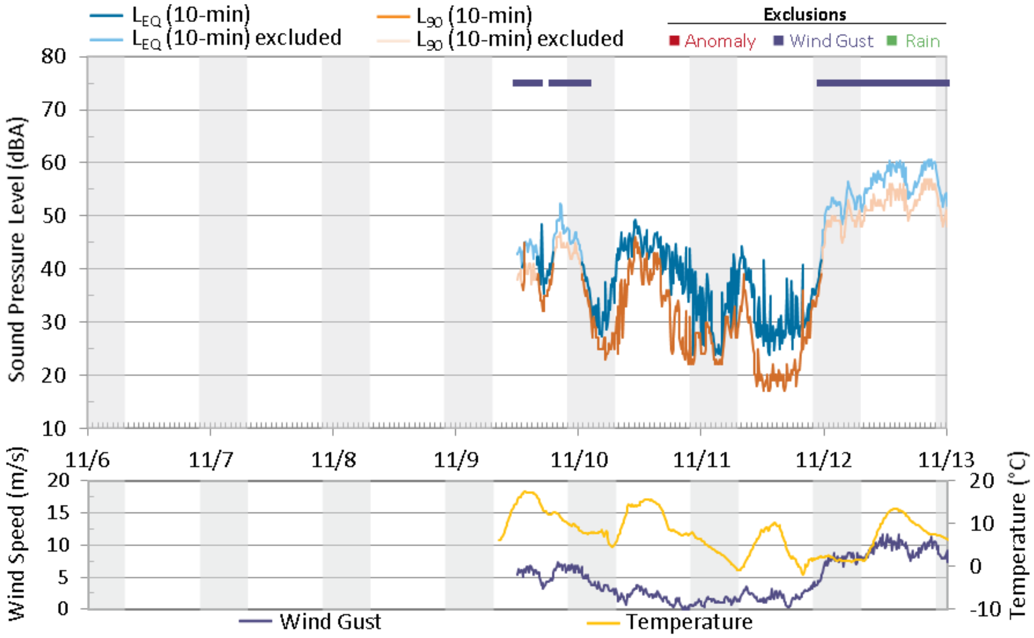

FIGURE 11: SOUND PRESSURE LEVELS OVER TIME - MONITOR B, NOVEMBER 9 TO NOVEMBER 13, 2016

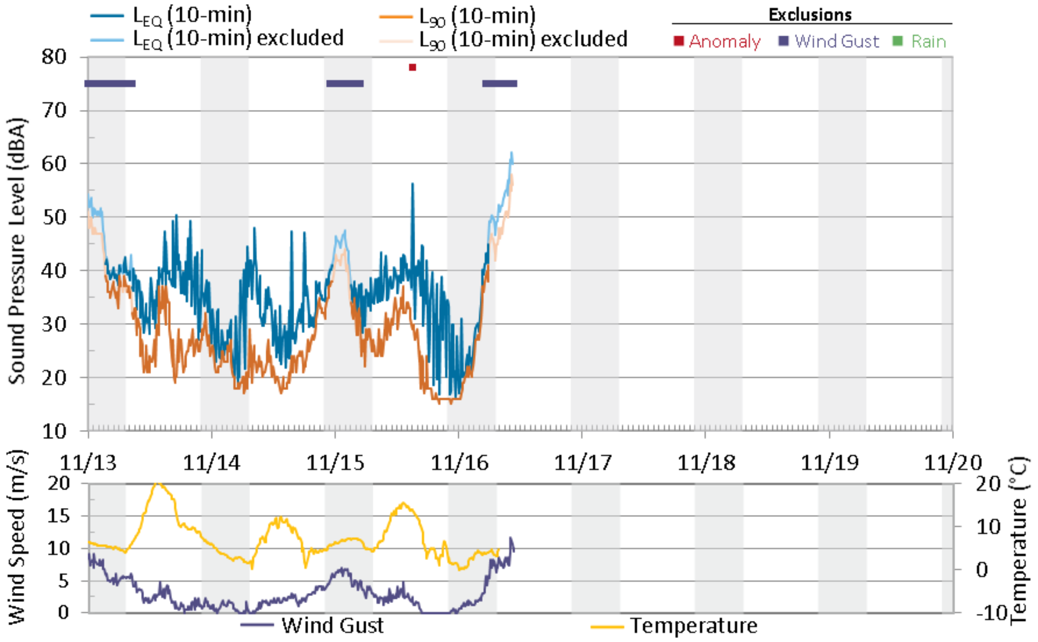

FIGURE 12: SOUND PRESSURE LEVELS OVER TIME - MONITOR B, NOVEMBER 13 TO NOVEMBER 16, 2016

5.4 | MONITORING RESULTS FOR MONITOR C

Background sound level results for Monitor C are shown in Figure 13 and Figure 14. Major sound sources at this site are farm equipment, farm animals, dogs, vehicle passbys, birds, and airplane overflights. Sound levels have a diurnal pattern, with sounds overall lower at night, except during windy periods or when dogs are barking near the monitor. Similar to other locations, sound levels are less dynamic at night, causing a convergence of the equivalent average and lower 10th percentile sound levels.

Daytime and nighttime equivalent average sound levels were 44 and 36 dBA respectively, and daytime and nighttime lower 10th percentile sound levels were 20 and 15 dBA respectively. The equivalent average sound levels reasonably low, particularly for a site with agricultural activity. Lower 10th percentile sound levels were close to the noise floor of the sound level meter that was used when there was no measurable wind. This is the most remote monitoring site, with a lack of major roadways for miles and few other homes, which contributes to the lower background sound level.

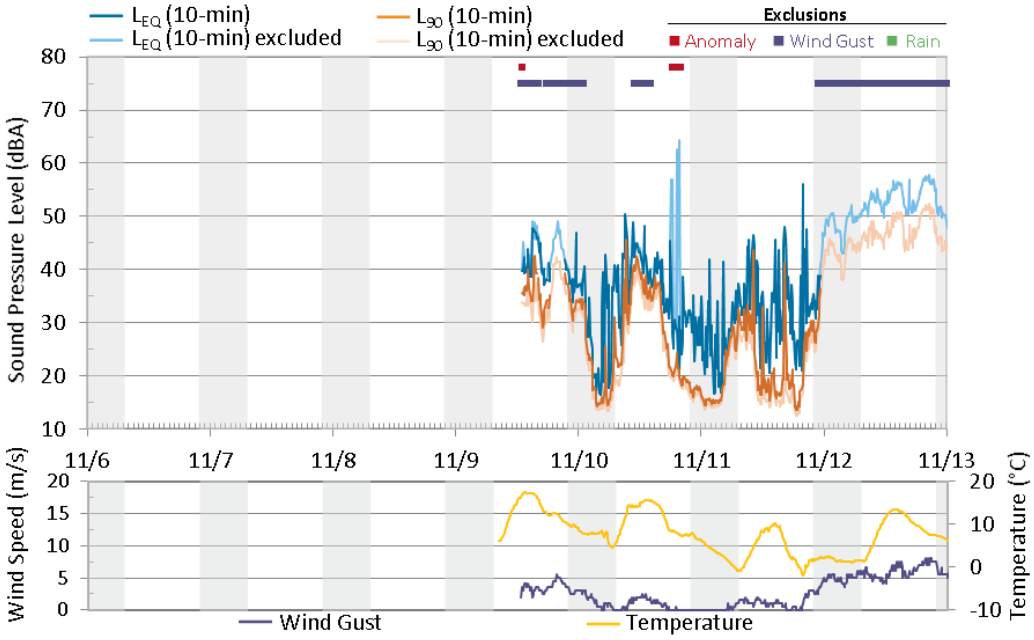

FIGURE 13: SOUND PRESSURE LEVELS OVER TIME – MONITOR C, NOVEMBER 9 TO NOVEMBER 13, 2016

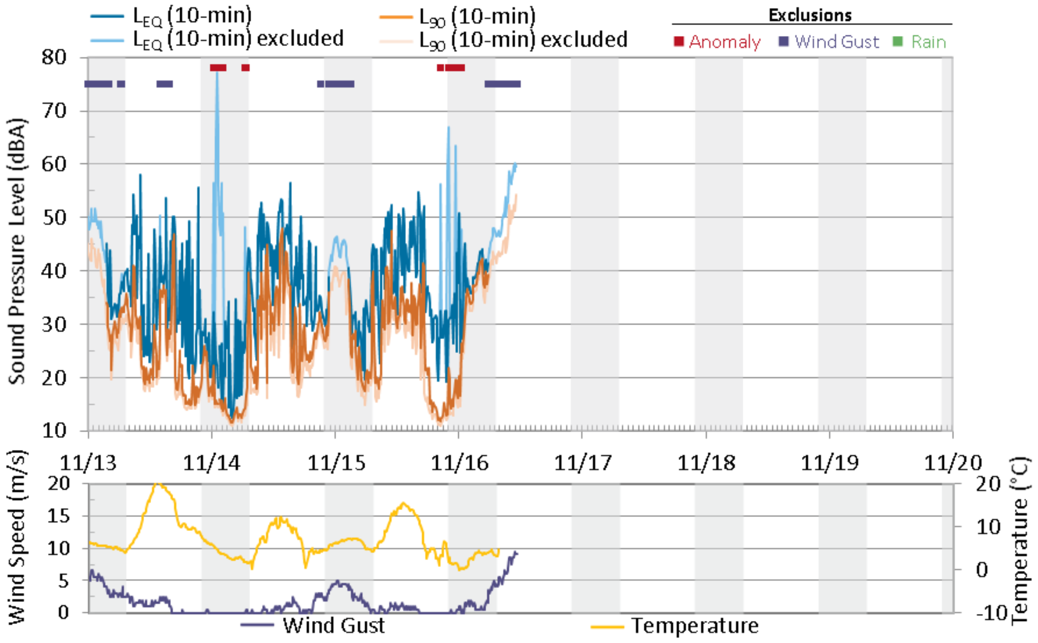

FIGURE 14: SOUND PRESSURE LEVELS OVER TIME - MONITOR C, NOVEMBER 13 TO NOVEMBER 16, 2016

6.0 SOUND PROPAGATION MODELING

6.1 | MODELING PROCEDURES

Modeling for the project was 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, 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.

Model input parameters are listed in Appendix B including the modeled sound power spectra for each turbine model.

For this analysis, we utilized a ground absorption factor for mixed porous and hard ground of G = 0.5, which is appropriate for comparing modeled results to the L_{EQ} metric used in the state standard. A 2 dB uncertainty factor was added to the turbine sound power per typical manufacturer specifications.

Two distinct receiver heights are included in the analysis. Residences[2] are modeled as discrete receivers at 4 meters (13 feet) above ground level. The 4-meter (13-foot) receiver height mimics the height of a second-story window. The sound pressure level contours in Figures 15 to 18 are calculated at a height of 1.5 meters (5 feet), to represent average listening height outside of homes.

A search distance up to 8,000 meters (5 miles) allows for the contributions of distant turbines to be considered at receivers. The contribution of distant turbines will depend on the geometry and geography of the project.

Four iterations were performed using the currently proposed turbine layout and turbine models which include the Gamesa G126 2.625 MW, GE 2.5-116 LNTE, Vestas V110 STE

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[2] There are no off-site businesses or governmental buildings in the relevant modeling area.

2.0 MW, Vestas V136 3.45 MW. Each model included sound from the proposed transformer at the collector substation. The modeled sound power spectra for each turbine is provided in Appendix B.

6.2 | MODEL RESULTS

A summary of the sound propagation model results for each turbine model is provided in Table 6, and Appendix C provides a list of the calculated overall sound pressure levels at each receiver for all four models and a map showing all receiver identification numbers for reference in the chart. Appendix D provides a discussion on low frequency noise and infrasound from wind turbines and a brief summary of low frequency model results.

As shown in Table 6, all residences are projected at 50 dBA or less, and all non-participating residences are projected at 41 dBA or less from the proposed project. The average across all residences is 39 to 40 dBA depending on which turbine model is selected.

TABLE 6: MODEL RESULTS SUMMARY

Residence Classification	GE2.5			G126			V110			V136		
	Avg. Leq	Max. Leq	Min. Leq	Avg. Leq	Max. Leq	Min. Leq	Avg. Leq	Max. Leq	Min. Leq	Avg. Leq	Max. Leq	Min. Leq
All	40	49	30	40	50	29	40	49	30	39	48	29
Participating	44	49	33	44	50	33	44	49	33	43	48	32
Non-Participating	36	40	30	36	41	29	36	40	30	35	40	29

Model results are also shown in Figure 15 through Figure 18 in a contour line map format. Results are presented as contour lines representing 5-dB increments of calculated A-weighted sound pressure levels.

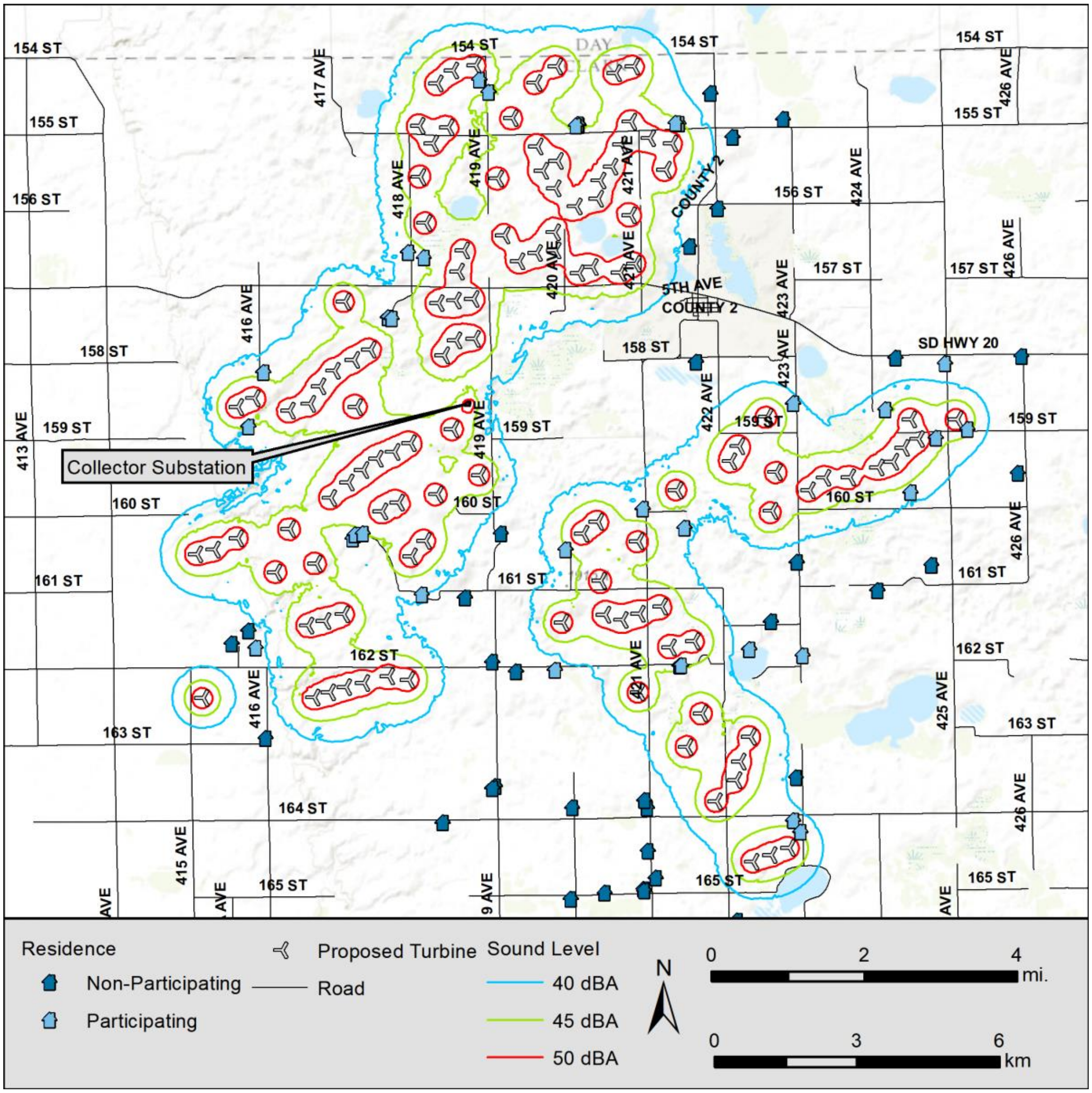

FIGURE 15: GAMESA G126 2.625 MW SOUND PROPAGATION MODELING RESULTS

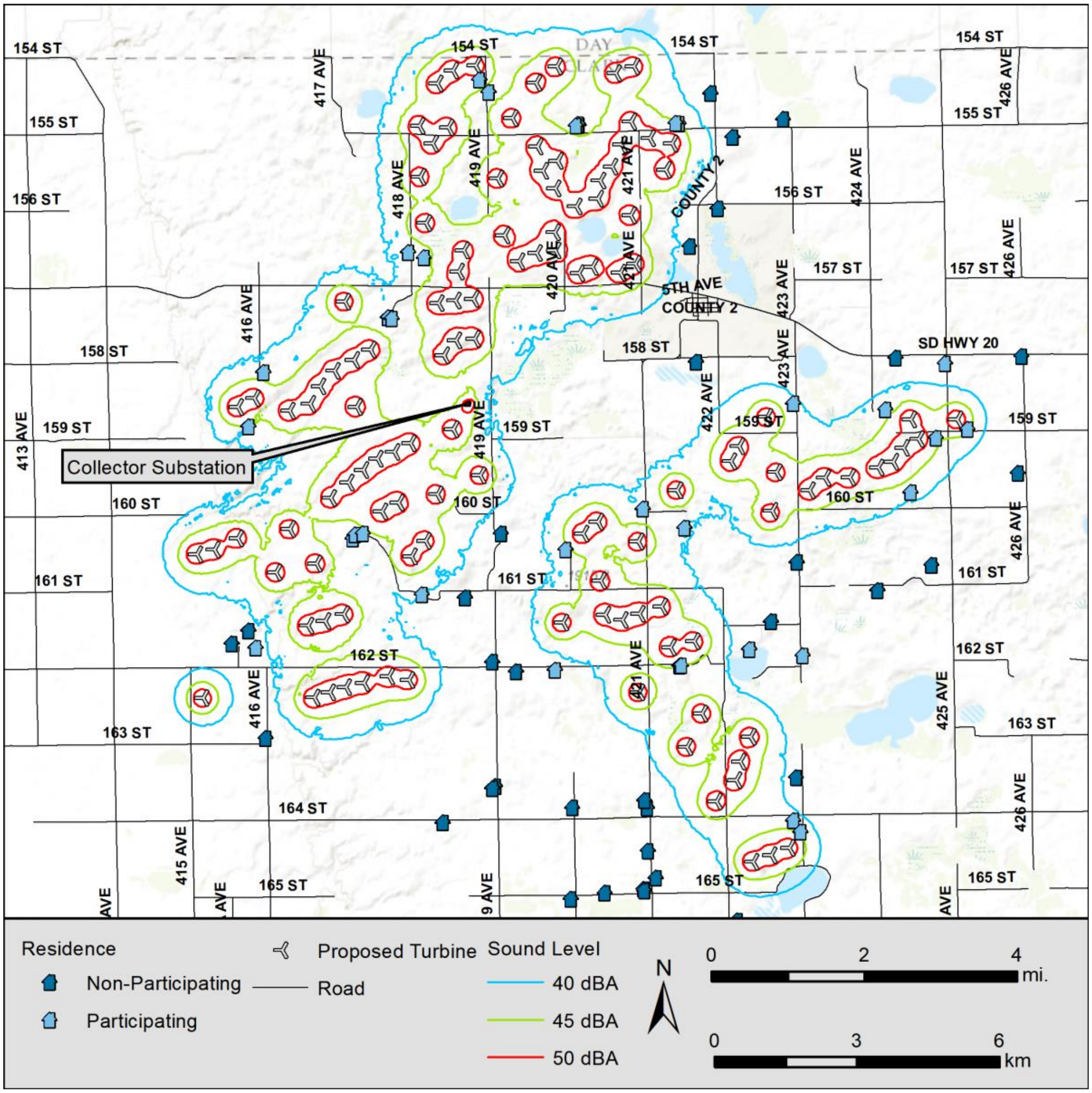

FIGURE 16: GE 2.5-116 LNTE SOUND PROPAGATION MODELING RESULTS

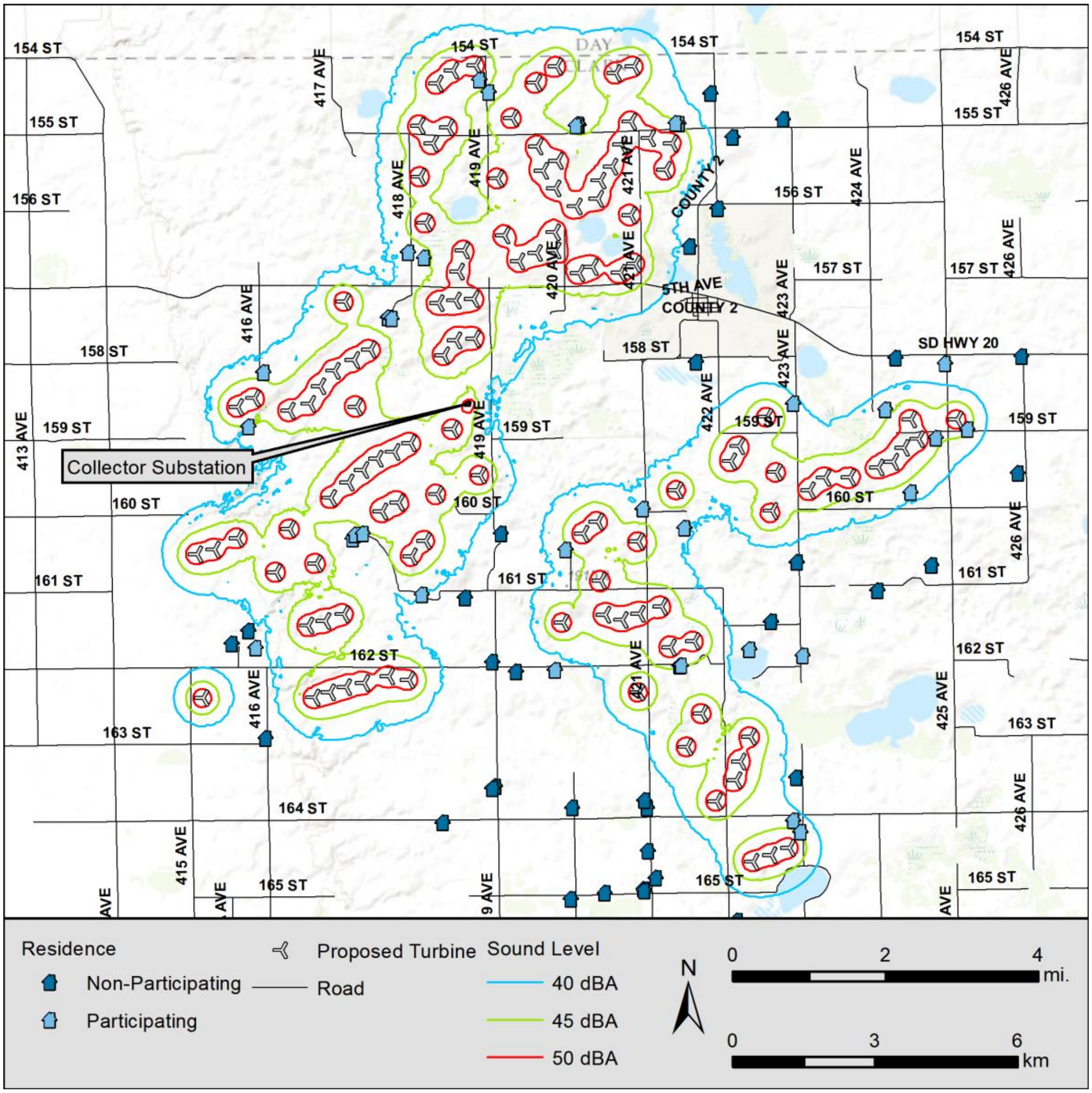

FIGURE 17: VESTAS V110 STE 2.0 MW SOUND PROPAGATION MODELING RESULTS

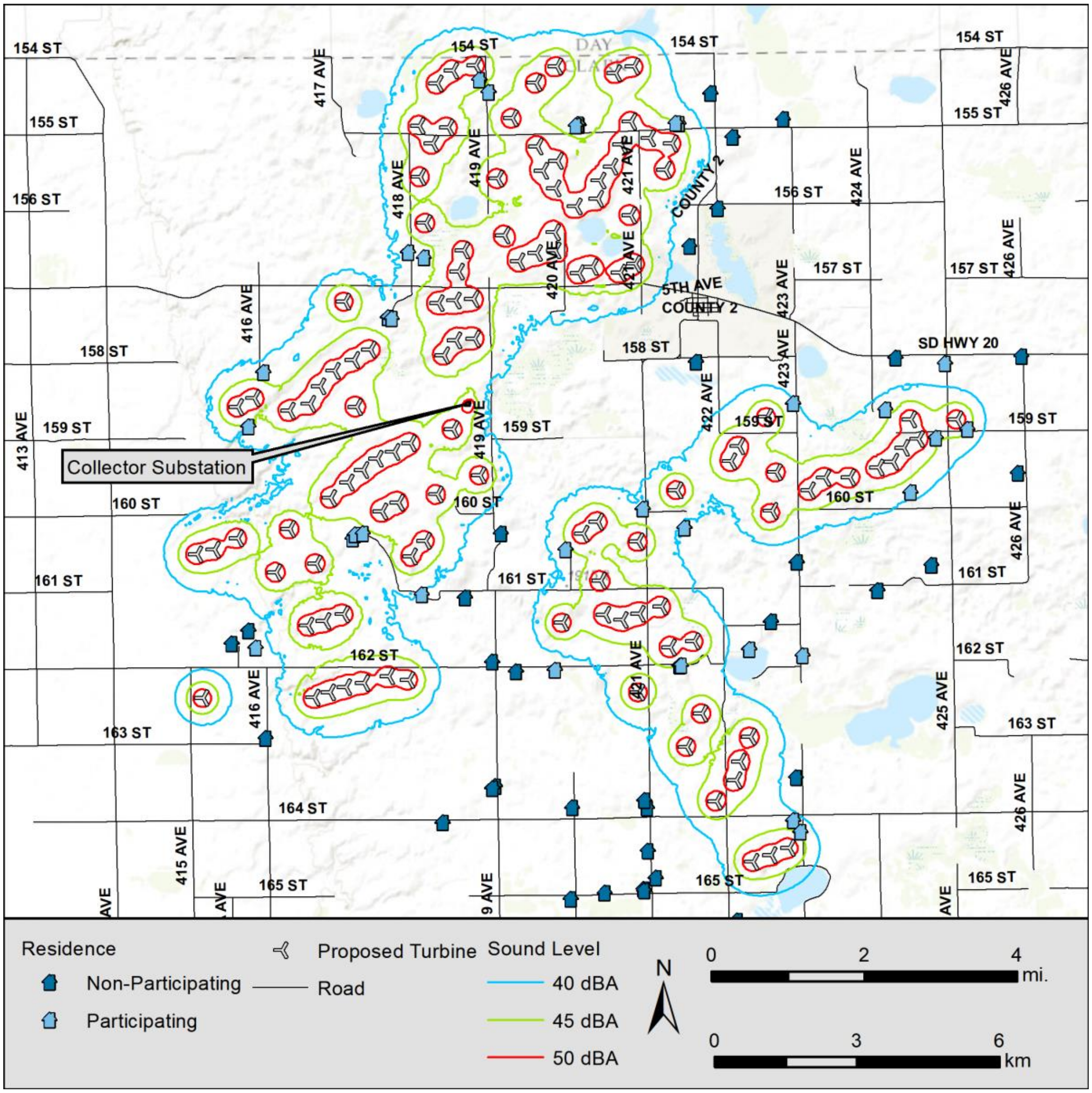

FIGURE 18: VESTAS V136 3.45 MW SOUND PROPAGATION MODELING RESULTS

7.0 CONCLUSIONS

Crocker Wind Farm is a proposed wind power generation facility in Clark County, South Dakota. The facility will include 120 wind turbines for a project rating of up to 400 MW. In preparation for its Site Permit Application, RSG conducted a sound level assessment of the project comparing projected wind farm sound levels with the Clark County and PUC noise limits for wind energy systems. Conclusions of the assessment are as follows:

1. Sound sources in the existing soundscape include agricultural equipment, farm animals and pets, vehicle passbys, birds, airplane overflights, and geophonic sounds such as wind in the trees or ground cover.
    a. Background sound levels vary some around the project site. For two of the monitor locations (Monitor B & C) the overall equivalent continuous sound level (Leq) at nighttime was 36 dBA, while at Monitor A, the nighttime sound level (Leq) was 52 dBA due to a fan for agricultural use which ran fairly consistently.
    b. On a 10-minute basis, nighttime equivalent continuous sound levels (Leq) generally ranged between 16 and 40 dBA at Monitors B and C, with the lowest levels coincident with low ground wind speeds.
2. Both the County noise limit and the State recommended limit that applies to this project is a 50 dBA equivalent continuous sound pressure level (Leq) at residences.
    a. Sound propagation modeling was performed in accordance with ISO 9613-2 at 69 discrete receivers that surround the project with spectral ground attenuation and a ground factor of G=0.5. These modeling parameters represent the Leq of the proposed facility.
    b. Modeling was completed for four different turbine models: Gamesa G126 2.625 MW, GE 2.5-116, Vestas V110 STE 2.0 MW, Vestas V136 3.45 MW. Each model run also included sound emissions from the transformer at the collector substation.
    c. For all turbine models, projected sound levels from the project are 50 dBA or less at all residences, 41 dBA or less at all non-participating residences, and the average sound level (Leq) across all residences is 39 or 40 dBA depending on the turbine model.

The information presented in this report leads us to conclude that the proposed Crocker Wind Farm can be constructed and operated in such a way as to comply with the Clark County and PUC noise limits for wind energy systems at all non-participating residences.

APPENDIX A: ACOUSTICS PRIMER

Expressing Sound in Decibel Levels

The varying air pressure that constitutes sound can be characterized in many different ways. The human ear is the basis for the metrics that are used in acoustics. 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".

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). 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 19.

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.

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

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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.

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.

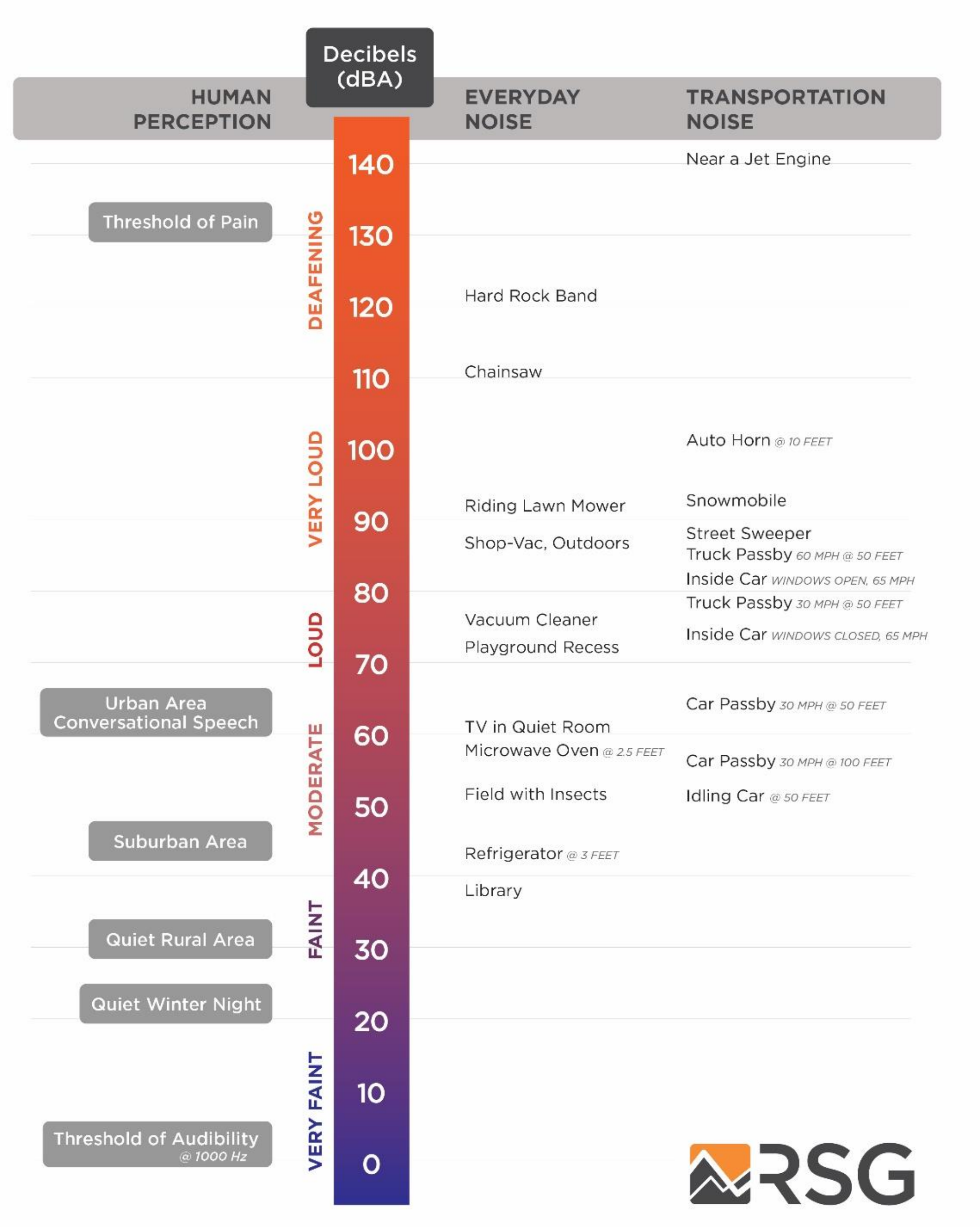

FIGURE 19: A SCALE OF SOUND PRESSURE LEVELS FOR TYPICAL SOUND SOURCES

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 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, sound pressure fluctuations are not "heard", but sometimes can be "felt". This is 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. 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". 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.[4] 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.

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[4] 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.

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 constant), Slow time response L_{Smax} (1-second time constant), or Continuous Equivalent level over a specified time period L_{EQmax}.

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 20. 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. 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 20, 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.

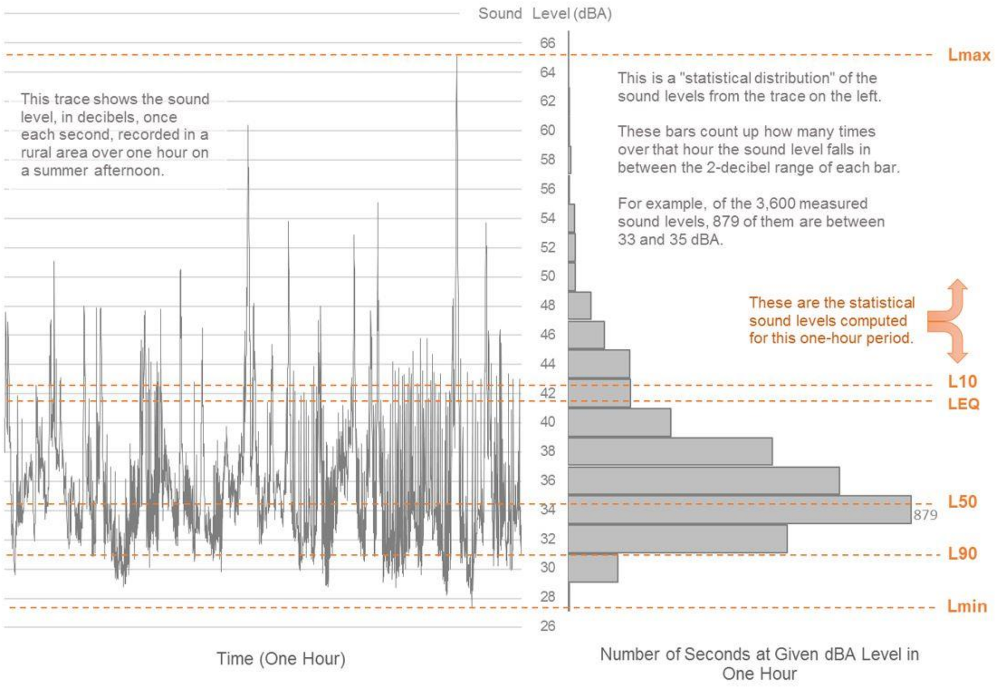

FIGURE 20: EXAMPLE OF DESCRIPTIVE TERMS OF SOUND MEASUREMENT OVER TIME

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. L_{50} (the “median level”) is exceeded 50% of the time: half of the time the sound is louder than L_{50}, and half the time it is quieter than L_{50}. Note that L_{50} (median) and L_{EQ} (mean) are not always the same, for reasons described in the previous section.

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 aren’t 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: SOURCE INFORMATION

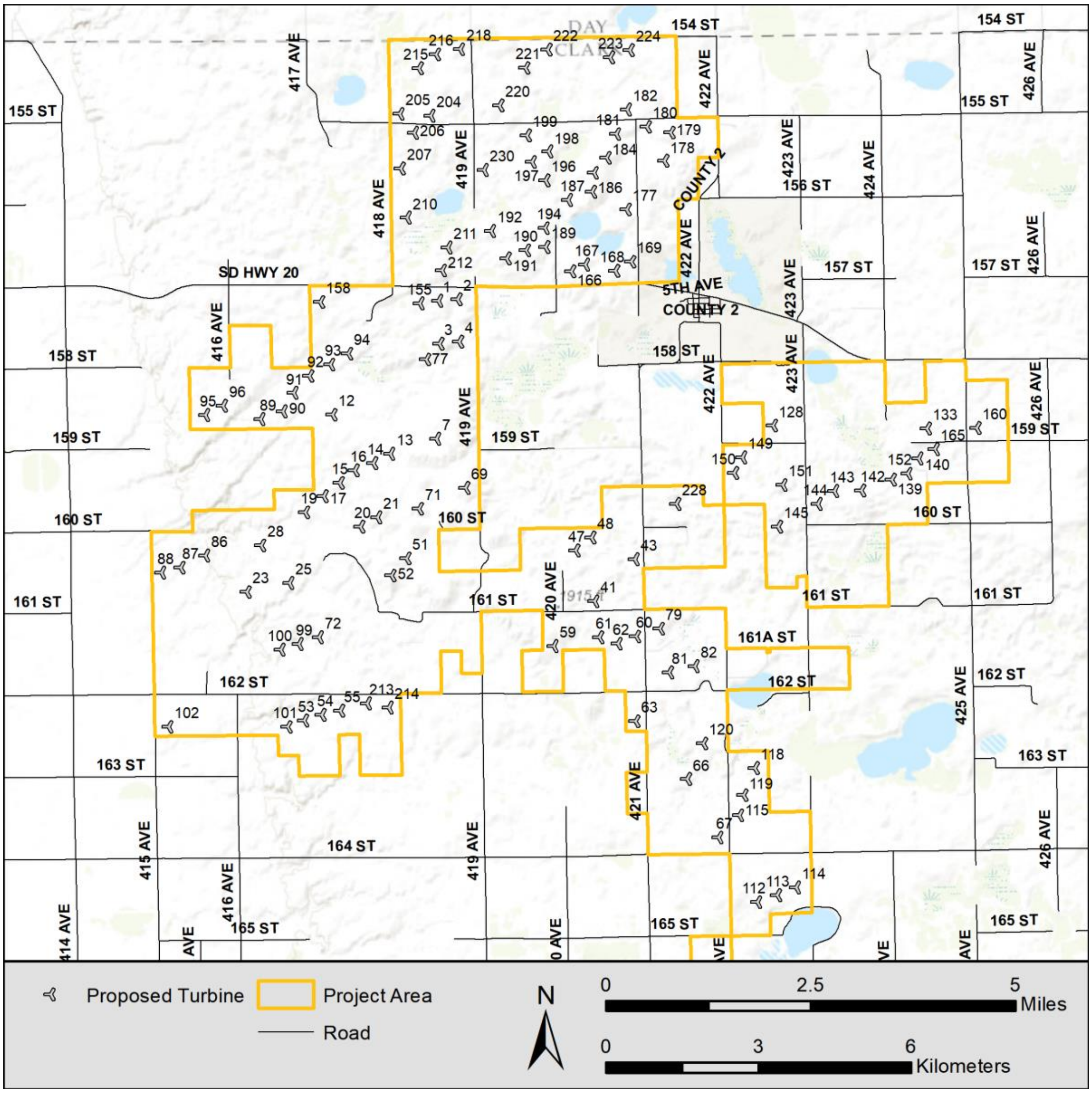

FIGURE 21: SOURCE LOCATIONS

TABLE 7: SOUND PROPAGATION MODELING PARAMETERS

Parameter	Setting
Ground Absorption	Spectral for all sources, Mixed Ground (G=0.5)
Atmospheric Attenuation	Based on 10 Degrees Celsius, 70% Relative Humidity
Reflections	None
Receiver Height	4 meters for residences, 1.5 meters for grid
Search Distance	8,000 meters

Note: Information from Table 8 and Table 9 has been redacted from this version of the study because they contain proprietary information provided by a third party.

TABLE 8: 1/1 OCTAVE BAND MODELED TURBINE SPECTRA (dBZ UNLESS OTHERWISE INDICATED) [5, 6]

Sound Source	1/1 Octave Band Center Frequency									Sum (dBA)	Sum (dBZ)
	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz		
Vestas V110 2.0 MW STE											
GE 2.5-116 LNTE											
Vestas V136 3.45 MW											
Gamesa G126 2.625 MW											
Transformer - Fans On	95	85	104	102	105	85	81	76	67	102.9	109.1

TABLE 9: TURBINE SOUND POWER LEVEL & LOCATIONS

Source ID	G126 - Modeled Sound Power (dBA)	GE 2.5-116 LNTE - Modeled Sound Power (dBA)	V110 STE - Modeled Sound Power (dBA)	V136 - Modeled Sound Power (dBA)	Coordinates (UTM NAD 83 Z14N)		
					X (m)	Y (m)	Z (m)
1					590446	4995368	643
2					590826	4995399	628
3					590462	4994532	642
4					590856	4994567	630
7					590405	4992661	653
12					588367	4993133	625
13					589507	4992362	628
14					589170	4992179	627
15					588511	4991794	626
16					588805	4992040	625
17					588196	4991533	613
19					587827	4991215	606
20					588910	4990931	610
21					589252	4991113	631
23					586676	4989647	580
25					587518	4989827	597
28					586966	4990561	590

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[5] STE stands for Serrated Trailing Edges which are used on some turbine locations for the V110.

[6] LNTE stand for Low Noise Trailing Edges which are used on some turbine locations for the GE 2.5-116.

Source ID	G126 - Modeled Sound Power (dBA)	GE 2.5-116 LNTE - Modeled Sound Power (dBA)	V110 STE - Modeled Sound Power (dBA)	V136 - Modeled Sound Power (dBA)	Coordinates (UTM NAD 83 Z14N)		
					X (m)	Y (m)	Z (m)
41					593513	4989472	637
43					594307	4990293	634
47					593136	4990460	633
48					593455	4990714	628
51					589815	4990311	639
52					589526	4989977	648
53					587806	4987122	592
54					588146	4987232	601
55					588519	4987316	604
59					592709	4988584	654
60					594328	4988774	631
61					593605	4988756	638
62					593971	4988637	634
63					594313	4987114	649
66					595331	4985968	640
67					595952	4984823	647
69					590976	4991691	664
71					590066	4991288	649
72					588098	4988758	598
77					590206	4994221	639
79					594791	4988927	632
81					594979	4988071	633
82					595484	4988193	629
86					585866	4990367	568
87					585381	4990128	555
88					585004	4990030	544
89					586955	4993047	614
90					587393	4993196	615
91					587601	4993558	617
92					587904	4993894	618
93					588322	4994123	625
94					588666	4994332	626
95					585865	4993126	602
96					586215	4993311	593
99					587704	4988626	587
100					587352	4988518	589

Source ID	G126 - Modeled Sound Power (dBA)	GE 2.5-116 LNTE - Modeled Sound Power (dBA)	V110 STE - Modeled Sound Power (dBA)	V136 - Modeled Sound Power (dBA)	Coordinates (UTM NAD 83 Z14N)		
					X (m)	Y (m)	Z (m)
101					587479	4987004	583
102					585141	4986998	543
112					596716	4983553	647
113					597103	4983688	638
114					597481	4983841	632
115					596357	4985266	639
118					596664	4986183	627
119					596443	4985662	636
120					595647	4986675	629
128					597016	4992918	632
133					600045	4992861	632
139					599358	4991855	633
140					599889	4992270	628
142					598757	4991642	642
143					598230	4991636	641
144					597909	4991376	641
145					597096	4990893	640
149					596421	4992296	626
150					596258	4991988	626
151					597212	4991751	655
152					599674	4991977	629
155					590086	4995319	629
158					588119	4995351	632
160					601023	4992868	631
165					600199	4992455	634
166					593055	4995948	651
167					593334	4996080	653
168					593924	4995957	661
169					594237	4996145	652
177					594145	4997168	645
178					594884	4998127	659
179					595007	4998682	657
180					594540	4998791	648
181					593942	4998652	651
182					594154	4999135	653
184					593745	4998184	659

Source ID	G126 - Modeled Sound Power (dBA)	GE 2.5-116 LNTE - Modeled Sound Power (dBA)	V110 STE - Modeled Sound Power (dBA)	V136 - Modeled Sound Power (dBA)	Coordinates (UTM NAD 83 Z14N)		
					X (m)	Y (m)	Z (m)
185					593500	4997892	658
186					593460	4997515	658
187					592998	4997353	641
189					592551	4996429	650
190					592161	4996366	647
191					591793	4996200	643
192					591487	4996743	642
194					592535	4996808	653
196					592552	4997736	652
197					592286	4998107	652
198					592607	4998308	653
199					592182	4998619	644
204					590293	4999012	647
205					589685	4999053	651
206					589971	4998678	647
207					589710	4997974	634
210					589826	4997002	633
211					590628	4996420	638
212					590518	4995975	645
213					589046	4987452	612
214					589469	4987379	619
215					590064	4999943	635
216					590394	5000214	633
218					590876	5000318	647
220					591643	4999214	651
221					592152	4999951	649
222					592588	5000305	641
223					593819	5000160	639
224					594210	5000303	638
228					595117	4991378	636
230					591342	4997941	631
Transformer 1	102.9	102.9	102.9	102.9	590756	4993157	574
Transformer 2	102.9	102.9	102.9	102.9	590723	4993159	573

APPENDIX C: RECEIVER INFORMATION

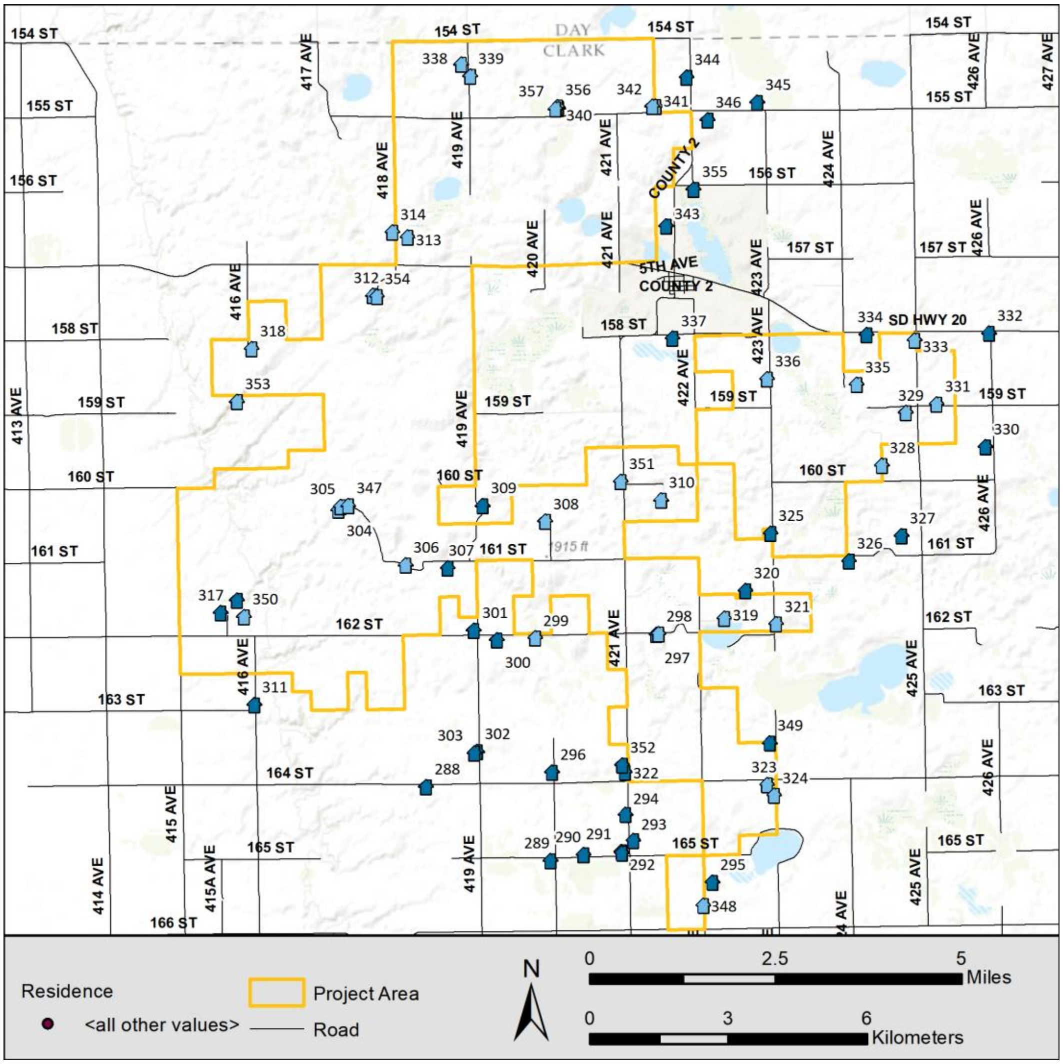

FIGURE 22: RECEIVER LOCATIONS AND SOUND PROPAGATION MODELING RESULTS

TABLE 10: DISCRETE RECEIVER RESULTS

Receiver ID	Receiver Status	Sound Pressure Level (dBA)				Relative Height (m)	Coordinates (UTM NAD83 Z14N)		
		GE2.5	G126	V110	V136		X (m)	Y (m)	Z (m)
288	Non-Participating	32	31	32	31	4	590214	4984376	546
289	Non-Participating	30	29	30	29	4	592904	4982768	566
290	Non-Participating	30	29	30	29	4	593620	4982900	566

Receiver ID	Receiver Status	Sound Pressure Level (dBA)				Relative Height (m)	Coordinates (UTM NAD83 Z14N)		
		GE2.5	G126	V110	V136		X (m)	Y (m)	Z (m)
291	Non-Participating	33	33	33	32	4	594437	4982966	578
292	Non-Participating	33	33	33	32	4	594440	4982939	578
293	Non-Participating	35	34	34	34	4	594692	4983211	579
294	Non-Participating	35	35	35	35	4	594518	4983774	579
295	Non-Participating	36	36	36	35	4	596399	4982306	575
296	Non-Participating	33	32	33	31	4	592935	4984692	567
297	Participating	46	47	46	46	4	595191	4987671	547
298	Participating	46	47	46	46	4	595234	4987683	545
299	Participating	40	40	40	39	4	592571	4987592	563
300	Non-Participating	38	38	38	37	4	591744	4987551	558
301	Non-Participating	38	38	38	37	4	591249	4987762	551
302	Non-Participating	32	31	32	31	4	591308	4985134	553
303	Non-Participating	33	32	33	31	4	591253	4985098	552
304	Participating	45	45	45	44	4	588306	4990357	527
305	Participating	45	46	45	45	4	588362	4990440	529
306	Participating	42	43	42	42	4	589764	4989175	547
307	Non-Participating	39	39	39	38	4	590677	4989109	553
308	Participating	45	46	45	45	4	592787	4990119	556
309	Non-Participating	40	40	40	39	4	591433	4990460	553
310	Participating	42	43	42	42	4	595289	4990578	556
311	Non-Participating	38	38	38	37	4	586482	4986149	483
312	Participating	44	45	44	44	4	589052	4995012	560
313	Participating	45	46	45	45	4	589809	4996270	546
314	Participating	44	44	44	43	4	589478	4996383	549
316	Non-Participating	40	41	40	40	4	586122	4988415	479
317	Non-Participating	39	40	39	39	4	585758	4988140	475
318	Participating	44	45	44	44	4	586436	4993857	529
319	Participating	39	40	39	39	4	596670	4988022	545
320	Non-Participating	38	37	37	37	4	597127	4988614	547
321	Participating	35	35	35	34	4	597789	4987895	548
322	Non-Participating	38	38	37	37	4	594514	4984684	575
323	Participating	43	44	43	43	4	597594	4984416	553
324	Participating	45	46	45	45	4	597744	4984181	553
325	Non-Participating	39	39	39	38	4	597663	4989857	549
326	Non-Participating	35	34	34	33	4	599365	4989264	549

Receiver ID	Receiver Status	Sound Pressure Level (dBA)				Relative Height (m)	Coordinates (UTM NAD83 Z14N)		
		GE2.5	G126	V110	V136		X (m)	Y (m)	Z (m)
327	Non-Participating	34	34	34	33	4	600501	4989800	544
328	Participating	43	44	43	43	4	600067	4991330	560
329	Participating	48	49	48	48	4	600592	4992469	557
330	Non-Participating	34	34	34	33	4	602317	4991734	549
331	Participating	47	48	47	47	4	601264	4992657	550
332	Non-Participating	32	32	32	31	4	602396	4994190	560
333	Participating	38	38	38	37	4	600783	4994038	562
334	Non-Participating	37	38	37	37	4	599751	4994157	558
335	Participating	45	46	45	44	4	599531	4993078	547
336	Participating	43	43	43	42	4	597588	4993203	554
337	Non-Participating	38	38	38	37	4	595548	4994076	551
338	Participating	49	50	49	48	4	590972	5000014	567
339	Participating	46	47	46	45	4	591168	4999758	562
340	Participating	46	46	46	45	4	593070	4999056	565
341	Participating	46	47	46	46	4	595172	4999096	573
342	Participating	47	48	47	47	4	595105	4999100	575
343	Non-Participating	37	38	38	37	4	595404	4996511	558
344	Non-Participating	39	39	39	38	4	595848	4999736	564
345	Non-Participating	34	33	34	33	4	597375	4999190	552
346	Non-Participating	39	39	38	38	4	596303	4998806	568
347	Participating	46	46	46	45	4	588527	4990461	530
348	Participating	33	33	33	32	4	596207	4981798	572
349	Non-Participating	40	40	40	39	4	597640	4985323	551
350	Participating	41	41	41	40	4	586274	4988056	482
351	Participating	44	44	44	43	4	594425	4990983	562
352	Non-Participating	37	38	37	37	4	594453	4984844	576
353	Participating	46	46	46	45	4	586112	4992711	509
354	Participating	44	45	44	44	4	589138	4994988	556
355	Non-Participating	39	39	39	38	4	596005	4997305	546
356	Participating	46	46	46	45	4	593049	4999085	565
357	Participating	46	46	46	45	4	593007	4999048	564

APPENDIX D: INFRASOUND & LOW-FREQUENCY NOISE

Infrasound is sound pressure fluctuations at frequencies below about 20 Hz. Sound below this frequency is only audible at very high magnitudes. Low frequency sound is in the audible range of human hearing, that is, above 20 Hz, but below 100 to 200 Hz depending on the definition.

Infrasound

Low frequency aerodynamic impulsive sound is typically associated with downwind rotors on horizontal axis wind turbines. In this configuration, the rotor plane is behind the tower relative to the oncoming wind. As the turbine blades rotate, each blade crosses behind the tower's aerodynamic wake and experiences brief load fluctuations. This causes short, low-frequency pulses or thumping sounds. Large modern wind turbines, like that which is proposed for Crocker Wind, are "upwind", where the rotor plane is upwind of the tower. As a result, this type of low frequency sound does not exist in these turbines. Infrasound emissions from upwind turbines are much lower than the older downwind turbines, and are well below established infrasonic hearing thresholds.

As an example, Figure 23 shows the sound levels 350 meters (1,148 feet) from a wind turbine when the wind turbine was operating (T-on) and shut down (T-off) for wind speeds at hub height greater than 9 m/s. Measurements were made over approximately two weeks.[7] The red 90 dBG line is shown here as the ISO 7196:1995 perceptibility threshold. As shown, the wind turbines generated measurable infrasound, but at least 20 dB below audibility thresholds.

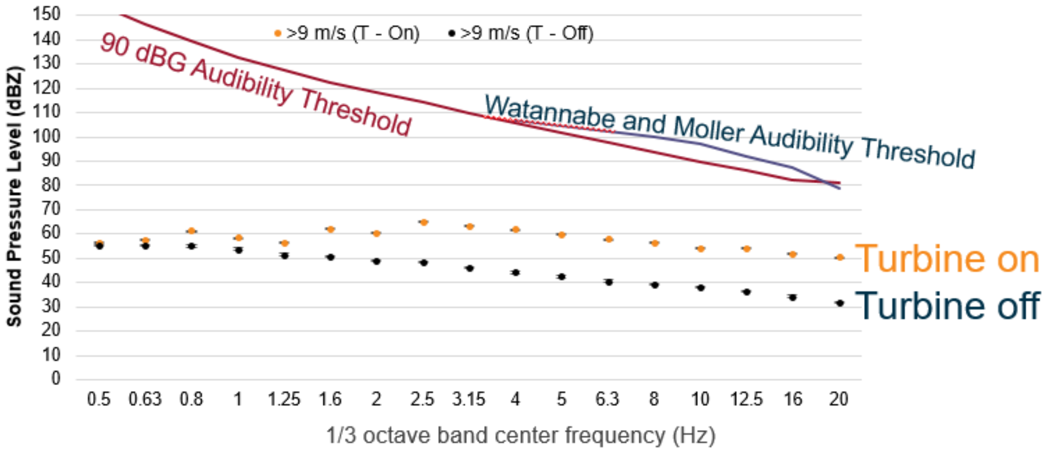

FIGURE 23: INFRASOUND FROM A WIND TURBINE AT 350 METERS (1,148 FEET) COMPARED WITH PERCEPTION THESHOLDS

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

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[7] RSG, et al., "Massachusetts Study on Wind Turbine Acoustics," Massachusetts Clean Energy Center and Massachusetts Department of Environmental Protection, 2016 – Graphic from RSG presentation to MassDEP WNTAG, March, 2016

Siemens SWT 2.3-93 model wind turbines. They found that at typical receptor distances away from a wind turbine, more than 1,000 feet away, wind turbine sound is typically audible starting at 50 Hz.[8]

Tachibana et al. measured sound levels from 34 wind projects around Japan over a three-year period.[9] They found that infrasound levels were "much lower than the criterion curve" proposed by Moorehouse et al.[10] RSG et al. studied infrasound levels at two wind turbine projects in the northeastern U.S. Both indoor and outdoor measurements were made.[7] Comparisons between turbine-on periods and adjacent turbine shutdown periods indicated the presence of wind-turbine-generated infrasound, but well below ISO 389-7[11] and Wattanabe et al.[12] 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 and typical residential distances from wind projects.[13]

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.[14,15,16] Some of these theories have focused on the human vestibular system, hypothesizing that sub-audible 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. In response, McCunney et al. and Leventhall contend that there has been no demonstration that humans can perceive sub-audible infrasound, citing the relative insensitivity of the inner ear (where the vestibular system is located) to airborne sound and the presence of other low to moderate magnitude infrasound sources in the body and the environment.[17,18]

Yokoyama et al. conducted laboratory experiments with subjects exposed to synthesized infrasound from wind turbines. In one experiment, he filtered synthesized wind turbine sound to eliminate high

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

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

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

[11] *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

[12] 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*

[13] 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.

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

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

[16] 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.

[17] 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.

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

frequency sound at ten different cutoff frequencies from 10 Hz to 125 Hz.[19] 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 the 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.[20]

Hansen et al. compared subject response to infrasound and "sham" infrasound.[21] 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 range blade swish than infrasonic components.[22]

Finally, research by Tonin, et al. found that response to infrasound was more determined by information the subject had received than the presence of infrasound in a sound signal.[23]

Low Frequency Sound

Low frequency sound is primarily generated by the generator and mechanical components in the nacelle. Much of the mechanical sound has been reduced in modern wind turbines through improved sound insulation. Low frequency sound can also be generated by the blades at higher wind speeds when the inflow air is very turbulent. However, at these wind speeds, low frequency sound from the wind turbine blades is often masked by wind sound at the downwind receptors.

Low frequency sound is absorbed less by the atmosphere and ground than higher frequency sound. Our modeling takes into account frequency-specific ground attenuation and atmospheric absorption factors that takes this into account.

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 12.2-2008 Table 11 lists low frequency noise criteria to prevent "perceptible vibration and rattles in lightweight wall and ceiling structures."[24] These criteria are shown in Table 11. While these are interior levels, the

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

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

[21] 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.

[22] 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.

[23] 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.

[24] "American National Standard Criteria for Evaluating Room Noise", American National Standards Institute ANSI/ASA S12.2-2008, Acoustical Society of America, (2008).

equivalent exterior sound levels will be higher due to building noise reduction.[25], [26], [27] Outside to inside noise reduction is a function of sound frequency and whether windows are open or closed. The exterior sound level criteria for windows open are shown in Table 12.

TABLE 11: ANSI 12.2 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

TABLE 12: EXTERIOR SOUND LEVELS FOR PERCEPTIBLE VIBRATION AND RATTLES IN LIGHTWEIGHT WALL AND CEILING STRUCTURES[25]

1/1 Octave Band Center Frequency	16 Hz	31.5 Hz	63 Hz
Clearly perceptible vibration and rattles likely	78 dB	81 dB	89 dB
Moderately perceptible vibration and rattle likely	68 dB	71 dB	79 dB

Crocker Model Results of Low Frequency Sound

Low frequency model results at the exterior of the worst-case receivers are provided in Table 13 for each turbine model. As shown in the Table 13, the worst-case results for each turbine option are below the exterior criteria (see Table 12) to prevent "moderately perceptible vibration and rattle" in lightweight wall and ceiling constructions for all turbine models.

TABLE 13: LOW FREQUENCY MODEL RESULTS FOR THE WORST CASE RECEIVERS[28]

Turbine Model Run	Maximum Modeled Level (dB)	
	31.5 Hz	63 Hz
GE 2.5-116 LNTE	62	62
G126	62	57
V110 STE	66	62
V136	61	59

Given the information presented in Appendix D, impacts due to infrasound and low-frequency sound are not anticipated.

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

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

[27] 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

[28] Sound emission data for the 16 Hz octave band is not available from the turbine manufacturers presented in Table 13.