**BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA**

**IN THE MATTER OF THE APPLICATION OF
CROWNED RIDGE, LLC FOR A FACILITIES PERMIT TO
CONSTRUCTION 300 MEGAWATT WIND FACILITY**

Docket No. EL19-XX

DIRECT TESTIMONY AND EXHIBITS

OF RICHARD LAMPETER

July 9, 2019

INTRODUCTION AND QUALIFICATIONS

Q. PLEASE STATE YOUR NAME AND BUSINESS ADDRESS.

A. My name is Richard Lampeter. My business address is 3 Mill & Main Place, Suite 250, Maynard, MA 01754.

Q. **BY WHOM ARE YOU EMPLOYED AND IN WHAT CAPACITY?**

A. I am employed at Epsilon Associates, Inc. ("Epsilon"). I am an Associate at the company and manage the Acoustics Group.

Q. **PLEASE DESCRIBE YOUR BACKGROUND AND QUALIFICATIONS**

A. I have over 15 years of experience in conducting impact assessments for various developments across the United States. Prior to joining Epsilon, I graduated from Lyndon State College in Vermont with a B.S. in Environmental Science. While at Epsilon, I have been involved in approximately 90 wind energy projects evaluating potential impacts from sound and/or shadow flicker. The projects I have worked on ranged in size from 1.5 megawatts ("MW") to over 300 MW. I utilize the WindPRO software package to calculate shadow flicker durations in the vicinity of a project on both a worst-case and expected basis. As part of project evaluations, I have assisted in refinements in wind turbine layouts to minimize shadow flicker at residences, evaluated curtailment options, and analyzed the impact of existing vegetation to modeled shadow flicker durations. My other areas of expertise include the measurement of ambient sound levels, modeling sound levels from proposed developments, evaluation of conceptual mitigation, and compliance sound level measurements. I have conducted impact assessments for power generating facilities, commercial developments, industrial facilities, and transfer stations. In addition to conducting and/or managing the impact assessments, I have presented the results of the analyses at public meetings to county and township boards. Additional detail regarding my education, background and experience is contained in my curriculum vita which is attached as Exhibit RL-1.

STATE OF MASSACHUSETTS)
) ss
COUNTY OF MIDDLESEX)

I, Richard Lampeter, being duly sworn on oath, depose and state that I am the witness identified in the foregoing prepared testimony and I am familiar with its contents, and that the facts set forth are true to the best of my knowledge, information and belief.

Richard Lampeter

Subscribed and sworn to before me this 26th day of June, 2019.

SEAL

Notary Public

My Commission Expires

KAREN LYN ROTH
Notary Public
Commonwealth of Massachusetts
My Commission Expires
April 10, 2026

Q. HAS THIS TESTIMONY BEEN PREPARED BY YOU OR UNDER YOUR DIRECT SUPERVISION?

A. Yes.

Q. HAVE YOU TESTIFIED BEFORE THE SOUTH DAKOTA PUBLIC UTILITIES COMMISSION?

A. Yes, in Docket No. EL19-003.

Q. PLEASE DESCRIBE THE PURPOSE OF YOUR DIRECT TESTIMONY.

A. The purpose of my testimony is to (1) set forth the proposed post-construction sound monitoring protocol and (2) address low frequency sound and infrasound.

Post Construction Sound Protocal

Q. WHAT POST-CONSTRUCTION SOUND MONITORING PROTOCOL ARE YOU PROPOSING?

A. The same protocol proposed in EL9-003 jointly agreed to by the Applicant in EL19-003 and Staff, which is attached as Exhibit RL-2. While not the only appropriate way to evaluate sound level compliance of a wind energy facility, the proposed methodology allows for a degree of confidence in the assessment of whether the sound level limit is being met by the wind energy facility. This is achieved through wind turbine operational requirements, the inclusion of background sound level measurements, ground level wind speed measurements, and the measurement location selection requirements. This protocol utilizes a sound level metric and sound level limit consistent with the most restrictive County sound level requirements and recent conditions on previously approved projects. If post-construction program is requested a test protocol is required which is good practice as it allows methodology details to be agreed upon in advance of any testing.

Low Frequency Sound and Infrasound

Q. WHAT IS LOW FREQUENCY SOUND AND INFRASOUND?

A. Low frequency noise and infrasound are present in the environment due to other sources besides wind turbines. For example, refrigerators, air conditioners, and washing machines generate infrasound and low frequency sound as do natural sources such as ocean waves. The frequency range of low frequency sound is generally from 20 Hz to 200 Hz, and the range below 20 Hz is often described as infrasound. However, audibility can extend to frequencies below 20 Hz if the energy is high enough. Since there is no sharp change in hearing at 20 Hz, the division between low frequency noise and infrasound should only be considered practical and conventional. The threshold of hearing is standardized for frequencies down to 20 Hz (Acoustics - Normal equal-loudness-level contours, International Standard ISO 226:2003, International Organization for Standardization, Geneva, Switzerland, (2003).

Q. HAVE YOU CONDUCTED A STUDY OF LOW FREQUENCY SOUND AND INFRASOUND IN THE CONTEXT OF WIND GENERATION?

A. Yes, I co-authored as study, presented in the peer reviewed journal article I co-authored (*Low frequency noise and infrasound from wind turbines,* R. O'Neal et al, Noise Control Engineering J., 59(2), 2011.), which is attached as Exhibit RL-3.

Q. PLEASE PROVIDE THE RESULTS OF YOUR STUDY?

A. The study set forth in Exhibit RL-3 found for the wind turbines studied that there was no audible infrasound either outside or inside homes at 1,000 feet from a wind turbine.

Additional findings included that sound levels met the ANSI standard for low frequency noise in bedrooms, classrooms, and hospitals, met the ANSI standard for thresholds of annoyance from low frequency noise, and met ANSI standard for vibration of light-weight walls or ceilings. In homes there may be slightly audible low frequency noise beginning at around 50 Hz (depending on other sources of low frequency noise); however, the levels are below criteria and recommendations for low frequency noise within homes.

Q. DOES THIS CONCLUDE YOUR TESTIMONY?

A. Yes.

Epsilon ASSOCIATES INC.

EDUCATION

B.S., Environmental Science, Lyndon State College, 2001

PROFESSIONAL SUMMARY

Mr. Lampeter has more than 15 years of experience in conducting community sound level impact assessments. His areas of expertise include the measurement of ambient sound levels, modeling sound levels from proposed developments, evaluation of conceptual mitigation, and compliance sound level measurements. Mr. Lampeter has conducted impact assessments for power generating facilities, commercial developments, industrial facilities, and transfer stations. Richard's understanding of acoustical standards and modeling software has allowed him to provide accurate and reliable modeling results to developers and communities.

Since 2004, Mr. Lampeter has been involved in approximately 90 wind energy projects. In addition to performing numerous sound level impact assessments for wind energy facilities, Mr. Lampeter has conducted shadow flicker analyses for approximately 50 wind energy projects across the United States. Mr. Lampeter frequently presents key aspects of analyses to boards and committees and has provided sworn expert testimony.

Mr. Lampeter utilizes his diverse skill set as he serves in a variety of rolls on projects, ranging from project manager, to modeler, to field scientist. Richard is adept at using Larson Davis, Norsonic, RION, and CEL sound level meters and various modeling software packages including, Cadna/A and WindPRO.

Mr. Lampeter also has experience in air quality modeling and meteorological monitoring. Richard has used a variety of air dispersion models including CAL3QHCR, AERMOD, and CALPUFF and has displayed expertise in working with HOBO and NovaLynx portable weather stations.

Mr. Lampeter has co-authored several papers ranging in topics from wind energy to metal shredders, one of which appeared in a peer-reviewed journal. Mr. Lampeter has been a speaker at CanWEA's annual conference on the topic of low frequency noise from wind turbines and presented shadow flicker guidance and a regulatory update in a New England Wind Energy Education Project webinar.

PROFESSIONAL EXPERIENCE

Noise Impact Assessment – Power Projects – Renewable Energy

- *NextEra Energy Resources – Tuscola Wind II, Tuscola County, MI.* Project Manager for pre- and post-construction sound level impact assessments for a 100 megawatt (MW) wind energy facility composed of 59 GE wind turbines. Modeling was performed in order to demonstrate compliance with the sound level limits in each community. During multiple public hearings, Mr. Lampeter responded to questions and comments. Following construction, operational sound levels were measured in each of the four townships per ordinance requirements.

- *Boreal Renewable Energy Development – Christopher House Wind Turbine Generator Project, Worcester, MA.* Project Manager for a sound level impact assessment prepared for a wind turbine feasibility study. Measured ambient background sound levels and modeled wind turbine sound levels under two scenarios. Impacts were compared to the local zoning ordinance and the Massachusetts Department of Environmental Protection (MassDEP) Noise Policy.

- *Palmer Renewable Energy Project, Springfield, MA.* Predicted future sound levels from a proposed 38 MW renewable biomass energy plant using the Cadna/A software package. Impacts were compared to state and local regulations with the results presented in the Environmental Notification Form.

- *NextEra Energy Resources – Pheasant Run Wind Energy Center, Huron County, MI.* Project Manager for a post-construction sound level compliance evaluation for a wind power generation facility composed of 88 wind turbines and an electrical substation. Sound levels were measured and evaluated at 15 residential locations. Following the submittal of a comprehensive report, results were presented to the Huron County Planning Commission.

- *Zotos International, Inc. – Two Wind Turbine Project, Geneva, NY.* Conducted a sound level impact assessment for two proposed wind turbines at the existing Zotos International facility. Calculated future sound levels using the Cadna/A noise calculation software. Prepared a comprehensive report comparing modeled sound levels to local regulations and relevant criteria. Presented the sound level assessment to the City of Geneva Planning Board.

- *FPL Energy (now NextEra Energy Resources) – Horse Hollow Wind Energy Center, Taylor County, TX.* Assisted in the development and execution of multiple sound level measurement programs for the 735 MW wind farm which at the time of its in-service date it was the world's largest wind farm. Analyzed sound level data in conjunction with power output data provided by NextEra Energy Resources and assisted in the preparation for legal proceedings.

- *Iberdrola Renewables – Groton Wind, Groton, NH.* Assisted in the collection of pre-construction ambient sound levels for a proposed 48 MW wind energy facility. Conducted post-construction sound level measurement programs in order to address the requirements of the State of New Hampshire Site Evaluation Committee Order and the Certificate of Site and Facility with Conditions for the Groton Wind Project. Analyzed the data collected for the evaluation of applicable limits.

- *NextEra Energy Resources – Lake Benton II Wind Project, Pipestone County, MN.* Project Manager for a sound level assessment for a repower project in Minnesota. The assessment consisted of an ambient measurement program and sound level modeling of the proposed wind turbines and existing wind turbines in the vicinity of the project. The findings were presented in a comprehensive report.

PRESENTATIONS

- "Sound Levels and the Evolving Regulatory Landscape." AWEA WINDPOWER 2016 Poster Presentation, May 23-26, 2016.
- "How to Address Post-Construction Sound Level Measurement Requirements." AWEA WINDPOWER 2015 Poster Presentation, May 18-21, 2015.
- "Evaluating Shadow Flicker in the Current Regulatory Environment." Massachusetts Wind Working Group, October 30, 2013.
- "Shadow Flicker Regulations and Guidance: New England and Beyond." New England Wind Energy Education Project Webinar, February 10, 2011
- "Low Frequency Sound and Infrasound from Wind Turbines." CanWEA 2010, Montreal, Canada, November 1-3, 2010. O'Neal, R.D., Hellweg, Jr., R.D. and R. M. Lampeter.

PROFESSIONAL ORGANIZATIONS

Institute of Noise Control Engineering (INCE)

PREVIOUS EMPLOYERS

NYC Department of Environmental Protection, June - August 2000.
Meyer Strong and Jones Engineers, P.C., May – August 1999.

- *Heritage Sustainable Energy – Big Turtle Wind Farm Phase 2, Huron County, MI.* Project Manager for a pre- and post-construction sound level assessment for a wind energy facility to consisting of 14 Gamesa wind turbines. Sound levels were evaluated with respect to limits in the Huron County Wind Energy Facility Overlay Zoning Ordinance. Presented the results of the post-construction compliance evaluation to the Huron County Planning Commission.
- *Confidential Project, OK.* Project Manager for a sound level impact analysis. Developed and executed sound level measurement program in response to complaints made by a resident living adjacent to the wind farm. Data were compared to a generally accepted guideline and presented in a letter report.
- *NextEra Energy Resources – Golden West Wind Energy Center, El Paso County, CO.* Project Manager for a post-construction sound level evaluation of 249.4 MW wind power generation facility composed of 145 GE wind turbines. Collected attended and unattended sound level and meteorological data during two measurement programs. Presented the findings of the study to the Board of County Commissioners.
- *NextEra Energy Resources – Eight Point Wind Energy Center, Steuben County, NY.* Assisted in the sound level modeling for the pre-construction impact assessment required as part of the NY State Article 10 process. Sounds levels were modeled using Cadna/A and incorporated CONCAWE meteorology.
- *NextEra Energy Resources – Lee/DeKalb Wind Energy Center, Lee and DeKalb Counties, IL.* Developed and executed a post-construction sound level measurement program for a 217.5 MW wind farm consisting of 145 GE 1.5xle wind turbines. Over 5,000 hours were collected over a 5-week period at 16 locations. The results of this program found that sound levels due to the wind turbines under worst-case conditions were at or below the Illinois Pollution Control Board noise limits.
- *FPL – St. Lucie Wind Turbine Generation Project, St. Lucie County, FL.* Assisted in the development and execution of an extensive sound level measurement and modeling program for a proposed wind farm in St. Lucie County, FL. Collected ambient sound level data and meteorological data. Calculated the sound levels resulting from the operation of the wind turbines using the WindPRO modeling software. Six wind turbines were proposed to be constructed along a beach in Florida.
- *Boreal Renewable Energy Development – Nauset Regional High School Wind Turbine Generator Project, Eastham, MA.* Conducted a sound level impact assessment for a wind turbine feasibility study. Prepared a comprehensive letter report comparing modeled sound levels to the MassDEP Noise Policy.
- *NextEra Energy Resources – Tuscola Bay Wind Energy Center, Tuscola, Bay, & Saginaw Counties, MI.* Managed a sound level impact assessment project for a proposed 120 MW wind power generation facility composed of 75 wind turbines. Modeling was performed in order to demonstrate compliance with the sound level limits in each community. During multiple public hearings, Mr. Lampeter responded to questions and comments. Following construction, operational sound levels were measured as required by the township's ordinance.

- *NextEra Energy Resources - Waymart Wind Farm, Waymart, PA.* Executed multiple post-construction sound level measurement programs around the 65 MW wind turbine facility. Analyzed pre- and post-construction sound level data. Summarized data in succinct letter reports.

- *Iberdrola Renewables – Wild Meadows, Alexandria & Danbury, NH.* Measured ambient sound levels for a proposed 75.9 MW wind energy facility. Sound levels were measured at eight locations representative of nearby residences in various directions from the proposed wind turbines.

- *NextEra Energy Resources – Pegasus Wind Energy Center, Tuscola County, MI.* Project Manager for a pre-construction acoustic study for a 62 wind turbine project. Both ambient sound level measurements and sound level modeling were components of the project. Presented analysis findings and responded to questions and comments during multiple public hearings.

- *John Deere Wind Energy – Michigan Wind 1 Wind Farm, Huron County, MI.* Measured and analyzed post-construction sound level data collected to assess compliance with the Huron County noise ordinance and address complaints. The wind farm is a 69 MW project consisting of 46 GE 1.5sle wind turbines. Sound levels were measured at 14 different locations over a 20-day period. Over 4,000 hours of data were collected and analyzed for this program.

- *Heritage Sustainable Energy – Big Turtle Wind Farm, Huron County, MI.* Project Manager for a sound level compliance evaluation for an existing 20 MW wind energy facility composed of 10 Gamesa wind turbines. Measured sound levels were evaluated with respect to limits in the Huron County Wind Energy Facility Overlay Zoning Ordinance.

- *Confidential Project, IA.* Project Manager for a sound level impact assessment for a wind farm in Iowa. Predicted future sound levels due to the operation of the wind turbines in areas surrounding the wind farm. Data were presented in tabular format and overlaid onto aerial photography.

- *NextEra Energy Resources – Osborn Wind Energy Center, MO.* Provided expert opinions regarding proposed amendments to the Clinton County Zoning Ordinance with respect to sound from a Wind Energy Conversion System. Provided sworn testimony under direct and cross examination at a Clinton County Planning & Zoning Commission hearing.

Noise Impact Assessment – Power Projects

- *Medical Area Total Energy Plant (MATEP), Boston, MA.* Managed multiple sound level measurement programs for the plant following the installation of two combustion turbines, gas compressors, and cooling towers. These programs included background sound level measurements, compliance operational sound level measurements, and evaluations of noise mitigation. The results of these measurement programs have been summarized in reports submitted to Veolia Energy and regulatory agencies. Assisted in the sound level modeling of a proposed 14.4 MW combustion turbine with a Heat Recovery Steam Generator. Collected

- *FPL Energy.* Assisted in AERMOD, CALMET, and CALPUFF modeling for a project in Virginia. Gathered and processed data for the project. Helped to create many of the model runs used in the analysis. Created several figures used in the report.

- *Columbus Center, Boston, MA.* Assisted in the microscale analysis of seven intersections around a proposed development over the Massachusetts Turnpike. Used ISC-Prime to estimate impacts from point sources and volume sources from proposed buildings and tunnels. Used CAL3QHCR to estimate impacts from mobile sources. These models were used to evaluate each of the four building alternatives. Provided graphics for the project.

Air Quality Monitoring

- *Massachusetts Broken Stone Company, Berlin, MA.* Participated in an air quality monitoring program for an existing asphalt plant. Assisted in the installation of a meteorological tower. Made routine trips to the facility to maintain and download data from the H_2S monitor.

- *Former Coal Tar Processing Facility, Island End River, Everett, MA.* Participated in an air quality monitoring program for a former industrial facility. Gathered data before and after a pilot study to document existing conditions. Used various types of sampling equipment including SUMMA Canisters and PUF samplers to collect samples during the pilot study.

Meteorological Monitoring

- *Wheelabrator Millbury Municipal Waste Combustor Facility, Millbury, MA.* Routinely collected data from a meteorological tower at a municipal waste facility. Assisted in the maintenance and calibration of the equipment. Provided quarterly reports.

PUBLICATIONS

- "Low frequency sound and infrasound from wind turbines." Noise Control Engineering Journal, Institute of Noise Control Engineering, Volume 59, Number 2, March-April 2011. O'Neal, R.D., Hellweg, Jr., R.D. and R. M. Lampeter.

- "Sound Defense for a Wind Turbine Farm." North American Windpower, Zackin Publications, Volume 4, Number 4, May 2007. O'Neal, R.D., and R.M. Lampeter.

CONFERENCE PAPERS

- "Evaluating and controlling noise from a metal shredder system." INTER-NOISE 2012, New York City, NY, August 19-22, 2012. O'Neal, R.D., Lampeter, R.M., Emil, C.B. and B.A. Gallant.

- "Low frequency sound and infrasound from wind turbines – a status update." NOISE-CON 2010, Baltimore, MD, April 19-21, 2010. O'Neal, R.D., Hellweg, Jr., R.D. and R. M. Lampeter.

- "Nuisance noise and the defense of a wind farm." INTER-NOISE 2009, Ottawa, Canada, August 23-26, 2009. O'Neal, R.D., and R.M. Lampeter.

G90 2.0 MW wind turbines. Results were presented in a comprehensive report which was submitted to the Ohio Power Siting Board.

- *First Wind - Weaver Wind, Hancock County, ME.* Sub-consultant to Normandeau Associates for a wind energy project consisting of approximately 15 wind turbines. Shadow flicker modeling was conducted for two options with the results compared to local regulations. The results of the analyses were presented at an Open House for the project.
- *NextEra Energy Resources – Montezuma Wind Farm, Solano County, CA.* Performed an analysis to estimate the hours per year of shadow flicker in the area surrounding the proposed wind farm. Impacts were presented visually as isolines overlaid onto an aerial image which was included in a concise letter report summarizing the results.
- *FPL – St. Lucie Wind Turbine Generation Project, St. Lucie County, FL.* Evaluated the potential for shadow flicker impacts at the nearest residences resulting from the operation of six wind turbines proposed as part of this project. Presented the results in a clear and concise report.
- *NextEra Energy Resources – Osborn Wind Energy Center, MO.* Provided expert opinions regarding proposed amendments to the Clinton County Zoning Ordinance with respect to shadow flicker from a Wind Energy Conversion System. Provided sworn testimony under direct and cross examination at a Clinton County Planning & Zoning Commission hearing.

Air Quality Modeling

- *Besicorp Empire Development Company, Rensselaer, NY.* Worked on modeling predicting $PM_{2.5}$ concentrations from truck and rail traffic associated with a newsprint facility and a cogeneration facility using CAL3QHCR. Produced graphics showing the estimated concentrations in the nearby area.
- *Alcoa Eastalco Works, Frederick, MD.* Assisted in the modeling of an existing aluminum facility. Worked closely with project managers in developing strategies to accurately address the numerous sources throughout the facility. Assisted in the running of CALMET, CALPUFF, and CALPOST. Developed various graphics to illustrate to the client the results of the modeling.
- *Storrow Drive Tunnel Reconstruction Project, Boston, MA.* Assisted in a microscale analysis using EPA MOBILE6 and CAL3QHC. Analyzed various reconfiguration scenarios. Presented the mesoscale and microscale analyses during an Advisory Committee Meeting.
- *Bangor-Hydro Electric Company, Bangor, ME.* Assisted in the renewal process for existing air permits for the Medway, Eastport, and Bar Harbor facilities of the Bangor-Hydro Electric Company. Utilized Satellite i-Steps for generating annual air emission statements.
- *JAMALCO, Jamaica.* Assisted with the modeling analysis for the Clarendon Alumina Works in Jamaica. ISCST3 was used to model various operating scenarios. Prepared graphics illustrating pollutant concentrations around the facility.

sound level data for various rooftop equipment. Conducted post-construction sound level measurements for the evaluation of the MassDEP Noise Policy.

- *Lean Flame, Watervliet Arsenal, NY.* Project Manager for a sound level impact assessment for a proposed GE Frame 5 gas turbine on land leased from the Watervliet Arsenal. Developed and executed an ambient sound level measurement program. Calculated sound levels at various locations surrounding the site using modeling software. Presented the analysis in a comprehensive report.
- *Hollingsworth & Vose, Inc. Combined Heat & Power Project, West Groton, MA.* Conducted a sound level impact assessment for the proposed CHP. Sound levels were modeled using the Cadna/A noise calculation software. Evaluated multiple project designs. Presented the analysis to the local planning board.
- *National Grid – East Main Street Substation, Westborough, MA.* Managed a sound level impact assessment for the proposed expansion of a substation. The expansion included the installation of a 115/13.8 kV transformer. Predicted future sound levels were compared to existing sound levels for evaluation with the MassDEP Noise Policy. Presented the analysis in a concise report.
- *St. Joseph's Hospital Combined Heat & Power Project, Syracuse, NY.* Measured existing sound levels and conducted a modeling analysis for a project including a Solar Turbines Mercury 50 gas turbine with an electrical output of 4.5 MW and a Heat Recovery Steam Generator capable of producing 45,000 lbs. of steam. Sound levels were evaluated both in the community and in a patient room above the project. Summarized the results of the post-construction sound level measurement program in a concise letter report.
- *Advanced Power, Brockton Power Project, Brockton, MA.* Performed acoustical modeling for the 350 MW power generating facility using a noise prediction software package. Completed a Best Available Noise Control Technology (BANCT) Analysis which evaluated various noise control options. Assisted in the preparation for the Energy Facilities Siting Board (EFSB) hearings.
- *Braintree Electric Light Department – Thomas A. Watson Generating Station, Braintree, MA.* Measured sound levels at various locations for a proposed 116 MW natural gas and oil-fired simple cycle electric power generation facility. Assisted in the acoustical modeling, including several rounds of mitigation analyses. Team member for compliance sound level measurement programs.
- *Milford Power Company, Milford, CT.* Executed an ambient sound level measurement program over a three-day period for a combined cycle electric generating facility proposed in southern Connecticut. Participated in an additional sound level measurement program while construction was under way to collect sound level data during periods of steam venting.
- *Union College Combined Heat & Power Project, Schenectady, NY.* Conducted an analysis of the sound associated with the operation of a proposed gas-turbine based CHP plant for Bette & Cringe, LLC. The proposed plant will include a gas turbine generator package with an expected

nominal gross power output of 1,804 kW. The NY DEC guidance document's 6 dBA increase over ambient limit was used as a guideline in evaluating noise impacts from the project.

- *Franklin Energy Center, Franklin, MA.* Conducted an ambient sound level measurement program around the Garelick Farms facility in Franklin to establish background sound levels before the construction of the cogeneration plant at the facility. Following construction of the plant, post-construction sound level measurements were taken. Drafted a sound level measurement letter report presenting the results of the program with respect to the Massachusetts Noise Policy.

- *FPL Energy - Jamaica Bay Peaking Facility, Far Rockaway, NY.* Participated in a sound level measurement program. Short-term and continuous measurements were made at the nearest residences.

- *Billerica Energy, Billerica, MA.* Assisted in the acoustical modeling using Cadna/A for a 480 MW simple cycle turbine facility. Modeled impacts under various scenarios and analyzed noise impacts at multiple locations.

- *Weaver's Cove Energy, Fall River, MA.* Assisted in the development and implementation of an extensive sound measurement program. Over a three-day period continuous and/or short-term measurements were taken at seven locations around the proposed liquefied natural gas (LNG) terminal. Obtained permission from local residences to install temporary noise equipment. Collected and organized the sound data for this project. Participated in an additional sound level measurement program to collect background sound level data in four communities which were in the vicinity of the proposed offshore berth.

- *Clifton Street Substation, Marblehead, MA.* Participated in multiple sound level measurement programs. Conducted a baseline noise measurement survey around the existing substation. Conducted a second survey after the existing transformer was replaced to assess compliance with permit conditions. Prepared a letter report summarizing the results.

Noise Impact Assessment – Quarries / Sand & Gravel / Asphalt

- *Aggregate Industries, Peabody, MA.* Project Manager for sound level measurement programs developed as part of the Special Permit requirements for the quarry and asphalt plant. Gathered data before and after mitigation measures were implemented, analyzed potential impacts due to a proposed relocation of equipment, and presented results at a Peabody Board of Health Meeting.

- *McCullough Crushing, Calais, VT.* Collected reference sound level data at an operating sand and gravel pit. Modeled future sound levels due to sand and gravel extraction and processing using Cadna/A. Prepared a comprehensive report evaluating potential community noise impacts.

- *Dalrymple Gravel & Contracting Co., Inc., Erwin, NY.* Measured reference sound levels for an off-road haul truck and associated hopper-loading activities at the existing Scudder Sand and Gravel Pit.

- *Pioneer Green Energy – Great Bay Wind I, Somerset County, MD.* Calculated the expected annual duration of shadow flicker from a 25-wind turbine project. Multiple layouts and wind turbine types were evaluated for the project. Reductions in shadow flicker due to vegetation were calculated for individual residences. A scaling factor due to curtailments was incorporated into the analysis. The results were presented in a stand-alone report.

- *NextEra Energy Resources – Golden West Wind Energy Center, El Paso County, CO.* Project Manager for a shadow flicker modeling analysis of an operating 249.4 MW wind power generation facility composed of 145 GE wind turbines. Presented the findings of the study to the Board of County Commissioners.

- *NextEra Energy Resources – Lake Benton II Wind Project, Pipestone County, MN.* Project Manager for a shadow flicker modeling analysis for a repower project in Minnesota. Shadow flicker modeling was conducted for 44 proposed wind turbines and four alternates.

- *NextEra Energy Resources – Eight Point Wind Energy Center, Steuben County, NY.* Conducted the shadow flicker analysis for the proposed wind energy project required as part of the NY State Article 10 process. The shadow flicker analysis was performed to determine the location and duration of shadow flicker resulting from the proposed 31 GE wind turbines.

- *NextEra Energy Resources – Pegasus Wind Energy Center, Tuscola County, MI.* Project Manager for a pre-construction shadow flicker modeling study for a 62 wind turbine project. Provided recommendations for layout adjustments to reduce shadow flicker. Presented analysis findings and responded to questions and comments during multiple public hearings.

- *Eolian Renewable Energy – Antrim Wind, Antrim, NH.* Conducted a shadow flicker analysis for a proposed 28.8 MW wind power generation facility to be composed of nine (9) Siemens SWT-3.2-113 3.2 MW wind turbines. There were no federal, state, or local regulations limiting the amount of shadow flicker resulting from the operation of the proposed wind turbines for this Project. However, the predicted shadow flicker at occupied buildings in the vicinity of the project were put into context by comparing the annual duration of shadow flicker to a value of 30 hours per year.

- *Heritage Sustainable Energy – Big Turtle Wind Farm Phase 2, Huron County, MI.* Project Manager for a shadow flicker analysis for a proposed wind energy facility. Shadow flicker resulting from the operation of 15 Gamesa wind turbines was calculated at discrete modeling points and isolines were generated from a grid encompassing the area surrounding the wind turbines.

- *NextEra Energy Resources – Tuscola Wind II, Tuscola County, MI.* Project Manager for a shadow flicker analysis for a proposed 100 MW wind power generation facility composed of 59 wind turbines. Results were presented in reports for each of the four townships which would have a wind turbine. Responded to questions and comments at multiple public hearings.

- *Iberdrola Renewables – Blue Creek Wind Farm, Van Wert and Paulding Counties, OH.* Project Manager for a shadow flicker analysis for a proposed wind farm in Ohio consisting of Gamesa

- *Banquet Hall, Whately, MA.* Conducted a sound level analysis for a proposed seasonal banquet hall. The noise source of concern was music being played during functions at the hall. Prepared a letter report comparing the modeling results to the MassDEP Noise Policy.

Noise Impact Assessment – Additional Projects

- *Chestnut Ridge Rod and Gun Club, Dover, NY.* Project Manager for a sound level impact analysis at an existing rod and gun club. Devised and executed a sound level measurement program. Developed mitigation strategies and calculated potential future noise impacts. Summarized all findings in a comprehensive letter report.

- *Storrow Drive Tunnel Reconstruction Project, Boston, MA.* Collected sound level data at various points along Storrow Drive. Presented the noise impact analysis during an Advisory Committee Meeting.

- *TMR Preserve, Dover, NY.* Conducted two sound level programs at a proposed sporting club. Took ambient measurements to document existing conditions in the area. Future conditions were simulated as individuals discharged several types of firearms at various shooting locations in the preserve. Compared measurements taken during these conditions to the existing conditions along with state and local noise regulations.

Shadow Flicker

- *Iberdrola Renewables – Desert Wind, Perquimans and Pasquotank Counties, NC.* Managed a shadow flicker impact assessment for a proposed wind power generation facility to be located in North Carolina. Shadow flicker from the 150 Gamesa G97 2.0 MW wind turbines was calculated. Separate reports were prepared for each county. Gave sworn testimony to the Board of Commissioners in each county.

- *NextEra Energy Resources – Tuscola Bay Wind Energy Center, Tuscola, Bay, & Saginaw Counties, MI.* Project Manager for a shadow flicker analysis for a proposed 120 MW wind power generation facility composed of 75 wind turbines. The expected duration of shadow flicker was calculated at sensitive receptors in the vicinity of the project. Responded to questions and comments at multiple public hearings.

- *Confidential Project, MA.* Calculated the duration of shadow flicker from a proposed wind turbine to be located in Massachusetts using the WindPRO shadow module.

- *State of Connecticut Siting Council, CT.* Contributor to the Epsilon project team providing professional consulting services for renewable energy projects to the Siting Council in CT. Examined analyses conducted, including shadow flicker, for a proposed wind energy project in CT. Reviewed submittals provided by the council and submitted comments.

- *State of New Hampshire, Concord, NH.* Conducted an independent review of the shadow flicker analysis for the proposed 24 MW Lempster Mountain Wind Power Project in Lempster, NH. Calculated the duration of shadow flicker using WindPRO software and compared the results to the developer's analysis.

- *Massachusetts Broken Stone Company, Berlin, MA.* Executed a sound measurement program for an existing asphalt company. Measured sound levels during operational and background conditions. Prepared a letter report summarizing the results.

- *Ambrose Brothers Inc., Sandwich, NH.* Executed two sound level programs at a sand and gravel excavation site. The first program involved measuring sound levels at the house of a concerned neighbor with a portable crusher at its original location. The second program involved measuring sound levels at the same residence with the crusher at a new location. Prepared letter reports for each of the measurement programs.

Noise Impact Assessment – Industrial

- *General Electric Company, Hudson River PCBs Superfund Site, Hudson River, NY.* Assisted in the Phase 1 RAM through the routine collection of sound level data in the community surrounding the dredging activity and processing facility. Collected reference sound level data of noise sources for the project.

- *Cianbro Corporation – Metal Fabrication Plant, Georgetown, MA.* Conducted an operational sound level measurement program around the existing facility during which sound levels were continuously measured at a property line and sound levels associated with individual operations/equipment were measured at a reference distance. Summarized the program and identified mitigation options in a letter report.

- *Berwick Iron and Metal Recycling, Berwick, ME.* Modeled a proposed metal shredder at an existing metal recycling facility using Cadna/A and proposed mitigation to minimize sound level impacts to the community. Participated in a post-construction sound level measurement program to assess compliance with respect to local sound level limits.

- *Former Coal Tar Processing Facility, Island End River, Everett, MA.* Participated in multiple sound measurement programs at a former industrial facility. Measured sound levels under existing conditions before and after a pilot study. Measured sound levels at nine locations during a pilot program to generate information about the relationships between dredging operations and their effects on area sound levels. Took individual reference measurements for each of the various types of equipment operated during the pilot study. Collected sound level data during periods of pile driving activity during the sheet pile wall installation phase of the project.

- *Excel Recycling, Freetown MA*. Conducted attended sound level measurements and detailed sound level modeling to evaluate potential mitigation options for an existing metal shredding and processing facility.

- *FedEx Distribution Facility, Billerica, MA.* Conducted a third-party review of a noise study for a proposed distribution facility. The review was performed for BETA Group who was hired by the Town of Billerica. Presented findings at a Billerica Board of Health meeting.

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Noise Impact Assessment –Transfer Stations / Landfills

- *Casella Waste Systems, Inc. - Juniper Ridge Landfill, Old Town, ME.* Conducted a sound level impact assessment for the proposed expansion of the existing Juniper Ridge Landfill. The analysis included mobile noise sources associated with the management of solid waste and a new stationary source, the proposed landfill gas to energy facility. Modeled sound levels were evaluated against both state and local regulations.
- *Holliston Solid Waste Transfer Station, Holliston, MA.* Participated in a sound level measurement program at a solid waste transfer station in Massachusetts. Coordinated with the transfer station and with local residences on the placement of noise equipment. Weekday and weekend measurements (short-term and continuous) were taken at up to six locations around the facility. Participated in additional sound level measurement programs following the enclosure of the C&D facility to evaluate various mitigation options.
- *Hardwick Landfill, Hardwick, MA.* Conducted multiple sound level measurement programs around an existing landfill. Sound levels were measured to evaluate the effectiveness of backup alarm mitigation and to compare levels with and without a gas flare operating. Presented the results of the measurement programs in concise letter reports.
- *Resource Recovery of Cape Cod Inc., Sandwich, MA.* Participated in a group effort in conducting two consecutive 12-hour ambient sound level measurements and one 5-hour ambient sound level measurement at multiple locations for a construction & demolition transfer station in Cape Cod. The study was conducted to establish background sound levels around the facility.

Noise Impact Assessment – Institutional

- *Town Hall Renovation, Orleans, MA.* Project Manager for a sound level impact analysis for the renovation of a town hall. Measured existing sound levels at several locations and calculated future sound levels from the proposed mechanical equipment at multiple evaluation points. Following construction and the installation of the new equipment, additional measurements were collected to compare current operational sound levels to background sound levels. All findings were summarized in concise letter reports.
- *Institute of Contemporary Art, Boston, MA.* Conducted a sound level measurement program at the future site of the ICA to determine the maximum noise impacts from airplanes taking off from Logan Airport. Coordinated with the Massport Noise Abatement Office to ensure that the desired runway was being used. Gathered detailed information characterizing the noise environment of the site.
- *Phillips Academy, Andover, MA.* Measured sound levels with and without the compressor system operating at the new ice hockey facility. Prepared a letter report comparing the results to the Massachusetts Noise Policy.
- *Harvard University, Boston, MA.* Conducted an ambient sound level measurement program. Sound levels were measured around the proposed Northwest Laboratory.

- *Northeastern University, Boston, MA.* Conducted an ambient sound level measurement program. The college was interested in constructing an additional building on campus and was concerned about the noise issues related to the project.

Noise Impact Assessment – Commercial / Residential

- *Stop & Shop Supermarkets.* Executed ambient sound level programs at numerous supermarket locations in New England. Gathered reference sound level data for mechanical equipment at an existing store. Analyzed the potential for impacts at residences due to the addition of mechanical equipment using the Cadna/A noise prediction software.
- *Washington Village Project, Boston, MA.* Evaluated predicted sound levels for the proposed redevelopment of an approximately 4.89-acre site in the South Boston neighborhood. The redevelopment will include eight new residential buildings with most containing ground floor retail, as well as new streets, plazas, and green spaces. Results of the analysis were presented in an Expanded Project Notification Form (PNF).
- *110 Broad Street Project, Boston, MA.* Conducted a sound level modeling analysis for the redevelopment of 7,680 square foot site. The project includes the restoration of the historic Bulfinch Building at 102 Broad Street and the construction of a new residential building with ground floor commercial/café space at 110-112 Broad Street. The predicted sound levels were evaluated with respect to the City of Boston noise standards with the results presented in an Expanded PNF.
- *55 India Street Project, Boston, MA.* Modeled and evaluated sound levels for mechanical equipment associated with a proposed 67,000 square foot building with ground floor commercial space and 44 residential units above. Results were presented in the Expanded PNF.
- *Parcel 1 Project, Boston, MA.* Analyzed sound level impacts from the mechanical equipment associated with the proposed residential/commercial development located in Boston's historic Bulfinch Triangle. Modeling was performed using Cadna/A with the results presented in the Expanded PNF.
- *Big Y Supermarket, Northampton, MA.* Measured sound levels during normal operations at the supermarket and gathered background sound levels without the supermarket operating.
- *Crosby's Market, Hamilton, MA.* Measured sound levels around the existing market at the nearest residences in response to concerns by neighbors over the renovation and expansion of the market.
- *Condominiums, Marblehead, MA.* Measured sound levels during the operation of condenser units located at a condominium. Prepared a letter report comparing the results to the town noise ordinance.

Proposed Post Construction Sound Protocol

The Project, exclusive of all unrelated background noise, shall not generate a sound pressure level (10-minute equivalent continuous sound level, Leq) of more than 45 dBA as measured within 25 feet of any non-participating residence unless the owner of the residence has signed a waiver, or more than 50 dBA (10-minute equivalent continuous sound level, Leq) within 25 feet of any participating residence unless the owner of the residence has signed a waiver. The Project Owner shall, upon Commission formal request, conduct field surveys and provide monitoring data verifying compliance with specified noise level limits. If the measured wind turbine noise level exceeds a limit set forth above, then the Project Owner shall take whatever steps are necessary in accordance with prudent operating standards to rectify the situation.

If a field survey and monitoring data is requested by the Commission, the Project Owner shall submit the test protocol to the Commission prior to conducting the survey and sound monitoring for approval. The test protocol shall include and be implemented as follows:

a) The post-construction monitoring survey shall be conducted following applicable American National Standard Institute (ANSI) methods.

b) Sound levels shall be measured continuously for 14 days in an effort to capture a sufficient quantity of valid readings meeting the wind conditions delineated below in subpart (e). A sufficient quantity shall be defined as 0.5% of the total number of samples, or a minimum of 10 for a 14 day measurement period. As a precaution against the possibility that a sufficient number of valid readings are not automatically recorded during the chosen 14 day sampling period, 10 on/off tests shall be carried out during the survey period when the project is operating at full power production irrespective of the ground level wind speed. For the on/off tests, all units in the project shall be shut down for a 10 minute period synchronized with the monitors clocks (starting, for example, at the top of the hour or 10 minutes after, 20 minutes after, etc.). The background level measured during the shut down interval can then be subtracted from the average of the levels measured immediately before and after it to determine the project-only sound level. The results from these tests may be used to make up for any shortfall in collecting 10 samples measured when the ground level wind speed is low.

c) Measurements shall be conducted at a select number of non-participating and participating residences with the highest expected noise levels and/or at specific residences identified in the Commission’s formal request. Typically, 4 to 6 measurement locations total should be selected.

d) Measurements shall be conducted using sound level meters meeting ANSI Type 1 specifications. An anemometer shall be placed within 20 feet of each microphone, and at a height of approximately 2 meters above the ground.

e) The measurement data shall be analyzed as follows:

i. At a minimum, the closest five wind turbines will be operating for evaluation periods and when at least the closest wind turbine is operating at a condition at full (within one decibel of maximum sound power levels) acoustic emissions.
ii. Discard those samples measured when the 10-minute average ground wind speed is greater than 5 m/s.
iv. Discard those samples measured during periods with precipitation.
v. If measured (total) sound levels exceed the sound level limits, determine project only sound levels by removing transient background noise (i.e. occasional traffic, activities of residents, farming activities, and wind gusts) based upon audio recordings, excessive wind gusts, personal observations, and/or comparison of sound level metrics.
vi. If measured (total) sound levels exceed the sound level limits, determine project only sound levels by removing, continuous background noise. This approach requires wind turbine shut-downs, where the background noise is measured directly. Background noise levels will be subtracted from total noise levels measured during these wind conditions to calculate turbine-only noise levels.
vii. As necessary, review of the frequency spectra of potential turbine-only samples to identify and remove outliers (spectral shape clearly differing from those samples measured under very low (less than 2 m/s) ground wind conditions, which are the samples most representative of turbine-only noise).

f) Compare the resulting turbine-only noise levels to the 45 and 50 dBA limits. Compliance shall be demonstrated if all samples are less than the limits.

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Low frequency noise and infrasound from wind turbines

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A common issue raised with wind energy developers and operators of utility-scale wind turbines is whether the operation of their wind turbines may create unacceptable levels of low frequency noise and infrasound. In order to answer this question, one of the major wind energy developers commissioned a scientific study of their wind turbine fleet. The study consisted of three parts: 1) a world-wide literature search to determine unbiased guidelines and standards used to evaluate low frequency sound and infrasound, 2) a field study to measure wind turbine noise outside and within nearby residences, and 3) a comparison of the field results to the guidelines and standards. Wind turbines from two different manufacturers were measured at an operating wind farm under controlled conditions with the results compared to established guidelines and standards. This paper presents the results of the low frequency noise and infrasound study. Since the purpose of this paper is to report on low frequency and infrasound emissions, potential annoyance from other aspects of wind turbine operation were not considered, and must be evaluated separately.

Primary subject classification: 14.5.4; Secondary subject classification: 21.8.1

1 INTRODUCTION

Early down-wind wind turbines in the US created low frequency noise; however current up-wind wind turbines generate considerably less low frequency noise. Epsilon Associates, Inc. ("Epsilon") was retained by NextEra Energy Resources, LLC ("NextEra"), formerly FPL Energy, to investigate whether the operation of their wind turbines may create unacceptable levels of low frequency noise and infrasound. This question has often been posed to NextEra, and other wind energy developers and operators of utility-scale wind turbines. NextEra is one of the world's largest generators of wind power with approximately 7,600 net megawatts (MW) in operation as of July 2010.

The project was divided into three tasks: 1) literature search, 2) field measurement program, and 3) comparison to criteria. Epsilon conducted an extensive literature search of the technical and scientific literature on the effects of low-frequency noise and infrasound and existing criteria in order to evaluate low-frequency noise and infrasound from wind turbines. After completion of the literature search and selection of criteria, a field measurement program was developed to measure wind turbine noise to compare to the selected criteria.

The frequency range 20–20,000 Hz is commonly described as the range of "*audible*" noise. The frequency range of low frequency sound is generally from 20 Hertz (Hz) to 200 Hz, and the range below 20 Hz is often described as "*infrasound*". However, audibility extends to frequencies below 20 Hz.

Low frequency sound has several definitions. American National Standards ANSI/ASA S12.2[1] and ANSI S12.9 Part 4[2] have provisions for evaluating low frequency noise, and these special treatments apply only to sounds in the octave bands with 16, 31.5, and 63-Hz mid-band frequencies. For these reasons, in this paper on wind turbine noise, we use the term "low frequency noise" to include 12.5 Hz–200 Hz with emphasis on the 16 Hz, 31 Hz and 63 Hz octave bands with a frequency range of 11 Hz to 89 Hz.

International Electrotechnical Commission (IEC) standard 60050-801:1994[3] defines "*infrasound*" as "Acoustic oscillations whose frequency is below the low frequency limit of audible sound (about 16 Hz)." This definition is *incorrect* since sound remains audible at frequencies well below 16 Hz provided that the sound level is sufficiently high. In this paper we define infrasound to be below 20 Hz, which is the limit for the standardized threshold of hearing. Since there is no sharp

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scientific papers and reports, there should be no adverse public health effects from infrasound or low frequency noise at distances greater than 305 meters (1,000 feet) from the wind turbine types measured: GE 1.5sle and Siemens SWT 2.3-93.

7 ACKNOWLEDGMENTS

Acknowledgement is made to NextEra Energy Resources, LLC ("NextEra"), formerly FPL Energy, for providing financial support for the study, allowing access to the wind farm, and supplying critical operational data. Epsilon determined all means, methods, and the testing protocol without interference or direction from NextEra. No limitations were placed on Epsilon by NextEra with respect to the testing protocol or upon the analysis methods; the conclusions are those of the authors.

8 APPENDIX: HOME NOISE REDUCTION USED TO DETERMINE EQUIVALENT OUTDOOR SOUND PRESSURE LEVEL CRITERIA BASED ON INDOOR CRITERIA

Since indoor measurements are not always possible, for comparison to outdoor sound levels the indoor criteria from ANSI/ASA S12.2 should be adjusted. Outdoor to indoor low frequency noise reductions have been reported by Sutherland for aircraft and highway noise for open and closed windows[9] and by Hubbard and Shepherd for aircraft and wind turbine noise for closed windows[10]. Table A1 presents the average low frequency octave band noise reductions from outdoor to indoors from these two papers for open and closed windows. Sutherland only reported values down to 63 Hz; whereas Hubbard and Shepherd presented values to less than 10 Hz. The closed window conditions of Ref. 10 were used to estimate noise reductions less than 63 Hz by applying the difference between values for open and closed windows from Ref. 9 data at 63 Hz. It should be noted that the attenuation for wind turbines in Ref. 10 is based on only three homes at two different wind farms, whereas the traffic and aircraft data are for many homes. The wind turbine open window values were determined from the wind turbine closed window values by subtracting the difference in values between windows closed and open obtained by Ref. 9.

To be conservative, we use the open window case instead of closed windows except for the adjustments to the Japanese guideline which specifically called for closed windows. To be further conservative, we use the wind turbine noise reduction data in Ref. 10 (adjusted to open windows). However, it should be noted that it is possible for some homes to have some slight amplification at low frequencies with windows open due to possible room resonances.

The average one-third octave band noise reductions used to determine equivalent outdoor one-third octave band criteria were determined in a similar manner. The first row of Table A2 and Fig. 20 present the average one-third octave band noise reductions values for *windows open* that were used to determine the equivalent outdoor one-third octave band criteria levels in Table 7 from the indoor criteria. The second row of Table A2 and Fig. 19 presents the one-third octave band noise reductions for windows closed determined by Ref. 10 for homes exposed to wind turbine sounds—these higher closed window noise reduction values were only used to determine equivalent outdoor levels for determining the equivalent Japanese guidance one-third octave band sound pressure level values for dealing with complaints of mental and physical discomfort from environmental sounds.

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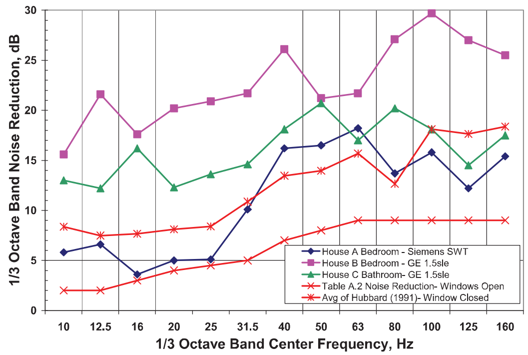

Fig. 19—One-third octave band interior noise reduction—Windows closed.

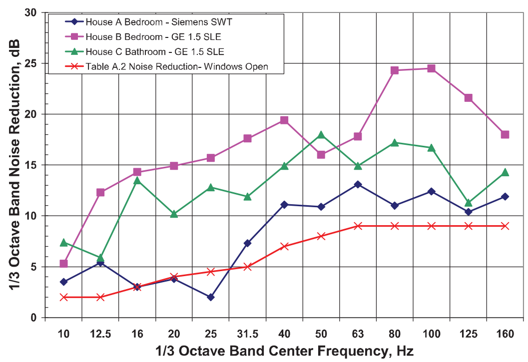

Fig. 20—One-third octave band interior noise reduction—Windows open.

cal discomfort from low frequency noise;

- have no audible infrasound to the most sensitive listeners; and
- might have slightly audible low frequency noise at frequencies at 50 Hz and above depending on other sources of low frequency noises in homes, such as refrigerators or external traffic or airplanes.

In accordance with the above findings, and in conjunction with our extensive literature search of

Table 14—Summary of octave band noise reduction—Interior measurements.

Home	Wind Turbine	Windows	16 Hz	31.5 Hz	63 Hz	125 Hz
A	Siemens SWT-2-3-93	Closed	5	6	16	14
A	Siemens SWT-2-3-93	Open	4	3	12	12
B	GE 1.5sle	Closed	20	22	22	27
B	GE 1.5sle	Open	13	17	18	21
C	GE 1.5sle	Closed	13	14	19	17
C	GE 1.5sle	Open	8	13	17	14
Table A1 Noise Reduction		Open	3	6	9	9

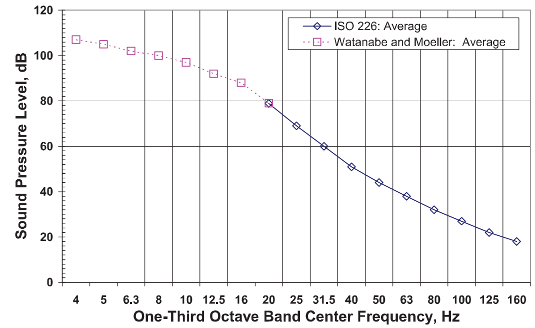

Fig. 1—Low frequency average threshold of hearing from ISO 226[6] and Watanabe and Moeller[7].

change in hearing at 20 Hz, the division into "low-frequency sound" and "infrasound" should only be considered "practical and conventional."

2 EFFECTS AND CRITERIA OF LOW FREQUENCY SOUND AND INFRASOUND

We performed an extensive world-wide literature search of over 100 scientific papers, technical reports and summary reports on low frequency sound and infrasound—hearing, effects, measurement, and criteria. Leventhall[4] presents an excellent and comprehensive study on low frequency noise from all sources and its effects. The Leventhall report also presents criteria in place at that time, which does not include some of the more recently developed ANSI/ASA standards on outdoor environmental noise and indoor sounds.

The United States government does not have specific criteria for low frequency noise. The US Environmental Protection Agency (EPA) has guidelines for the protection of public health with an adequate margin of safety in terms of annual average A-weighted day-night average sound level (L_{dn}), but there are no corrections or adjustments for low frequency noise. The US Department of Transportation (DOT) has A-weighted sound pressure level criteria for highway projects and airports, but these do not have adjustments for low frequency noise. The following sections describe the low frequency and infrasound criteria to which wind turbine sounds are compared in later sections.

2.1 Threshold of Hearing and Audibility

Moeller and Pedersen[5] present an excellent summary on human perception of sound at frequencies below 200 Hz. The ear is the primary organ for sensing infrasound. Hearing becomes gradually less sensitive for decreasing frequencies. But, humans with a normal hearing organ can perceive infrasound at least down to a few hertz if the sound level is sufficiently high.

The threshold of hearing is standardized for frequencies down to 20 Hz[6]. Based on extensive research and data, Moeller and Pedersen propose normal hearing thresholds for frequencies below 20 Hz; however, their proposed threshold is higher than that obtained by Watanabe and Moeller[7]. To be conservative, we have used the data from Watanabe and Moeller[7] for the region below 20 Hz. (See Fig. 1.) Moeller and Pedersen[5] suggest that the curve for low frequency thresholds for normal hearing is "probably correct within a few decibels, at least in most of the frequency range."

The hearing thresholds show considerable variability from individual to individual with a standard deviation among subjects of about 5 dB independent of frequency between 3 Hz and 1000 Hz with a slight increase at 20−50 Hz. This implies that the audibility threshold for 97.5% of the population is greater than the values in Fig. 1 minus 10 dB and for 84% of the population is greater than the values in Fig. 1 minus 5 dB. Moeller and Pedersen suggest that the "pure-tone threshold can with a reasonable approximation be used as a guideline for the thresholds also for [low frequency] non-sinusoidal sounds"[5]; ISO 226 has thresholds for frequencies at and above 20 Hz and approximately equates the thresholds and equal loudness contours for non-sinusoidal sounds to those in the standard for sinusoidal sounds[6].

As frequency decreases below 20 Hz, if the noise source is tonal, the tonal sensation ceases. Below 20 Hz tones are perceived as discontinuous. Below 10 Hz it is possible to perceive the single cycles of a tone, and the perception changes into a sensation of pressure at the ears.

Below 100 Hz, the dynamic range of the auditory system decreases with decreasing frequency, and the compressed dynamic range has an effect on equal loudness contours: a slight change in sound level can change the perceived loudness from barely audible to loud. This combined with the large variation in individual hearing may mean that a low frequency sound that is inaudible to some may be audible to others, and may be relatively loud to some of those for whom it is audible. Loudness for low frequency sounds grows considerably faster above threshold than for sounds at higher frequencies[5].

Non-auditory perception of low frequency and infrasound occurs only at levels above the auditory threshold. In the frequency range of 4–25 Hz and at "*levels 20–25 dB above [auditory] threshold it is possible to feel vibrations* in various parts of the body, e.g., the lumbar, buttock, thigh and calf regions. A feeling of pressure may occur in the upper part of the chest and the throat region" [emphasis added][5].

2.2 ANSI S12.9-Parts 4 and 5—Evaluating Outdoor Environmental Sound

American National Standard ANSI/ASA S12.9-2007/Part 5[8] has an informative annex which provides guidance for designation of land uses compatible with existing or predicted annual average adjusted day-night average outdoor sound level (DNL). Ranges of the DNL are outlined, within which a specific region of compatibility may be drawn. These ranges take into consideration the noise reduction in sound level from outside to inside buildings as commonly constructed in that locality and living habits there. There are adjustments to day-night average sound level to account for the presence of low frequency noise, and the adjustments are described in ANSI S12.9 Part 4, which use a sum of the sound pressure levels in octave bands with center frequencies of 16, 31 and 63 Hz.

ANSI S12.9/Part 4 identifies two thresholds: annoyance is minimal when the 16, 31.5 and 63 Hz octave band sound pressure levels are each less than 65 dB and there are no rapid fluctuations of the low frequency sounds. The second threshold is for increased annoyance which begins when rattles occur, which begins at L_{LF} 70–75 dB. L_{LF} is 10 times the logarithm of the ratio of time-mean square sound pressure in the 16, 31.5, and 63-Hz octave bands divided by the square of the reference sound pressure.

The adjustment procedure for low frequency noise to the average annual A-weighted sound pressure level in ANSI S12.9/Part 4 uses a different and more complicated metric and procedure (Equation D.1) than those used for evaluating low frequency noise in rooms contained in ANSI/ASA S12.2. (See Sec. 2.3). Since we are evaluating low frequency noise and not A-weighted sound levels, we do not recommend using the procedure for adjusting A-weighted levels. Instead we recommend using the following two guidelines from ANSI S12.9/Part 4: a sound pressure level of 65 dB in each of the 16-, 31.5-, and 63 Hz octave bands as an indicator of minimal annoyance, and 70–75 dB for the summation of the sound pressure levels from these three bands as an indicator of possible increased annoyance from rattles.

2.3 ANSI/ASA S12.2—Evaluating Room Noise

ANSI/ASA S12.2-2008[1] discusses criteria for evaluating room noise, and has two separate provisions for evaluating low frequency noise: (1) the potential to cause perceptible vibration and rattles, and (2) meeting low frequency portions of room criteria curves. Since the ANSI S12.2 criteria are for indoor sounds, in order to determine equivalent outdoor criteria for comparison to outdoor measurements, data from Sutherland[9] and Hubbard and Shephard[10] were used to determine typical noise reductions from outdoor to indoor with windows open. (The Appendix of this paper describes the noise reductions used to determine equivalent outdoor criteria to indoor criteria.) Table A1 presents octave band noise reductions applied in this evaluation along with the average low frequency octave band noise reductions from outdoor to indoors from Refs. 9 and 10 for open and closed windows. Table A2 presents the one-third octave band noise reductions applied in the analysis that were determined in the same manner using data from the same references.

Vibration and Rattles: Outdoor low frequency sounds of sufficient amplitude can cause building walls to vibrate and windows to rattle. Homes have low values of transmission loss at low frequencies, and low frequency noise of sufficient amplitude may be audible within homes. Window rattles are not low frequency noise, but may be caused by low frequency noise. ANSI/ASA S12.2 presents limiting levels at low frequencies for assessing (a) the probability of *clearly* perceptible acoustically induced vibration and rattles in lightweight wall and ceiling constructions, and (b) the probability of *moderately* perceptible acoustically induced vibration in similar constructions. The limiting sound pressure levels in the octave bands with center frequencies of 16, 31.5 and 63 Hz are presented in Table 1.

Applying the outdoor to indoor attenuations for wind turbine sources with windows open given in the last row of Table A1 to the ANSI/ASA S12.2 indoor sound pressure levels in Table 1 yields the equivalent

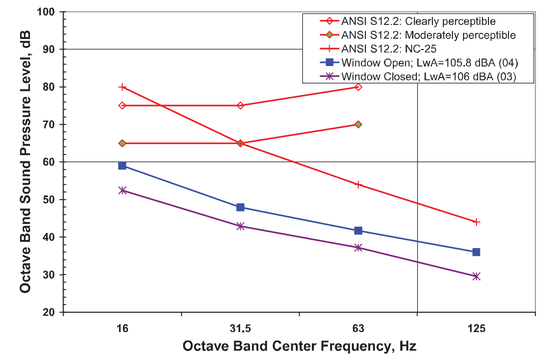

Fig. 17—GE 1.5sle wind turbine indoor sound levels at 290 meters compared to ANSI 12.2 criteria for perceptible vibrations and NC-25 (Home "B").

turbines at 305 meters (1,000 feet) under high output/high noise levels met the equivalent outdoor ANSI/ASA S12.2 criteria at 31 Hz.

6 CONCLUSION

Sound levels from Siemens SWT 2.93-93 and GE 1.5sle wind turbines under maximum noise conditions at a distance more than 305 meters (1,000 feet) from the nearest residence meet the low frequency and infrasound standards and criteria published by several independent agencies and organizations. At this distance the wind farms:

- meet ANSI/ASA S12.2 indoor levels for low frequency sound for bedrooms, classrooms and hospitals;
- meet ANSI/ASA S12.2 indoor levels for moderately perceptible vibrations in light-weight walls and ceilings;
- meet ANSI/ASA S12.2 criteria for balanced spectrum from low frequency sounds;
- meet ANSI S12.9/Part 4 thresholds for annoyance from low frequency sound and beginning of rattles;
- meet UK DEFRA disturbance based guidelines for low frequency sound;
- meet Japan Ministry of Environment Guidance for evaluating complaints of rattling from low frequency noise;
- meet Japan Ministry of Environment Guidance for evaluating complaints of mental and physi-

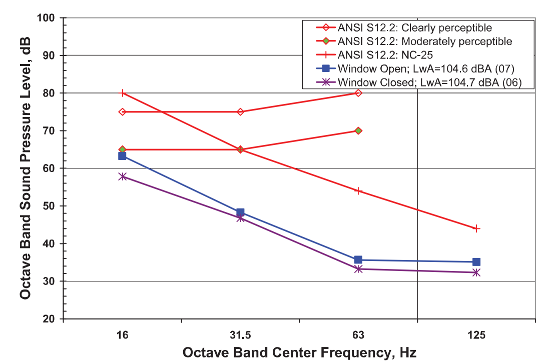

Fig. 18—GE 1.5sle wind turbine indoor sound levels at 312 meters compared to ANSI 12.2 criteria for perceptible vibrations and NC-25 (Home "C").

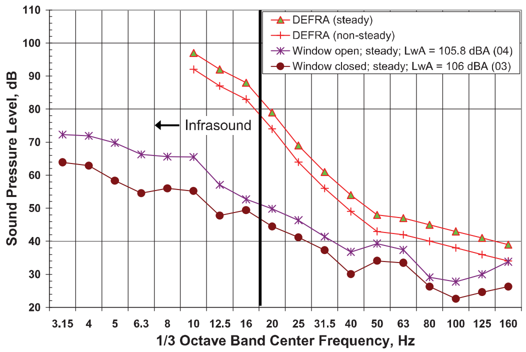

Fig. 15—GE 1.5sle wind turbine indoor sound levels at 290 meters compared to DEFRA criteria (Home "B").

was used in our analysis for obtaining the equivalent outdoor DEFRA criteria, the average of the three homes has a greater noise reduction than assumed in the Appendix and all houses at all frequencies have higher values with one minor exception. Only Home "A" at 25 Hz had a lower noise reduction (3 dB), and this difference is not critical since the measured indoor sounds at 25 Hz at each of these home was significantly lower than the indoor DEFRA criteria and the indoor Japanese criteria. Furthermore, the outdoor measurements for both Siemens and GE wind turbines at 305 meters (1,000 feet) under high output/high noise levels met the equivalent outdoor DEFRA criteria at 25 Hz.

Table 14 presents the measured octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in Table 14 are the octave band noise reductions used in Table 2 of this paper to obtain equivalent outdoor criteria for the indoor ANSI/ASA S12.2 criteria for perceptible vibration and for NC-25 and NC-30. It can be seen that for the window closed condition, the measured noise reductions for all houses were greater than that used in our analysis. For the open window case, the average of the three homes has a greater noise reduction than the values from Table A1, and all houses at all frequencies have higher values with one minor exception. Only Home "A" at 31 Hz (which contains the 25 Hz one-third octave band) had a lower noise reduction (3 dB), and this difference is not critical since the measured indoor sounds at 31 Hz at each of these homes was significantly lower than the indoor ANSI/ASA S12.2 criteria. Furthermore, the outdoor measurements for both Siemens and GE wind

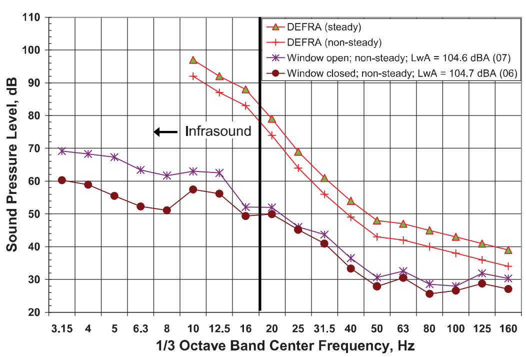

Fig. 16—GE 1.5sle wind turbine indoor sound levels at 312 meters compared to DEFRA criteria (Home "C").

Table A1—Average low frequency octave band home noise reductions from outdoor to indoors in dB (from Ref. 9 and 10).

Noise Source	Window condition	Octave Band Center Frequency 16 Hz	31.5 Hz	63 Hz	125 Hz
Average aircraft and traffic sources	Closed windows	16	15	18	20
Average aircraft and traffic sources	Open windows	(11)*	(10)*	12	11
Average Wind Turbine	Closed windows	8	11	14	18
Average Wind Turbine	Open windows	(3)*+	(6)*+	9+	9+

* No data are available for windows open below 63 Hz octave band. The values for 16 Hz and 31 Hz were obtained by subtracting the difference between the levels for 63 Hz closed and open conditions to the 16 and 31 Hz closed values.
\+ Used in this paper to determine equivalent outdoor criteria from indoor criteria in Tables 2 and 4

outdoor sound pressure levels that are consistent with the indoor criteria and are presented in Table 2.

Room Criteria Curves: ANSI/ASA S12.2 has three primary methods for evaluating the suitability of noise within rooms: a survey method—A-weighted sound levels, an engineering method—noise criteria (NC) curves, and a method for evaluating low-frequency fluctuating noise using room noise criteria (RNC) curves. ANSI/ASA S12.2 states "The RNC method should be used to determine noise ratings when the noise from HVAC systems at low frequencies is loud and is suspected of containing sizeable *fluctuations or surging*." [emphasis added] The NC curves are appropriate to evaluate low frequency noise from wind turbines in homes since wind turbine noise does not have significant fluctuating low frequency noise sufficient to warrant using RNC curves and since A-weighted sound levels do not adequately determine

Table A2—Average low frequency one-third octave band noise reduction in dB for homes from outdoor to indoors.

Condition	One-Third Octave Band Center Frequency, Hz 10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Open Window*	2	2	3	4	4.5	5	7	8	9	9	9	9	9
Average Closed Window with wind turbines[10] **	8	7	8	8	8	11	13	14	15	12	18	18	18

* Used to determine equivalent outdoor levels as shown in Table 7.
** Used to determine equivalent outdoor levels as shown in Table 9.

Table 1—ANSI/ASA S12.2 measured interior sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures.[1]

Condition	Octave-band center frequency (Hz) 16	31.5	63
Clearly perceptible vibration and rattles likely	75 dB	75 dB	80 dB
Moderately perceptible vibration and rattles likely	65 dB	65 dB	70 dB

001111

Table 2—Equivalent outdoor sound pressure levels to the ANSI/ASA S12.2 indoor sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures for wind turbines.

Condition	Octave-band center frequency (Hz) 16	31.5	63
Clearly perceptible vibration and rattles likely	78 dB	81 dB	89 dB
Moderately perceptible vibration and rattles likely	68 dB	71 dB	79 dB

if there are low frequency problems. [ANSI/ASA S12.2, Sec. 5.3 gives procedures for determining if there are large fluctuations of low frequency noise.]

Annex C.2 of ANSI/ASA S12.2 contains recommended room criteria curves for bedrooms, which are the rooms in homes with the most stringent criteria: NC and RNC criteria curve between 25 and 30. The recommended NC and RNC criteria for schools and private rooms in hospitals are the same. The values of the sound pressure levels in the 16–125 Hz octave bands for NC curves 25 and 30 are shown in Table 3. Applying the outdoor to indoor attenuations for wind turbine sources with windows open given in the last row of Table A1 to the ANSI/ASA S12.2 indoor sound pressure levels for NC-25 and NC-30 in Table 3 yields the equivalent outdoor sound pressure levels that are consistent with the indoor criteria and are presented in Table 4.

ANSI/ASA S12.2 also presents a method to determine if the levels below 500 Hz octave band are too high in relation to the levels in the mid-frequencies which could create a condition of "spectrum imbalance". The method for this evaluation is:

- Calculate the speech interference level (SIL) for the measured spectrum. [SIL is the arithmetic average of the sound pressure levels in the 500, 1000, 2000 and 4000 Hz octave bands.] Select the NC curve equal to the SIL value with a symbol NC(SIL).
- Plot the measured spectra and the NC curve equal to the SIL value on the same graph and determine the differences between the two curves in the octave bands below 500 Hz.
- Estimate the likelihood that the excess low-frequency levels will annoy occupants of the space using Table 5.

Table 3—ANSI/ASA S12.2 low frequency octave band sound pressure levels for noise criteria curves NC-25 and NC-30. [Table 1 from Ref. 1].

NC Criteria	Octave-band-center frequency, Hz 16	31.5	63	125
NC-25	80	65	54	44
NC-30	81	68	57	48

2.4 Other Criteria

2.4.1 World Health Organization (WHO)

No specific low frequency noise criteria are proposed by the WHO. The Guidelines for Community Noise report[11] mentions that if the difference between

Table 4—Equivalent outdoor sound pressure levels to the ANSI/ASA S12.2 low frequency octave band sound pressure levels for noise criteria curves NC-25 and NC-30. [Table 1 from Ref. 1].

NC Criteria	Octave-band-center frequency, Hz 16	31.5	63	125
NC-25 equivalent outdoor	83	71	63	53
NC-30 equivalent outdoor	84	74	66	57

Table 5—Measured sound pressure level deviations from an NC (SIL) curve that may lead to serious complaints[1].

Octave-band frequency, Hz=>	Measured Spectrum—NC(SIL), dB 31.5	63	125	250
Possible serious dissatisfaction	*	6–9	6–9	6–9
Likely serious dissatisfaction	*	>9	>9	>9

* Insufficient data available to evaluate

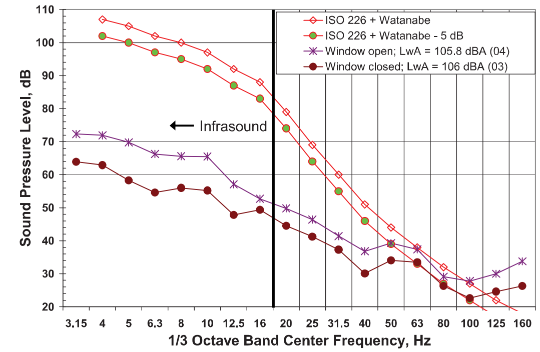

Fig. 13—GE 1.5sle wind turbine indoor sound levels at 290 meters compared to audibility criteria (Home "B").

the spectrum was balanced, and the criteria for moderately perceptible vibrations in light-weight walls and ceilings were also met.

5.3 Noise Reduction from Outdoor to Indoor

Simultaneous outdoor and indoor measurements made at the three residences within the Horse Hollow Wind Farm discussed above, were used to determine noise reductions of the homes for comparison to that used in the determination of equivalent outdoor criteria for indoor criteria, such as ANSI/ASA S12.2 and DEFRA. Indoor measurements were made with windows open and closed. Tables 11 and 13 list the conditions of measurement for these houses.

Figures 19 and 20 present the measured one-third octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in these same figures are the one-third octave noise reductions discussed in the Appendix of this paper to obtain equivalent outdoor criteria for the indoor DEFRA criteria as well as the equivalent outdoor criteria for the Japanese mental and physical discomfort indoor criteria. It can be seen that for the window closed condition in Fig. 19, the measured noise reductions for all houses were greater than that used in our analysis for determining the equivalent outdoor criteria for the Japanese mental and physical discomfort indoor criteria. For the open window case in Fig. 20, which

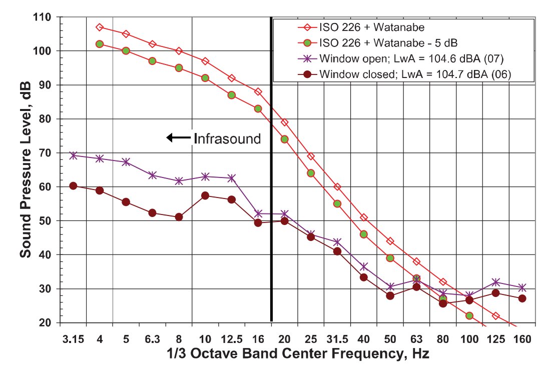

Fig. 14—GE 1.5sle wind turbine indoor sound levels at 312 meters compared to audibility criteria (Home "C").

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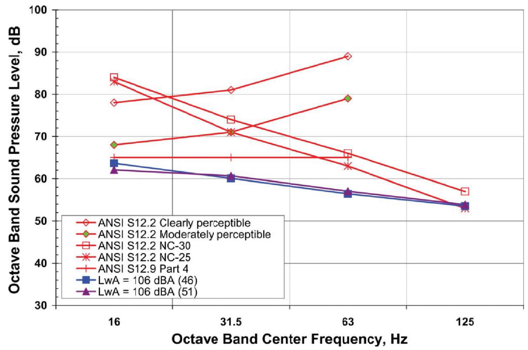

Fig. 12—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to ANSI criteria.

approximately 3.0 meters wide (10 feet) by 3.6 meters long (12 feet), bedroom furniture, carpeted flooring, two relatively new double-hung windows (no storm windows), paneling on the interior walls, and bricked exterior walls. The sound level meter was located just off-center in the room. The room in Home "C" where interior measurements were made had the following characteristics: approximately 2.4 meters wide (8 feet) by 3.6 meters long (12 feet), bathroom fixtures, linoleum flooring, one old casement window (no storm window), paneling on the interior walls, and wooden exterior walls. The sound level meter was located in the center of the room.

Figure 13 plots the indoor one-third octave band sound levels (L_{eq}) for Home "B", and Fig. 14 plots the indoor one-third octave band sound levels for Home "C". The results show that infrasound is inaudible to even the most sensitive people at around 305 meters (1,000 feet) from these wind turbines with the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 63 Hz may be audible depending on background sound levels.

Figure 15 plots the indoor one-third octave band sound levels (L_{eq}) for Home "B", and Fig. 16 plots the indoor one-third octave band sound levels (L_{eq}) for Home "C". The results show the DEFRA disturbance criteria were met for steady and non-steady low frequency sounds.

Although not shown in Figs. 15 and 16, the one-third octave band levels meet the Japan Ministry of Environment criteria for evaluating complaints of mental and physical discomfort since both samples meet the more stringent DEFRA criteria for "non-steady" sounds, which is more stringent than the Japan criteria.

Figure 17 plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "B", and Fig. 18 plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "C". The results show the ANSI/ASA S12.2 low frequency criteria for perceptible vibration were met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for bedrooms, classrooms and hospitals were met,

Table 13—Summary of operational parameters—GE 1.5sle (Indoor).

Parameter	Home "B" (closed/open)	Home "C" (closed/open)
Distance to nearest WTG	290 meters	312 meters
Time of day	09:29-09:39/09:40-09:50	11:49-11:59/12:00-12:10
WTG power output	1,017 kW/896 kW	651 kW/632 kW
A-weighted sound power level	106 dB/105.8 dB	104.7 dB/104.6 dB
Measured wind speed @ 2 m	6.2 m/s/6.8 m/s	6.4 m/s/5.9 m/s
L_{Aeq}	27.1 dB/36.0 dB	33.6 dB/39.8 dB
L_{A90}	23.5 dB/33.7 dB	27.6 dB/34.2 dB
L_{Ceq}	47.1 dB/54.4 dB	50.6 dB/55.1 dB

* Includes K, uncertainty factor of 2 dB

Table 6—DEFRA proposed criteria[13] for the assessment of low frequency noise disturbance: Indoor L_{eq} one-third sound pressure levels for non-steady and steady low frequency sounds.

	One-Third Octave Band Center Frequency, Hz												
Location	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Non-Steady L_{eq}, dB	92	87	83	74	64	56	49	43	42	40	38	36	34
Steady L_{eq}, dB	97	92	88	79	69	61	54	48	47	45	43	41	39

the C-weighted sound level and A-weighted sound level is greater than 10 decibels, then a frequency analysis should be performed to determine if there is a low frequency issue. A document prepared for the World Health Organization states that "there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above detection threshold may cause perceptual effects but these are of the same character as for 'normal' sounds. Reactions caused by extremely intense levels of infrasound can resemble those of mild stress reaction and may include bizarre auditory sensations, describable as pulsation and flutter"[12].

2.4.2 The UK Department for Environment, Food, and Rural Affairs (DEFRA)

The report prepared by the University of Salford for the UK Department for Environment, Food, and Rural Affairs (DEFRA) on low frequency noise proposed one-third octave band sound pressure level L_{eq} criteria and procedures for assessing low frequency noise[13]. The guidelines are based on complaints of disturbance from low frequency sounds and are intended to be used by Environmental Health Officers.

Existing low frequency noise criteria from several countries were reviewed and experiences with low frequencies complaints were considered in developing the proposed guidelines. The criteria are "based on 5 dB below the ISO 226 average threshold of audibility for steady [low frequency] sounds." However, the DEFRA criteria are at 5 dB lower than ISO 226 only at 20–31.5 Hz; at higher frequencies the criteria are equal to the Swedish criteria which are higher levels than ISO 226 less 5 dB. For frequencies lower than 20 Hz, DEFRA uses the thresholds from Ref. 7 less 5 dB.

The DEFRA criteria are based on measurements in an unoccupied room, and it was noted by a practicing consultant that measurements should be made with windows closed[14]. However, we conservatively used windows open conditions for our assessment to determine equivalent outdoor criteria since the DEFRA measurement procedure does not explicitly state measurements are with windows closed. If the low frequency sound is "steady" then the criteria may be relaxed by 5 dB. A low frequency noise is considered steady if either $L_{10}-L_{90} < 5$ dB or the rate of change of sound pressure level (Fast time weighting) is less than 10 dB per second in the third octave band which exceeds the criteria by the greatest margin.

Applying indoor to outdoor one-third octave band transfer functions for open windows (as presented in Table A2 from analysis of data in Refs. 9 and 10) yields *equivalent* one-third octave band sound pressure level proposed DEFRA criteria for outdoor sound levels. Table 6 presents the indoor DEFRA proposed criteria for non-steady and steady low-frequency sounds. Table

Table 7—Equivalent outdoor L_{eq} one-third sound pressure levels for non-steady and steady sounds to the DEFRA indoor criteria[13] for the assessment of low frequency noise disturbance.

	One-Third Octave Band Center Frequency, Hz												
Location	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Non-Steady Equivalent outdoor * L_{eq}, dB	94	89	86	78	68.5	61	56	51	51	49	47	45	43
Steady Equivalent Outdoor* L_{eq},	99	94	91	83	73.5	66	61	56	56	54	52	50	48

* With windows open

Table 8—Japan Ministry of Environment Guidance for evaluating complaints of low frequency noise: Reference one-third octave band sound pressure level values for complaints of rattling.

	One-Third Octave Band Center Frequency, Hz										
Location	5	6.3	8	10	12.5	16	20	25	31.5	40	50
Outdoor L_{eq}, dB	70*	71*	72*	73	75	77	80	83	87	93	99

* The reference values are several dB lower than the supporting data contained in Ref. 15. At 5 Hz, window rattles started at about 74 dB in one study and 79 dB in another; at 6.3 Hz, rattles started at 74 dB in the first study and at 78 dB in the second; and at 8 Hz, window rattle started at 74 dB in the first study and 77 dB in the second study.

7 presents the DEFRA equivalent outdoor criteria for non-steady and steady low frequency sounds.

2.4.3 Japan Ministry of Environment

The Japan Ministry of Environment has published a handbook to deal with low frequency noise problems and has established reference values for guidance in dealing with complaints of rattling windows and doors and complaints of "mental and physical discomfort"[15]. It was noted that traditional Japanese houses have relatively light-weight and sensitive windows and partitions[16].

Table 8 presents the Japanese reference outdoor one-third octave band sound pressure level values for guidance in dealing with complaints of rattling from environmental sounds from 5 Hz to 50 Hz. From 10 Hz to 50 Hz the guidance levels are equal to the observed threshold of rattles from two studies with a total of 78 samples. However, for the bands centered at 5, 6.3 and 8 Hz, the reference values are several dB lower than the supporting data contained in these two studies[15]. At 5 Hz, the lowest observed window rattle was at 74 dB in one study and 79 dB in another; at 6.3 Hz, rattles started at 74 dB in the first study and at 78 dB in the second; and at 8 Hz, window rattle started at 74 dB in the first study and 77 dB in the second study. Thus the reference values at 5, 6.3 and 8 Hz in Table 8 are conservative in comparison to the other values by 4, 3, and 2 dB respectively.

Table 9 presents the Japanese reference one-third octave band sound pressure level values for guidance in dealing with complaints of mental and physical discomfort from environmental sounds when evaluated indoors. Evaluation measurements are to be performed with windows closed to the outside. The values in Table 9 are less stringent than the DEFRA values in Table 6 for non-steady sounds but more stringent than the DEFRA values for steady sounds in some one-third octave bands. In order to obtain equivalent outdoor sound levels, the average noise reduction from wind turbine noise with windows closed from Ref. 10 was applied to the Japan reference values. Table 9 presents the Japanese indoor reference values, the noise reductions for windows closed[10] and the equivalent outdoor reference values. These equivalent outdoor values are less stringent than the equivalent outdoor DEFRA values in Table 7 for both non-steady sounds and steady sounds except for the 80 Hz band in which the Japanese level is 1 dB more stringent than the DEFRA level for steady sounds.

2.4.4 C-weighted minus A-weighted ($L_{pC}-L_{pA}$)

Leventhall[4] and others indicate that the difference in C-weighted and A-weighted sound pressure levels can be a predictor of annoyance. Leventhall states that if ($L_{pC}-L_{pA}$) is greater than 20 dB there is "a potential for a low frequency noise problem." He further states that ($L_{pC}-L_{pA}$) cannot be a predictor of annoyance but is a simple indicator that further analysis may be needed. This is due in part to the fact that the low frequency noise may be inaudible even if ($L_{pC}-L_{pA}$) is greater than 20 dB.

3 LITERATURE REVIEW

The authors performed an extensive literature search of over 100 scientific papers, technical reports and summary reports on low frequency sound and infrasound—hearing, effects, measurement, and criteria. The following paragraphs briefly summarize the findings from some of these papers and reports.

3.1 Leventhall

Leventhall[4] presents an excellent study on low frequency noise from all sources and its effects. The report presents criteria in place at that time and includes data relating cause and effects. Leventhall[17] reviewed data and allegations on alleged problems from low frequency noise and infrasound from wind turbines, and concluded the following: "It has been shown that there is insignificant infrasound from wind turbines and that there is normally little low frequency noise." "Turbulent air inflow conditions cause enhanced levels of low frequency noise, which may be disturbing, but the overriding noise from wind turbines is the fluctuating audible swish, mistakenly referred to

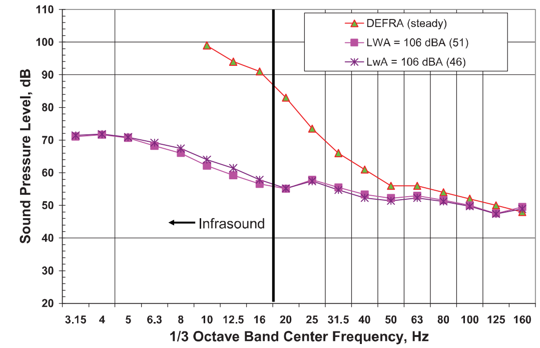

Fig. 10—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to outdoor equivalent DEFRA criteria.

bedrooms are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB). The 16, 31.5, 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4.

5.2.2 Indoor measurements—GE 1.5sle

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from GE 1.5sle WTGs. In each house, measurements were made in a room facing the wind turbines, and were made with a window both open and closed. These residences are designated Homes "B" and "C" and were approximately 305 meters (1,000 feet) from the closest GE WTG. Operational conditions were maximum turbine noise and high ground winds at Home "B", and within 1.5 dB of maximum turbine noise and high ground level winds at Home "C". Home "B" was near a string of multiple WTGs, four of which were within 610 meters (2,000 feet) of the house, while Home "C" was at the end of a string of WTGs, two of which were within 610 meters of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 13.

The room in Home "B" where interior measurements were made had the following characteristics:

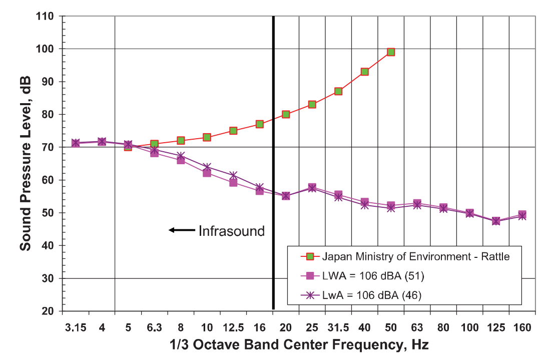

Fig. 11—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to Japan Ministry of Environment rattle criteria.

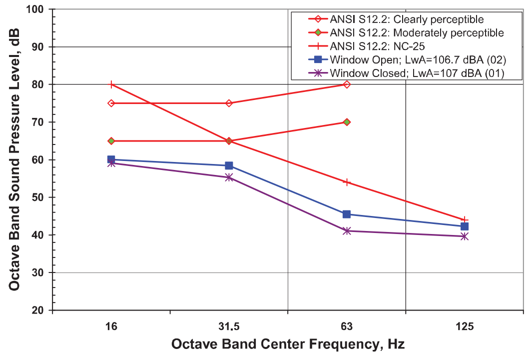

Fig. 8—Siemens SWT-2.3-93 wind turbine indoor sound levels at 323 meters compared to ANSI 12.2 criteria for perceptible vibrations and NC-25 (Home "A").

frequencies; at 5 Hz the mean value is 70 dB (standard deviation = 0.9 dB), while the two presented measurements are approximately 1 dB higher, an insignificant increase. When one considers that the 5 Hz sound level is 3 dB lower than the observed threshold of rattle, one concludes that the Japanese criteria are met.

Table 12—Summary of operational parameters—GE 1.5sle (Outdoor).

Parameter	Sample #46	Sample #51
Distance to nearest WTG	305 meters	305 meters
Time of day	23:10-23:20	00:00-00:10
WTG power output	1,293 kW	1,109 kW
A-weighted sound power level*	106 dB	106 dB
Measured wind speed @ 2 m	4.1 m/s	3.3 m/s
L_{Aeq}	50.2 dB	50.7 dB
L_{A90}	49.2 dB	49.7 dB
L_{Ceq}	62.5 dB	62.8 dB

* Includes K, uncertainty factor of 2 dB

The measured outdoor sound levels also meet the outdoor equivalent Japan Ministry of Environment criteria for evaluating complaints of mental and physical discomfort. This comparison is not presented in a figure since these criteria are generally less stringent than the DEFRA criteria.

Figure 12 plots the 16, 31.5, 63 and 125 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. The results show that all outdoor equivalent ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for

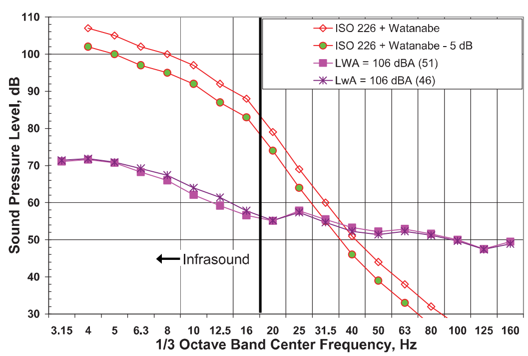

Fig. 9—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to audibility criteria.

Table 9—Japan Ministry of Environment Guidance for evaluating complaints of low frequency noise: Reference one-third octave band sound pressure level values for complaints of mental and physical discomfort.

	One-Third Octave Band Center Frequency, Hz									
Location	10	12.5	16	20	25	31.5	40	50	63	80
Indoor L_{eq}, dB	92	88	83	76	70	64	57	52	47	41
Noise Reduction*, dB	8	7	8	8	8	11	13	14	15	12
Equivalent Outdoor L_{eq}, dB	100	95	91	84	78	75	70	66	62	53

* from Hubbard[10] windows closed condition

as "infrasound" or "low frequency noise". "Infrasound from wind turbines is below the audible threshold and of no consequence". Other studies have shown that wind turbine generated infrasound levels are below threshold of perception and threshold of feeling and body reaction.

3.2 DELTA

The Danish Energy Authority project on "low frequency noise from large wind turbines" comprises a series of investigations in the effort to give increased knowledge on low frequency noise from wind turbines[18]. One of the conclusions of the study is that wind turbines do not emit audible infrasound, with levels that are "far below the hearing threshold." Audible low frequency sound may occur both indoors and outdoors, "but the levels in general are close to the hearing and/or masking level." "In general the noise in the critical band up to 100 Hz is below both thresholds". The final report notes that for road traffic noise (in the vicinity of roads) the low frequency noise levels are higher [than wind turbine] both indoors and outdoors.

3.3 Hayes McKenzie Partnership

Hayes McKenzie Partnership Ltd performed a study for the UK Department of Trade & Industry (DTI) to investigate complaints of low frequency noise that came from three of the five farms with complaints out of 126 wind farms in the UK[14]. The study concluded that:

- Infrasound associated with modern wind turbines is not a source which will result in noise levels that are audible or which may be injurious to the health of a wind farm neighbor.
- Low frequency noise was measureable on a few occasions, but below DEFRA criteria. Wind turbine noise may result in indoor noise levels within a home that is just above the threshold of audibility; however, it was lower than that of local road traffic noise.
- The common cause of the complaints was not associated with low frequency noise but the occasional audible modulation of aerodynamic noise, especially at night.
- The UK Department of Trade and Industry, which is now the UK Department for Business Enterprise and Regulatory Reform (BERR), summarized the Hayes McKenzie report: "The report concluded that there is no evidence of health effects arising from infrasound or low frequency noise generated by wind turbines."[19].

3.4 Howe

Howe performed extensive studies on wind turbines and infrasound and concluded that infrasound was not an issue for modern wind turbine installations—"while infrasound can be generated by wind turbines, it is concluded that infrasound is not of concern to the health of residences located nearby."[20]. Since then Gastmeier and Howe[21] investigated an additional situation involving the alleged "perception of infrasound by individual." In this additional case, the measured indoor infrasound was at least 30 dB below the audibility threshold given by Ref. 7 as presented in Fig. 1.

3.5 Branco

Branco and other Portuguese researchers have studied possible physiological affects associated with high amplitude low frequency noise and have labeled these alleged effects as "Vibroacoustic Disease" (VAD)[22]. "Vibroacoustic disease (VAD) is a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices, and caused by excessive exposure to low frequency noise."

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Hayes[23,24] concluded that levels from wind farms are not likely to cause VAD after comparing noise levels from alleged VAD cases to noise levels from wind turbines in homes of complainers. Noise levels in aircraft in which VAD has been hypothesized are considerably higher than wind turbine noise levels. Hayes also concluded that it is "unlikely that symptoms will result through induced internal vibration from incident wind farm noise."[23]. Other studies have found no VAD indicators in environmental sound that have been alleged by VAD proponents[25].

3.6 French National Academy of Medicine

In 2006, the French National Academy of Medicine recommended[26] "*as a precaution* construction should be suspended for wind turbines with a capacity exceeding 2.5 MW located within 1500 m of homes." [emphasis added] However, this precaution is not because of definitive health issues but because:

- Sound levels one km from some wind turbine installations "occasionally exceed allowable limits" for France (note that the allowable limits are long term averages).
- French prediction tools for assessment did not take into account sound levels created with wind speeds greater than 5 m/s.
- Wind turbine noise has been compared to aircraft noise (even though the sound levels of wind turbine noise are significantly lower), and exposure to high level aircraft noise "involves neurobiological reactions associated with an increased frequency of hypertension and cardiovascular illness. Unfortunately, no such study has been done near wind turbines."[27].

In March 2008, the French Agency for Environmental and Occupational Health Safety (AFSSET) published a report on "the health impacts of noise generated by wind turbines", commissioned by the Ministries of Health and Environment in June 2006 following the report of the French National Academy of Medicine in March 2006[28]. The AFSSET study recommends that one does not define a fixed minimum distance between wind farms and homes, but rather to model the acoustic impact of the project on a case-by-case basis. One of the conclusions of the AFSSET report is: "The analysis of available data shows: The absence of identified direct health consequences concerning the auditory effects or specific effects usually associated with exposure to low frequencies at high level." ("L'analyse des données disponibles met en évidence: L'absence de conséquences sanitaires directes recensées en ce qui concerne les effets auditifs, ou les effets spécifiques généralement attachés à l'exposition à des basses fréquences à niveau élevé.").

4 FIELD PROGRAM

Two types of utility-scale wind turbines were studied for this field program. These two turbines are among the most commonly used in the NextEra fleet: General Electric (GE) 1.5sle (1.5 MW), and Siemens SWT-2.3-93 (2.3 MW).

Sound levels for these wind turbine generators (WTGs) vary as a function of wind speed from cut-in wind speed to maximum sound level. Cut-in wind speed for the GE 1.5sle wind turbine is 3.5 m/s while the Siemens wind turbine has a cut-in wind speed of 4 m/s. Maximum reference sound power levels for the GE 1.5sle and Siemens 2.3-93 are approximately 104 dB and 105 dB respectively as provided by the manufacturer. These sound power levels are reached at electrical output levels of approximately 924 kW and 1767 kW for the GE and Siemens units, respectively. Under higher wind speeds, the sound levels from the wind turbines do not increase although electrical power output does continue to increase up to the rated power of each wind turbine (1500 kW and 2300 kW respectively).

Each wind turbine manufacturer has an uncertainty factor "K" of 2 dB to guarantee the turbine's sound power level. (K accounts for both measurement variations and production variation[29].) The results presented later in this paper include sound power values which have added the manufacturer's K value to the reference values, that is, 2 dB above the expected reference levels for the measured wind conditions and power output.

Real-world data were collected from operating wind turbines to compare to the low frequency noise guidelines and criteria discussed previously in Sec. 2. These data sets consisted of outdoor measurements at various reference distances, and concurrent indoor/outdoor measurements at residences within the wind farm.

NextEra provided access to the Horse Hollow Wind Farm in Taylor and Nolan Counties, Texas in November 2008 to collect data on the GE 1.5sle and Siemens SWT-2.3-93 wind turbines. The portion of the wind farm used for testing is relatively flat with no significant terrain. The land around the wind turbines is rural and primarily used for agriculture and cattle grazing. The siting of the sound level measurement locations was chosen to minimize local noise sources except the wind turbines and the wind itself. Hub height for these wind turbines is 80 meters above ground level (AGL).

Two of the authors collected sound level and wind speed data over the course of one week under a variety of operational conditions. Weather conditions were dry the entire week with ground level winds ranging from calm to 12.5 m/s (28 mph) over a 1-minute average. In order to minimize confounding factors, the data collection tried to focus on periods of maximum sound levels from

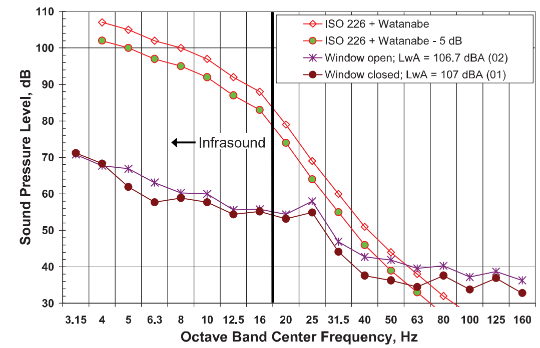

Fig. 6—Siemens SWT-2.3-93 wind turbine indoor sound levels at 323 meters compared to audibility criteria (Home "A").

monitoring location. Representative sound level data from two 10-minute periods are presented herein and include contributions from all wind turbines as measured by the recording equipment. One data set is representative of time periods with low frequency sound level values near the maximum and the other data set is representative of the mean. The standard deviations for the low frequency one-third octave band levels for the twelve measurement periods were between 0.3–1.9 dB with the largest variation in the 10–16 Hz bands and the lowest at 160 Hz. The key operational and meteorological parameters for these two measurement periods are listed in Table 12.

Figure 9 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 305 meters (1,000 feet) from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 31.5–40 Hz may be audible depending on background sound levels.

Figure 10 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was "steady" according to DEFRA procedures, and the results show the low frequency sound meet or are within 1 dB of outdoor equivalent DEFRA disturbance criteria.

Figure 11 compares the one-third octave band sound levels (L_{eq}) for both samples of high output conditions to the Japan Ministry of Environment levels for evaluating complaints on rattle. The rattle criteria is met at all

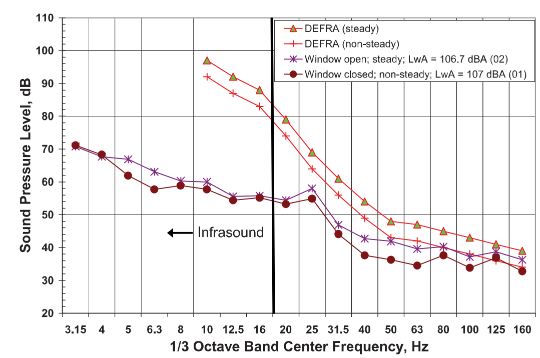

Fig. 7—Siemens SWT-2.3-93 wind turbine indoor sound levels at 323 meters compared to DEFRA criteria (Home "A").

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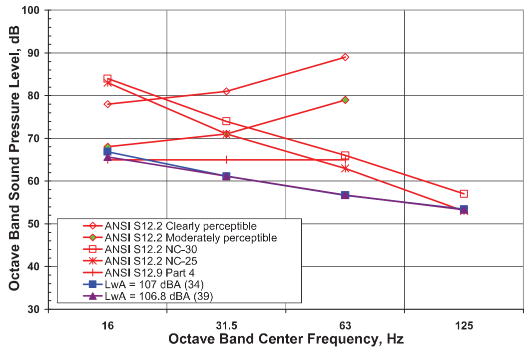

Fig. 5—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to ANSI criteria.

(~9 m/s) which dominated the sound environment. The remaining residence is designated Home "A" and was approximately 323 meters (1,060 feet) from the closest Siemens WTG. The home was near a string of multiple WTGs, four of which were within 610 meters (2,000 feet) of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 11.

The room in Home "A" where interior measurements were made had the following characteristics: approximately 3.6 meters wide (12 feet) by 4.9 meters long (16 feet), no furniture, carpeted flooring, two relatively new double-hung windows (no storm windows), sheetrock interior walls, and clapboard exterior walls. The sound level meter was located in the center of the room.

Figure 6 plots the indoor one-third octave band sound levels (L_{eq}) for Home "A". The results show that infrasound is inaudible to even the most sensitive people approximately 1,000 feet from these wind turbines with

Table 11—Summary of operational parameters—Siemens SWT-2.3-93 (Indoor).

Parameter	Home "A" (closed/open)
Distance to nearest WTG	323 meters
Time of day	07:39-07:49/07:51-08:01
WTG power output	1,884 kW/1564 kW
A-weighted sound power level*	107 dB/106.7 dB
Measured wind speed @ 2 m	3.2 m/s/3.7 m/s
L_{Aeq}	33.8 dB/38.1 dB
L_{A90}	28.1 dB/36.8 dB
L_{Ceq}	54.7 dB/57.1 dB

* Includes K, uncertainty factor of 2 dB

the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at or above 50 Hz may be audible depending on background sound levels.

Figure 7 plots the indoor one-third octave band sound levels (L_{eq}) for Home "A". The low frequency sound was "steady" according to DEFRA procedures under the window open condition, and the results show that all indoor DEFRA disturbance criteria are met.

Although not shown in Fig. 7, the one-third octave band levels meet the Japan Ministry of Environment criteria for evaluating complaints of mental and physical discomfort since in the frequency range of the Japan criteria both samples meet the more stringent DEFRA criteria for "non-steady" sounds, which is more stringent than the Japan criteria.

Figure 8 plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "A". The results show the ANSI/ASA S12.2 low frequency criteria for perceptible vibration were easily met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for bedrooms, classrooms and hospitals were met, the spectrum was balanced, and the criteria for moderately perceptible vibrations in lightweight walls and ceilings were also met.

5.2 GE 1.5sle

5.2.1 Outdoor measurements—GE 1.5sle

Sound level data during twelve 10-minute periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 305 meters (1,000 feet) from the closest GE 1.5sle WTG. This site was actually part of a string of more than 30 WTGs, four of which were within 610 meters (2,000 feet) of the

the wind turbines (moderate to high hub height winds) and light to moderate ground level winds.

Ground level (2 meters AGL) wind speed and direction were measured continuously at one representative location. Wind speeds near hub height were also measured continuously using the permanent meteorological towers maintained by the wind farm.

A series of simultaneous interior and exterior sound level measurements were made at four houses owned by participating landowners within the wind farm. Two sets were made of the GE WTGs, and two sets were made of the Siemens WTGs. Data were collected with both windows open and windows closed. Due to the necessity of coordinating with the homeowners in advance, and reasonable restrictions on time of day to enter their homes, the interior/exterior measurement data sets do not always represent ideal conditions. However, enough data were collected to compare to the criteria and draw conclusions on low frequency noise.

Sound level measurements were also made simultaneously at two reference distances from a string of wind turbines under a variety of wind conditions. Using the manufacturer's sound power level data, calculations of the sound pressure levels as a function of distance in flat terrain were made to aid in deciding where to collect data in the field. Based on this analysis, two distances from the nearest wind turbine were selected—305 meters (1,000 feet) and 457 meters (1,500 feet)—and were then used where possible during the field program. Distances much larger than 457 meters (1,500 feet) were not practical since an adjacent turbine string could then be closer and affect the measurements, or would put the measurements beyond the boundaries of the wind farm property owners. Brief background sound level measurements were conducted several times during the program whereby the Horse Hollow Wind Farm operators were able to shutdown the nearby WTGs for a brief (20 minutes) period. This was done in real time using cell phone communication.

All the sound level measurements described above were attended. One series of unattended overnight measurements was made at two locations for approximately 15 hours to capture a larger data set. One measurement was set up approximately 305 meters (1,000 feet) from a GE 1.5sle WTG and the other was set up approximately 305 meters (1,000 feet) from a Siemens WTG. The location was chosen based on the current wind direction forecast so that the sound level equipment would be downwind for the majority of the monitoring period. By doing this, the program was able to capture periods of strong hub-height winds and moderate to low ground-level winds.

All sound levels were measured using two Norsonic Model Nor140 precision sound analyzers, equipped with a Norsonic-1209 Type 1 Preamplifier, a Norsonic-1225 half-inch microphone and a 7-inch Aco-Pacific untreated foam windscreen Model WS7. The instrumentation meets the "Type 1—Precision" requirements set forth in American National Standards Institute (ANSI) S1.4 for acoustical measuring devices[30]. The microphone was tripod-mounted at a height of 1.5 meters (five feet) above ground. The measurements included simultaneous collection of broadband (A-weighted) and one-third-octave band data (3.15 hertz to 20,000 hertz bands). Sound level data were primarily logged in 10-minute intervals to be consistent with the wind farm's Supervisory Control And Data Acquisition (SCADA) system which provides electrical power output (kW) in 10-minute increments. A few sound level measurements were logged using 20-minute intervals for use in determining home transmission loss values. The meters were calibrated and certified as accurate to standards set by the National Institute of Standards and Technology. These calibrations were conducted by an independent laboratory within the past 12 months. Ground level wind speed and direction were measured with a HOBO H21-002 micro weather station (Onset Computer Corporation). The wind data were sampled every three seconds and logged every one minute.

5 RESULTS AND COMPARISON TO CRITERIA

Results from the field program are organized by wind turbine type. For each wind turbine type, results are presented per location type (outdoor or indoor) with respect to applicable criteria. Results are presented for 305 meters (1,000) feet from the nearest wind turbine. Data were also collected at 457 meters (1,500 feet) from the nearest wind turbine which showed lower sound levels. Therefore, wind turbines that met the criteria at 305 meters also met it at 457 meters. Data were collected under both high turbine output and moderate turbine output conditions (defined as sound power levels 2 or 3 dB less than the maximum sound power levels), and low ground-level wind speeds. The sound level data under the moderate conditions were equivalent to or lower than the high turbine output scenarios, thus confirming the conclusions from the high output cases. None of the operational sound level data were corrected for background noise. A-weighted sound power levels presented in this section (used to describe turbine operation) were estimated from the actual measured power output (kW) of the wind turbines and the sound power levels as a function of wind speed plus an uncertainty factor K of 2 dB.

Outdoor measurements are compared to criteria for audibility, for UK DEFRA disturbance using equivalent outdoor levels, for rattle and annoyance criteria as

Table 10—Summary of operational parameters—Siemens SWT-2.3-93 (Outdoor).

Parameter	Sample #34	Sample #39
Distance to nearest WTG	305 meters	305 meters
Time of day	22:00-22:10	22:50-23:00
WTG power output	1,847 kW	1,608 kW
A-weighted sound power level*	107 dB	106.8 dB
Measured wind speed @ 2 m	3.3 m/s	3.4 m/s
L_{Aeq}	49.4 dB	49.6 dB
L_{A90}	48.4 dB	48.6 dB
L_{Ceq}	63.5 dB	63.2 dB

* Includes K, uncertainty factor of 2 dB

contained in ANSI S12.9/Part 4, for evaluating complaints of rattling using Japan Ministry of Environment guidance, and for perceptible vibration using equivalent outdoor levels from ANSI/ASA S12.2. Indoor measurements are compared to criteria for audibility, for UK DEFRA disturbance, for evaluating complaints of mental and physical discomfort using Japan Ministry of Environment guidance, and for suitability of bedrooms, hospitals and schools and perceptible vibration from ANSI/ASA S12.2.

5.1 Siemens SWT-2.3-93

5.1.1 Outdoor measurements—Siemens SWT-2.3-93

Sound levels during six 10-minute periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 305 meters (1,000 feet) from the closest Siemens WTG. This site was actually part of a string of 15 WTGs, four of which were within 610 meters (2,000 feet) of the monitoring location. Representative sound level data from two 10-minute periods are presented herein and include contributions from all wind turbines as measured by the recording equipment. One data set is representative of time periods with low frequency sound level values near the maximum measured and the other data set is representative of the mean. The standard deviations for the low frequency one-third octave band levels for the six measurement periods were between 0.2–0.7 dB. The key operational and meteorological parameters during these two measurement periods are listed in Table 10.

Figure 2 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 305 meters (1,000 feet) from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound above 40 Hz may be audible depending on background sound levels.

Figure 3 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was "steady" according to DEFRA procedures, and the results show that all outdoor equivalent DEFRA disturbance criteria are met.

Figure 4 compares the one-third octave band sound levels (L_{eq}) for both samples of high output conditions to the Japan Ministry of Environment levels for evaluating complaints on rattle. The rattle criteria is met at all frequencies except at 5 Hz where the mean value is 1 dB (standard deviation of 0.4 dB) higher than the Japanese evaluation value. When one considers that the 5 Hz sound level is 3 dB lower than the observed threshold of rattle, one concludes that the Japanese criteria are met.

The measured outdoor sound levels also meet the outdoor equivalent Japan Ministry of Environment

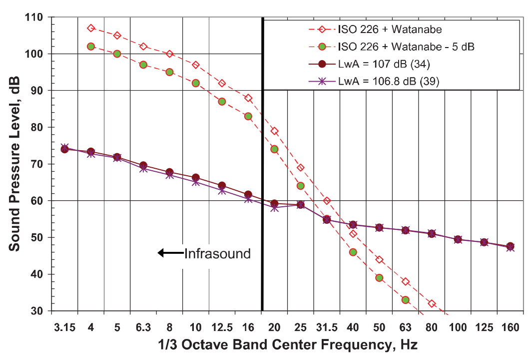

Fig. 2—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to audibility criteria.

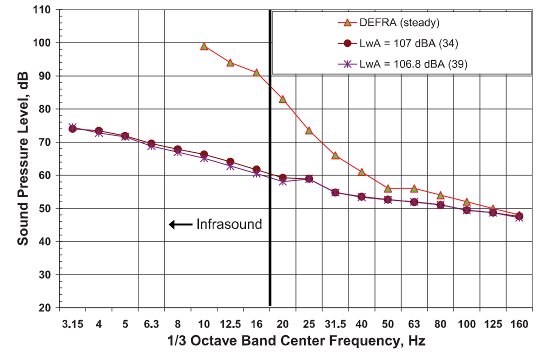

Fig. 3—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to outdoor equivalent DEFRA criteria.

criteria for evaluating complaints of mental and physical discomfort. This comparison is not presented in a figure since these criteria are generally less stringent than the DEFRA criteria.

Figure 5 plots the 16, 31.5, 63, and 125 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. In addition, the results show that all outdoor equivalent ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for bedrooms are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB). The 31.5 and 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4, and the 16 Hz sound level is within 1.5 dB of this level, which is an insignificant increase since the levels were not rapidly fluctuating.

5.1.2 Indoor measurements—Siemens SWT-2.3-93

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from Siemens WTGs. In each house a 10-minute measurement was made in a room facing the wind turbines with a window both open and closed. Results from the testing at one of the homes are not presented due to the very high ground level winds

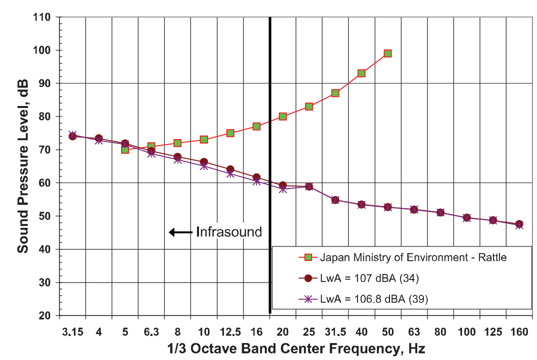

Fig. 4—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to Japan Ministry of Environment rattle criteria.