

**7<sup>th</sup> International Conference**  
**on**  
**Wind Turbine Noise**  
**Rotterdam – 2<sup>nd</sup> to 5<sup>th</sup> May 2017**

**A Rigorous Method of Addressing Wind Turbine Noise**

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**Summary**

A rigorous and repeatable method is proposed to monitor and assess wind turbine noise. The method had to consider that an effective monitoring system must take into account more than just averaging sound power levels over a long term. The method recognizes that humans are bothered by the changes and annoying characteristics that occur, as well as long term averages. Others describe this as the need to determine how the special characteristics of sound quality may impact quality of life. To verify this approach, assessments were conducted using the method at two wind power developments. Use of this rigorous method permitted gathering evidence of the presence of characteristics described as annoying by residents. The evidence produced by this method is clear: the method itself is repeatable and it considers the requirements of a more comprehensive system. In contrast, compliance methods currently in use have not demonstrated the capability of verifying non-conformance of the same wind power developments, even though in one case the monitoring has been in progress for eight years. Use of the proposed method will permit others to gather quality evidence in a similar manner.

**1. Introduction**

Until as late as the 1960's, noise from most any source was considered only as an annoyance. In 1970, though, the perception of noise changed, with the publication by Karl D. Kryter of the seminal work, titled, "*The Effects of Noise on Man.*" Even now, nearly 50 years later, as one reads through Kryter's work, themes often discussed today keep reappearing:

- Masking, Loudness, and Auditory Fatigue
- Equal Loudness Contours
- Perceived Noisiness (Annoyance)
  - Loudness Versus Noisiness
  - Influence of Cognitive Values
- Judged Perceived Noisiness and Perceived Noise Level
- Background Noise in Real Life
- Effective Perceived Noise Level
- Laboratory Versus Field Test Conditions
- Relative Accuracy of Physical Units for Predicting Judged Received Noisiness
- Community Reactions to Noise
- Indoor versus Outdoor Listening – Relative Judgements
- Non-Auditory System Responses to Noise
  - Health
- General Physiological Responses to Noise
  - Stress and Health
  - Sleep and Health
- Effects of Noise on Mental and Motor Performance

Kryter went on in other papers such as, “*Non-Auditory Effects of Environmental Noise*,” published in 1972, to outline a need for a measurement basis other than just direct physical measurements. As he noted, “The most direct, and perhaps most valid, insight into the possible presence and magnitude of stress reactions in general living environments is probably that which has been obtained from attitude surveys and real-life behaviour of people.” The fact that people are reacting is more important than a simple measure. Although Kryter noted that “it appears” people adapt to noise, he acknowledged that, “This conclusion is deduced from a relatively small amount of research and incompletely tested concepts.”

Yet, only 50 years later, a noise source unimagined by Kryter, wind turbines, some nearly 200 metres tall, can be found across the countryside in many countries. Some wind turbines, are located as close as 400 to 500 metres to homes. Yet, the work by Kryter has continued through many who have followed him, such as Klaus Genuit, and André Fiebig, of HEAD acoustics, in Germany, who noted in, “*Psychoacoustics and its Benefit for the Soundscape Approach*,” published in *Acta Acustica United* in 2006, “The increase of complaints about environmental noise shows the unchanged necessity of researching this subject. By relying on sound pressure levels averaged over long time periods and suppressing all aspects of quality, the specific properties of environmental noise situations cannot be identified because annoyance caused by environmental noise has a broader linkage with various acoustical properties such as frequency spectrum, duration, impulsive, tonal and low-frequency components, etc. than only with SPL [Sound Pressure Level]. In many cases these acoustical properties affect the quality of life.”

Others, such as Mathias Basner and Wolfgang Babisch have furthered the work of Kryter at conferences such as the International Conference on the Biological Effects of Noise (ICBEN) publishing works such as:

- “*ICBEN review of research on the biological effects of noise 2011-2014*”, concluding, “These reviews demonstrate that noise is a prevalent and often underestimated threat for both auditory and nonauditory health and that strategies for the prevention of noise and its associated negative health consequences are needed to promote public health,”
- “*Auditory and non-auditory effects of noise on health*,” *Lancet*, 2014
- “*Cardiovascular effects of environmental noise*,” 2014.

Still, the regulation of wind turbines is largely based on simple parameters such as a 40 dBA  $L_{eq}$  limit, often averaged over long time intervals, and aspects of the quality of the sound are largely ignored, such as the difference from the natural environment of this omnipresent source that may be 15 or more dB greater than ambient, and often cyclical or tonal as opposed to random. Compliance protocols have been established in some jurisdictions that are so complex, that today, 10 years after wind arrays commenced operation, it has been impossible to complete reports based on the protocol to show compliance. Meanwhile, the turbines continue to operate, while real-life behavioral changes (as projected by Kryter) are occurring, such as walking away from family homes, leaving them unsold, after complaints to the operator and regulator resulted in no remediation.

Numerous papers, including some by this author, have identified what are dismissed with disdain as “anecdotal reports” of adverse impacts that occurred with the start up of wind turbines in the environment of those impacted. However, there is a solid basis for presenting such lists. It mirrors the approach taken by most medical doctors when a patient first presents himself or herself with a new adverse health complaint. Taking a patient “history” is the way most doctors begin. Similarly, engineers and problem solvers often begin to address a new problem by looking for changes that have occurred. Yet, some maintain there is no proof that the start up of the turbines was the change that caused the impact, even though the conditions

diminish when the person vacates the area, and recur when the person returns. They may attribute it to the stress self-generated by refusing to accept a change. Ignoring those suffering will not result in solving the problem predicted by Kryter of people making real-life behavioral changes. The rigorous method established in this paper permits measuring the physical emissions (noise) from wind turbines, and confirming some aspects of the quality of the noise that are identified as problematic to demonstrate evidence of the cause for the suffering.

## 2. Predicting Noise from a Wind Turbine Array

Wind turbines are licensed on the basis of a predicted sound pressure level that will occur at a receptor after the array is put into service. Part of the rigorous approach in this paper is to be able to duplicate those calculations of predicted sound pressure levels, and to understand some of their limitations. The intent is to describe a method that can be simply replicated without requiring the use of complex computer models. Understanding the problem without having to revert to mystical (and usually expensive) “black box” algorithms that return inexplicable results is the goal. This prediction method is based on the International Standards Organization (ISO) standard 9613-2 “*Acoustics – Attenuation of sound during propagation outdoors. Part 2 – General method of calculation.*” It is not the newest standard used for this purpose, but it is still widely used to generate a first approximation. There are numerous limitations of the code such as:

- It recommends that it be used for distances not over 1000 metres, while we use it to predict attenuation out to 2 or 3 kilometres.
- It assumes a point source of the sound, while for wind turbines, the predominant noise source is in the region of the blade tips, so may follow a locus equal to the rotor diameter, and the distance to the receptor may only be a few (perhaps 3 to 10) times that distance, so the source is certainly not equivalent to a point source.
- The code specifies it is for use with ground based sources such as road or railways so that the distance from the source to the receptor is many times the height of either, while wind turbines with noise emitters up to 200 metres overhead really are not ground based when the distance to receptors may only be a few times the height of the source.
- It only considers frequencies down to 63 Hz, while for wind turbines the low frequencies may be a predominant factor.
- It is based on generally soft ground from the source to the receptor, while in winter, frozen ground conditions, or during inversion conditions over water, the code is limited, particularly when single values of ground attenuation are chosen.

Still, even with these limitations, an estimate based on ISO 9613-2 gives at least a first approximation, and it will be used in this paper.

### 2.1 Determining Distance to Turbines Within Area of Interest

As a general rule, turbines to be considered will be bounded by a circle with a radius not over 5 or 6 times the distance to the closest turbine. Beyond that, the predominating effect of the closest turbine will be so dominant that calculating the effect of more distant turbines is of limited value. The simplest method of determining the distances to applicable wind turbines is to use a scaled ruler on a map showing the turbine locations centred about the point of interest. If more than a few cases will need to be calculated, a template of scaled concentric circles is prepared as shown in Figure 1.

The map might be available from the developer’s public filings, or if that is not readily available, even a printout from “Google Maps” can be used. From the figure it is possible within a few minutes to estimate the distance from point of interest, R145 to all turbines within 3 km as shown in the table below the figure.

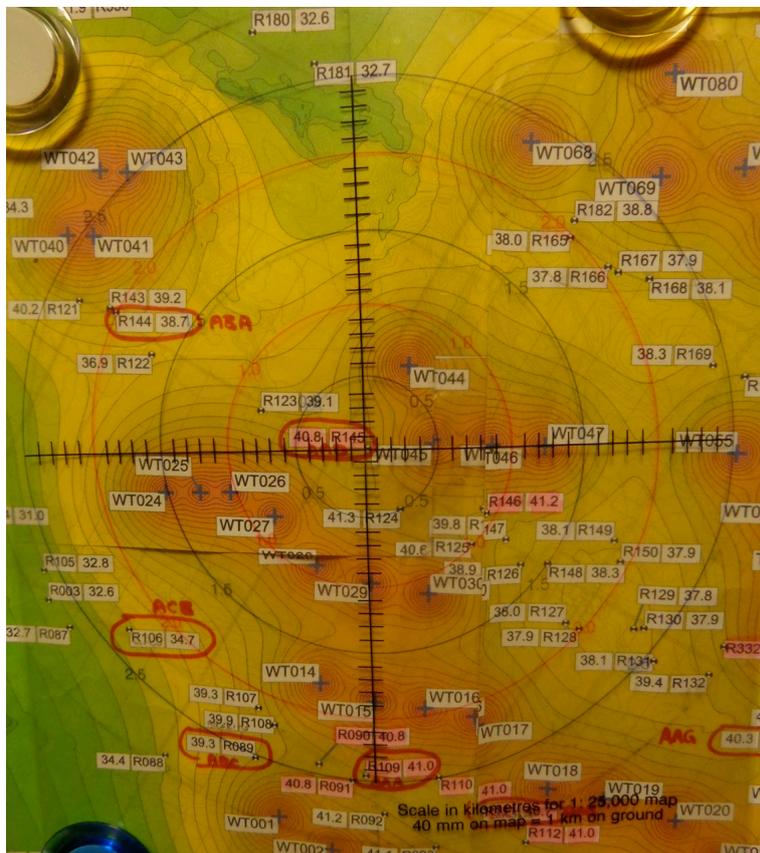


FIGURE 1 – A Simple Map Tool

WT 045 – 460m	WT 044 – 650m		WT 027 – 800m	WT 046 – 850m
WT 028 – 950m	WT 029 – 1000m		WT 030 – 1200m	WT 047 – 1250m
WT 014 – 1800m	WT 015 1900m		WT 016 – 2000m	WT 041 – 2400m
WT 040 – 2600m	WT 043 – 2600m		WT 042 – 2700m	WT017 – 2200m
WT018 – 2800m	WT001 – 2900m		WT055 – 2500m	WT056 – 2900m
WT068 – 2300m	WT 069 – 2600m			

If one wants a more precise set of distances to turbines, (as were used for the calculations in this paper) and listings of the coordinates of each turbine and point of interest are available, either from a developer's documentation, or from a field trip with a hand held GPS unit, then a more rigorous calculation can be performed by calculating the results from:

$$\text{Distance} = \text{Square Root } [ |X \text{ coordinate}_1 - X \text{ coordinate}_2|^2 + |Y \text{ coordinate}_1 - Y \text{ coordinate}_2|^2 ]$$

In this case, the coordinates of R145 and WT 045 are given in the developer's records as:

$$X_R = 459854 \quad Y_R = 4907073$$

$$X_{WT} = 460305 \quad Y_{WT} = 4907113$$

$$\text{Solving, Distance} = \text{Square Root } [ |459854-460305|^2 + |4907073-4907113|^2 ] = 453 \text{ (m)}$$

Accordingly solving for all the turbines identified by the 3000-metre template (rounding up the suggested 6 x closest turbine distance) gives results of:

WT 045 – 453m	WT 044 – 632m		WT 027 – 818 m	WT 046 – 840m
WT 028 – 942m	WT 029 – 988m		WT 030 – 1153m	WT 047 – 1216m
WT 014 – 1771m	WT 015 – 1861m		WT 016 – 1961m	WT 041 – 2532m
WT 040 – 2536m	WT 043 – 2487m		WT 042 – 2626m	WT 017 – 2125m
WT 018 – 2829m	WT 001 – 2881m		WT 055 – 2494m	WT 056 – 2851m
WT 068 – 2263m	WT 069 – 2601m			





### 3. Measuring the Actual Noise Levels

The brief overview of potential influences on the turbine Sound Power Level, and propagation, lead to the need to conduct measurements to determine if the actual measurements match the predictions. We will discuss the key parameters of a basic measurement system.

#### 3.1 System Requirements

Measuring sound pressure levels with a sound level meter is really not adequate to be able to determine annoyance. A calibrated recording system is critical to be able to determine the quality characteristics of the sound, and to select time segments for analysis that are free from extraneous influences such as vehicles, wildlife, humans, and environmental conditions of rain or heavy wind. In reality it is not difficult to listen to recordings and to select relatively “clean” sound signatures of the desired parameter independent of extraneous influences.

This paper will describe one possible system. There is no claim made that this is the “only” manner of doing the job, nor should the mention of any particular manufacturer be considered as an exclusive endorsement. It is simply that this works for us, and outlines some of the specifications to consider in setting up a wind turbine recording system.

Characteristics of the recording system used:

- Microphone – a good quality, omnidirectional microphone with a wide frequency band, and a relatively low noise floor. Typical measurement microphones are condenser type, which require some sort of power supply for polarization. Systems used to prepare this report include:
  - ACO Pacific 7046 free field microphone capsule with 4012 companion preamp, and PS9200 9V battery operated external power supply for 200V polarization.
    - Frequency response  $\pm 2$  dB 3 Hz to 20 kHz
    - Sensitivity 50 mV/Pa
    - Noise Floor 10 – 12 dBA
  - Earthworks M30BX omnidirectional measurement microphone, with internal 6 V battery for polarization
    - Frequency response specification 9 Hz to 30 kHz  $+1/-3$ dB (although observed to be wider)
    - Sensitivity 30 mV/Pa
    - Noise Floor 22 dBA equivalent



Figure 4 – Microphone Wind Screen and Mounting  
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## Primary and Secondary windscreen

- Outdoor measurements typically require a primary and secondary windscreen to reduce the effects of ambient breezes passing over the microphone capsule
- For us, the Ontario wind turbine measurement protocol requires use of a 90 mm primary windscreen and a concentric 450 mm secondary windscreen. The secondary one we use has 25 mm of reticulated open cell foam, with 8 pores per 10 mm. It is fabricated from two 16 inch (40.6mm) diameter open wire metal flower baskets, with a cylindrical 16 inch (40.6mm) central open mesh section to produce an oblong wind screen suitable to enable the microphone with its primary windscreen used to have the cartridge at the centre of the outer wind screen.

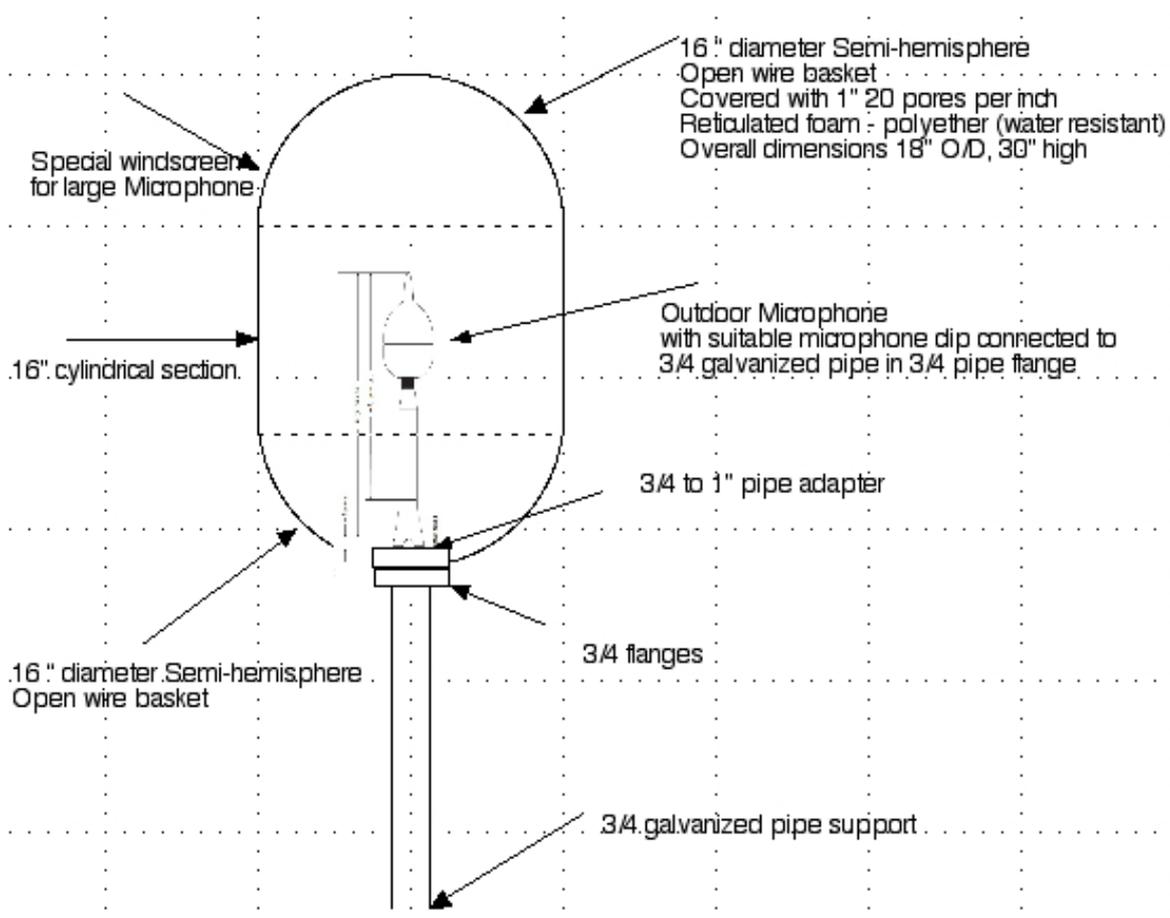


Figure 5 – Schematic of Secondary Windscreener

## • USB Digitizer

- We use a M-Audio Fast Track Audio Interface
  - Accepts two microphone inputs (to enable simultaneous indoor and outdoor measurements to be conducted).
  - Can supply phantom power to microphones if required, but we avoid this by using the microphones with integral battery power supplies.
  - Up to 24 bit, 48 kHz operation (but generally used at the standard 44.1 kHz sampling frequency).
  - The interface can be powered from the USB bus of the computer it is plugged into, or in the case of some models from an external power supply. In our usage, we have found that the newer "Fast Track Pro" models of the interface are prone to AC contamination that generates 60 Hz and harmonic contamination of the produced digital signal if the

computer that the interface is connected to by the USB bus is plugged into AC power, while the older first and second generation Fast Track interfaces ones were not prone to AC contamination.

- Recording Software
  - We've had good success using Audacity for the Macintosh. For a free software application, it is very versatile, and permits separation of a two track "stereo" recording (as generated when making a simultaneous indoor and outdoor recording) into separate "monaural" tracks for individual calibration and processing.
- Recording Platform
  - Here we are using an antique Macintosh iBook G4 computer, to run Audacity. It gives us about 6 to 8 hours of "unplugged" recording capability, remote from "mains" power. Could we upgrade? Certainly, but we are also of the opinion that "if it works and it isn't broke, don't fix it." Consistent use of the same system eliminates a source of concern for change when comparing two sets of results. We've also used newer models of the Macintosh. No doubt "that other platform" might also be used, but we cannot comment.
- Signal Processing Software
  - Audacity by itself will meet most of the user's needs for signal processing. The Audacity program permits saving files in .wav format, for later processing, and permits doing Fast Fourier Transform (FFT) analysis. This breaks the signal into equal slices of frequency width, which permits identification of special frequency concerns such as tonality. Audacity also provides a signal generator to generate noise (white, pink, or Brownian), or tones (of various nature). With a bit of effort, simultaneous signals can be overlaid to produce a multi-featured signal that can replicate measured conditions for controllable listening tests. A "Poster" presentation will be used at the conference to demonstrate some of these replica signals for an audio "jury" listening test, but they will not be part of the conference presentation which will focus on the assessment method, and evaluation of the results it generated.
  - An alternative versatile audio signal-processing program used is the Faber Acoustics Electroacoustics Toolbox. An especially convenient feature it has is to enable calibrator traces to be input so that all subsequent recordings from the same recording campaign are automatically recorded in a calibrated manner.
- Calibrator
  - You will require a 1000Hz calibrator to calibrate your microphone system before and after each set of recordings (between set up and teardown).
  - We use a Lutron Model SC-941 sound calibrator that generates a 94 dB 1000 Hz signal in compliance with an ISO-9001 quality management system.
  - It must be periodically tested against a traceable national standard.

### **3.2 Conducting Measurements at K2 Wind Power Development**

Ontario presents perhaps a unique situation for wind turbine transient monitoring. The Ontario electrical grid has typical daily demands ranging from 12,000 to 15,000 MW at night, and from 18,000 to 22,000 MW in the daytime. The typical contributors to that Ontario electrical grid are from 10,000 to 12,000 MW of base load nuclear, 3000 to 7000 MW of hydraulic generation, and 1000 to 7000 MW of natural gas fired generation. On top of that "dispatchable generation" (can be called on to increase or decrease generation on demand), Ontario has installed some 6,800 MW of "variable generation" (4,600 MW of wind generators and 2,200 MW of solar) that

generate depending on the availability of their natural resource. Often, when the wind blows best, as it is wont to do when the system load is smaller than the baseload generation, the Ontario Independent System Operator has the authority to “curtail” wind generators (stop accepting wind generation, while they are still being paid as if generating). The result is a common occurrence of having wind power on and off at short notice. Figure 6 is a typical output chart for the K2 wind power development for 5 days in January 2017 showing many occasions when the turbine output changed even though the monitoring system shows it was capable of (and paid for) higher outputs. The chart is generated from data of the Ontario Independent Electrical System Operator with “capability” provided by specially installed wind test towers at the wind power development, and “output” from the revenue metering system. The chart shows the values for the average condition for the hour preceding and not the actual hour ending value.

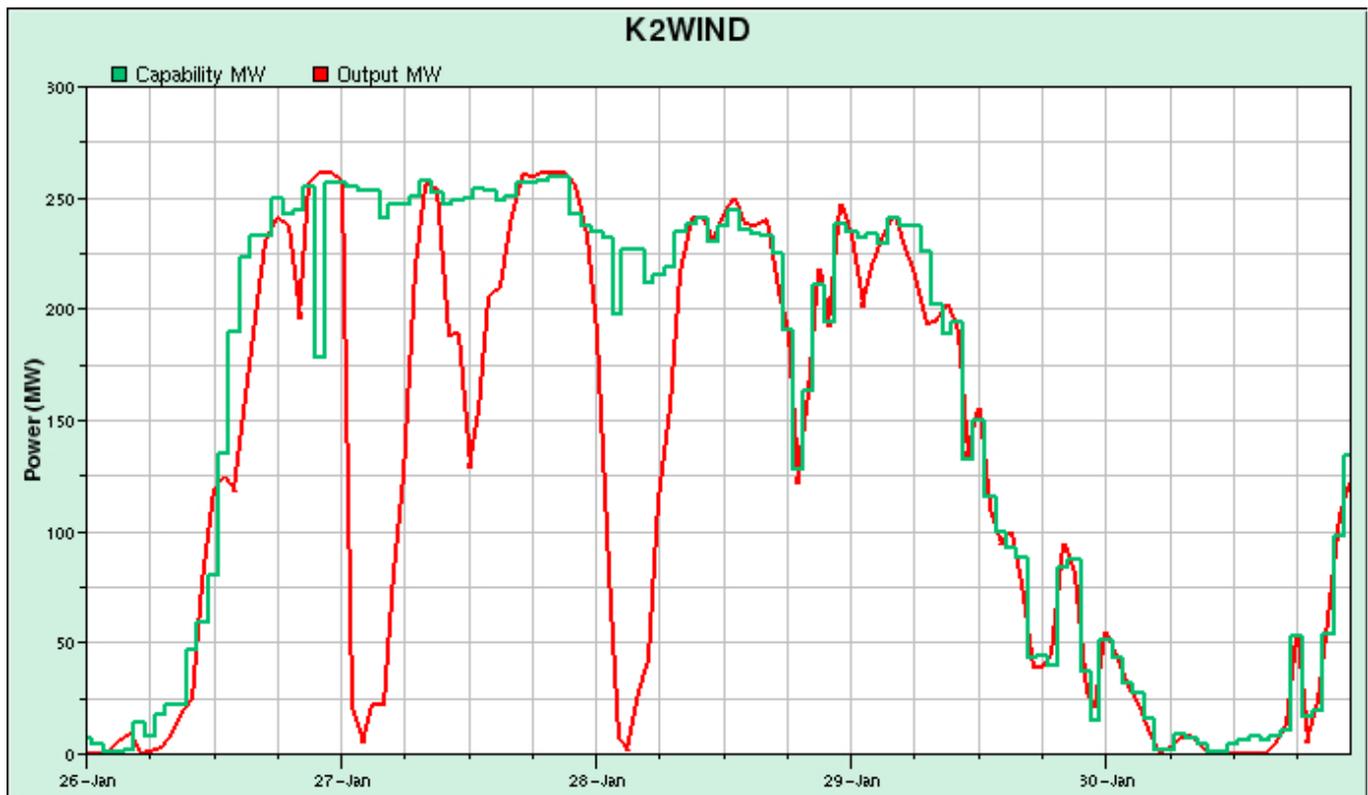


FIGURE 6 – K2 Wind Capability and Output January 26 to 30, 2017

As a result there are lots of opportunities to carry out monitoring as turbines go from intermediate or high power to low power even though the wind conditions may be relatively unchanged.

A family who live in this K2 Wind power development, presented to the Multi-Municipal Wind Turbine Working Group, comprised of elected and municipally appointed citizen representatives from about 14 municipalities in Bruce, Grey, and Huron Counties. It tries to address citizen issues related to wind project operation. The residents reported these turbines to be tonal, emitting a “sickening” sound, ever since operation started about a year ago. “We have complained to the operator and the regulator, and nothing has improved. Anything you can do to help,” they asked, “would be appreciated.”

The working group visited their home, and found that the Ministry of the Environment and Climate Change had installed a short term monitoring station at the home for 9 days. The residents could press a button when they believed the turbines were problematic to start a 10-minute recording for later analysis by the MOECC staff. The residents were also asked to make

recordings of times when the turbines were not problematic, and any comment they had at the time any recording was initiated. At the end of the monitoring period, the Ministry staff provided the residents with a USB stick containing the twenty-seven 10 minute recording files as .wav documents (twenty-five initiated by the residents plus the initial and final test initiated by the Ministry staff). The Ministry reported that it could find no problems with the turbines. In the majority of the cases (19 of the 25 initiated by the residents) the staff reported that no assessment of the data could be made as the recording also showed indications of wind in trees, or wildlife. The Ministry staff found the turbines were compliant in the 6 cases they did evaluate. The Ministry report identified their assessment of the dBA rating for each recording, and the Ministry comments. Looking at the Ministry report and listening to the sound files provided some interesting insights when preparing this paper, as shown in Figure 7.

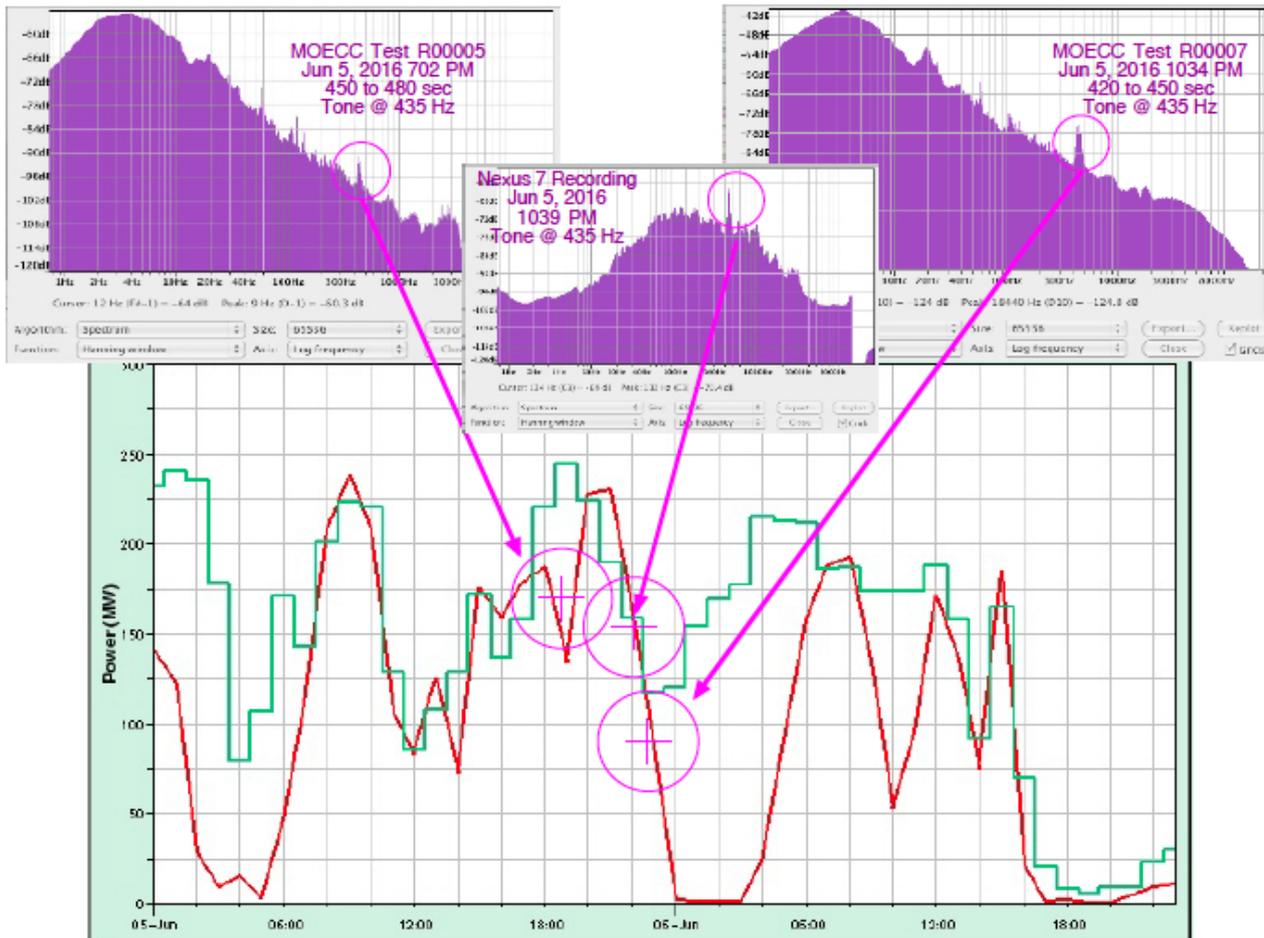


FIGURE 7 – Initial Assessment of Recordings and Turbine Output for June 5

The problematic periods seemed to be occurring as the turbines were curtailed, and the FFT charts generated by Audacity from the Ministry recordings for this initial look certainly seemed to show indicators of tonality at about 450 Hz that matched listening to the recordings. This tonality did not correlate to either tree noise or wildlife, as proven by generating a broad tonal test signal centred at 450 Hz as shown in the FFT of the sound sample and doing a listening test of that test tone. The residents provided an additional recording done on a hand held Nexus 7 tablet. While not of measurement protocol standards, it too revealed a very obvious tonal character.

Monitoring was set up by the author at this home, making simultaneous recordings indoor (in a vacant bedroom using the ACO Pacific microphone) and outdoor (using the Earthworks microphone) connected to the recording system described previously.

The wind power development capability and output for K2 Wind for one of the monitoring periods on Nov 10 and 11 is shown in Figure 8.

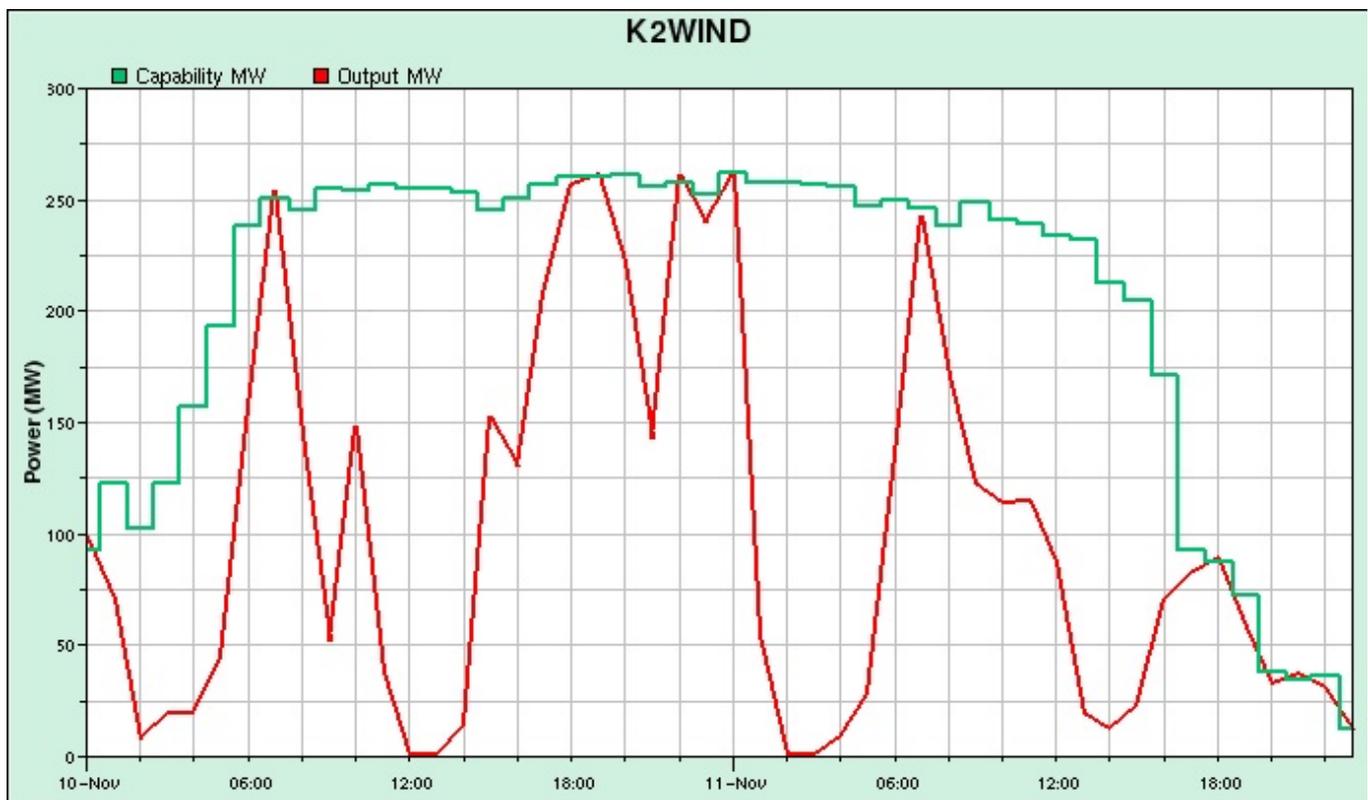


Figure 8 – K2 Wind Output and Capability on Nov 10 & 11, 2016

Evaluation of the outdoor recordings, considering the extremes of high power operation (at full output of 262 MW) and curtailed operation (when generating 21 MW while capable of 262 MW) produced the FFT shown in Figure 9.

While the sound pressure level was higher during the high power operation; when the turbines were curtailed, a very clear tonal peak centred about 450 Hz was seen. This tonal peak was about 10 dB in magnitude above the baseline sound present at the time and would be clearly noticeable. (The author personally observed it at times during the monitoring period.)

Then, attention was turned to compare the conditions indoors and outdoors for the same times, as shown in Figure 10.

The most obvious observation was that while the higher frequencies are attenuated when passing through the house walls (this is a well insulated house with thermal windows), the low frequencies below about 100 Hz are nearly as high as outdoors, and the indoor sound FFT shows much more “roughness” with variation in the order of 10 dB at frequencies about 200 Hz, and at lower frequencies. This was similar to the observations made previously by the author and presented to the Acoustical Society of America at the ASA 168<sup>th</sup> meeting in Indianapolis, titled, “Room modes – a predictor of wind turbine annoyance.” That paper arose after a study at a different home in another wind power development with a different turbine type showed that in rooms where annoyance was felt, the frequencies flagged by room mode calculations and the low frequency spikes observed from the wind turbine measurements coincided.

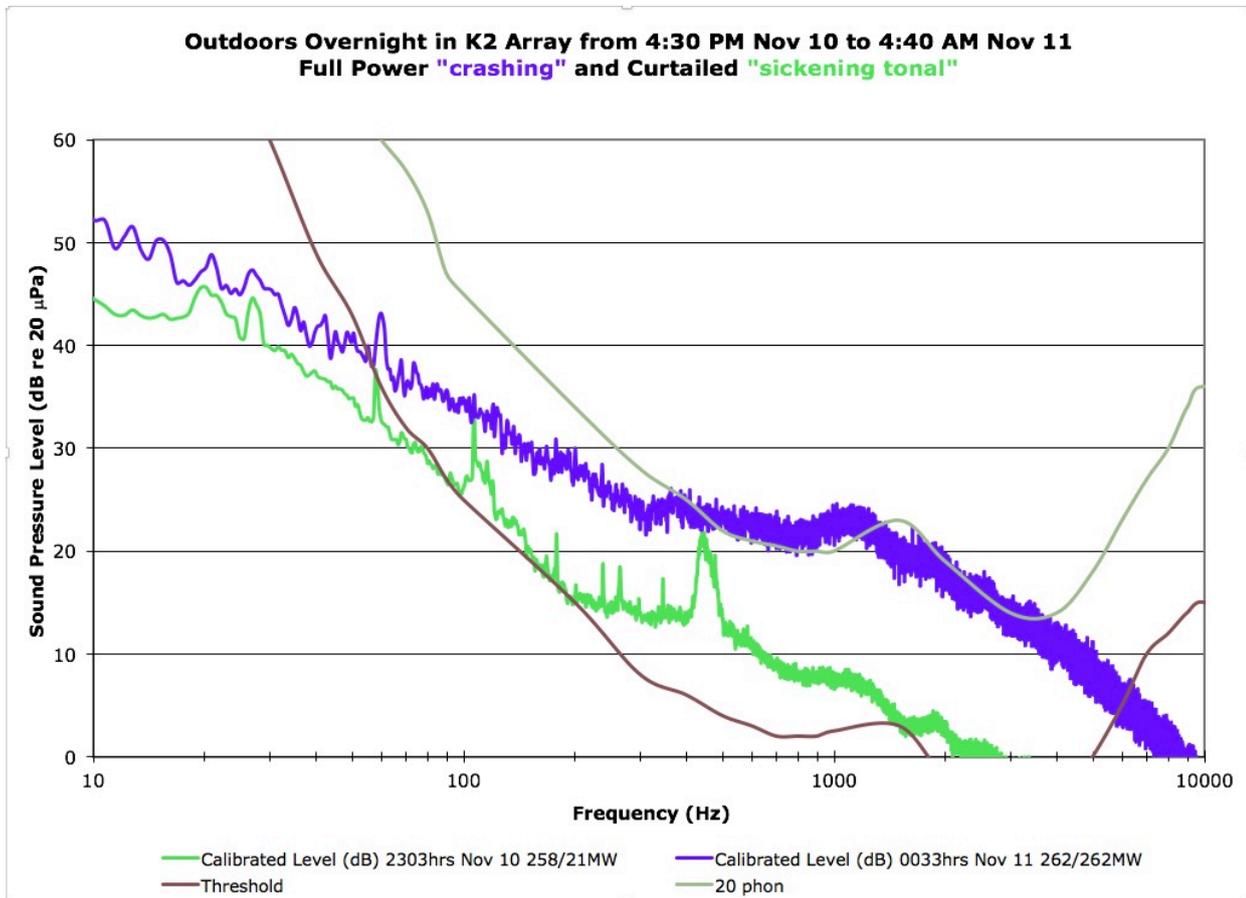


FIGURE 9 – Outdoors Overnight in K2 array

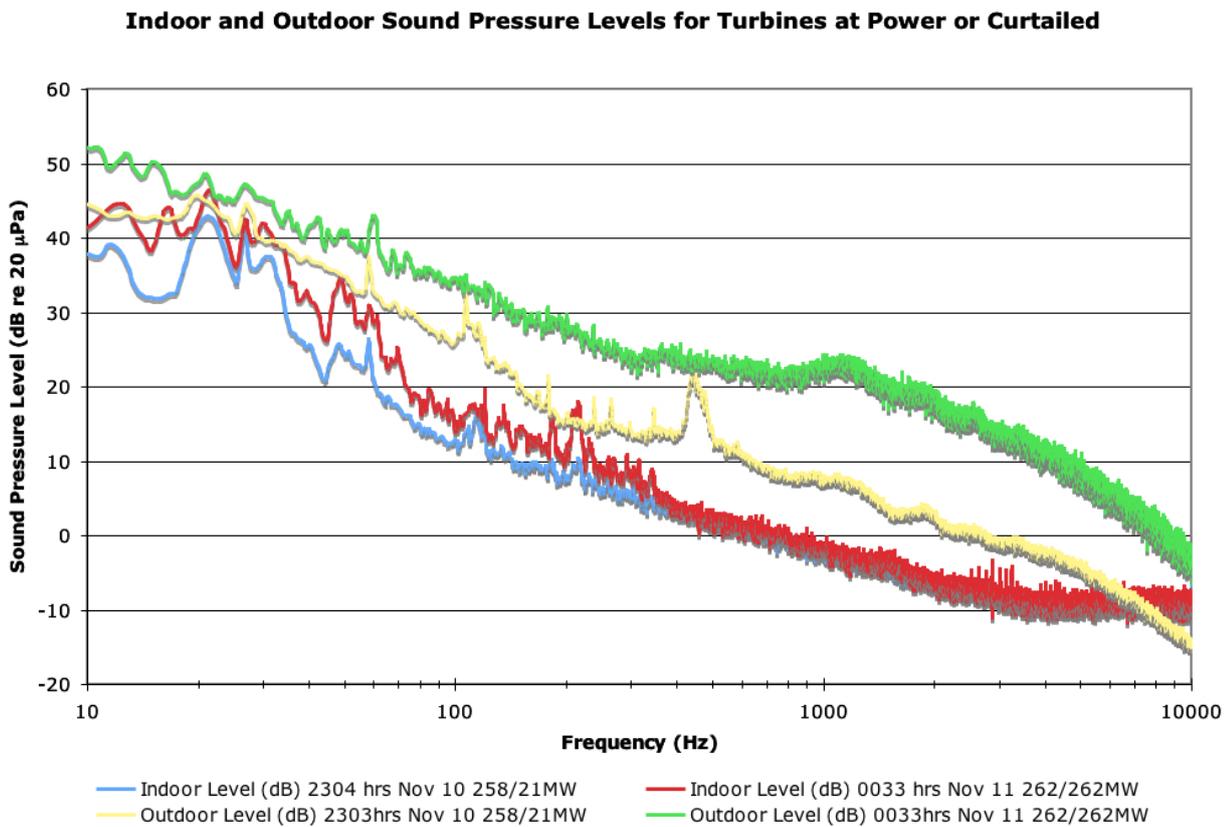


FIGURE 10 – Indoor and Outdoor Comparisons at the Same Times in K2 Array

Carrying out a more in depth analysis of the Ministry of the Environment and Climate Change provided sound samples from June 7 to 11 permitted more observations to be made. Figure 11 shows the K2 Wind Capacity and Output for June 11 and 12.

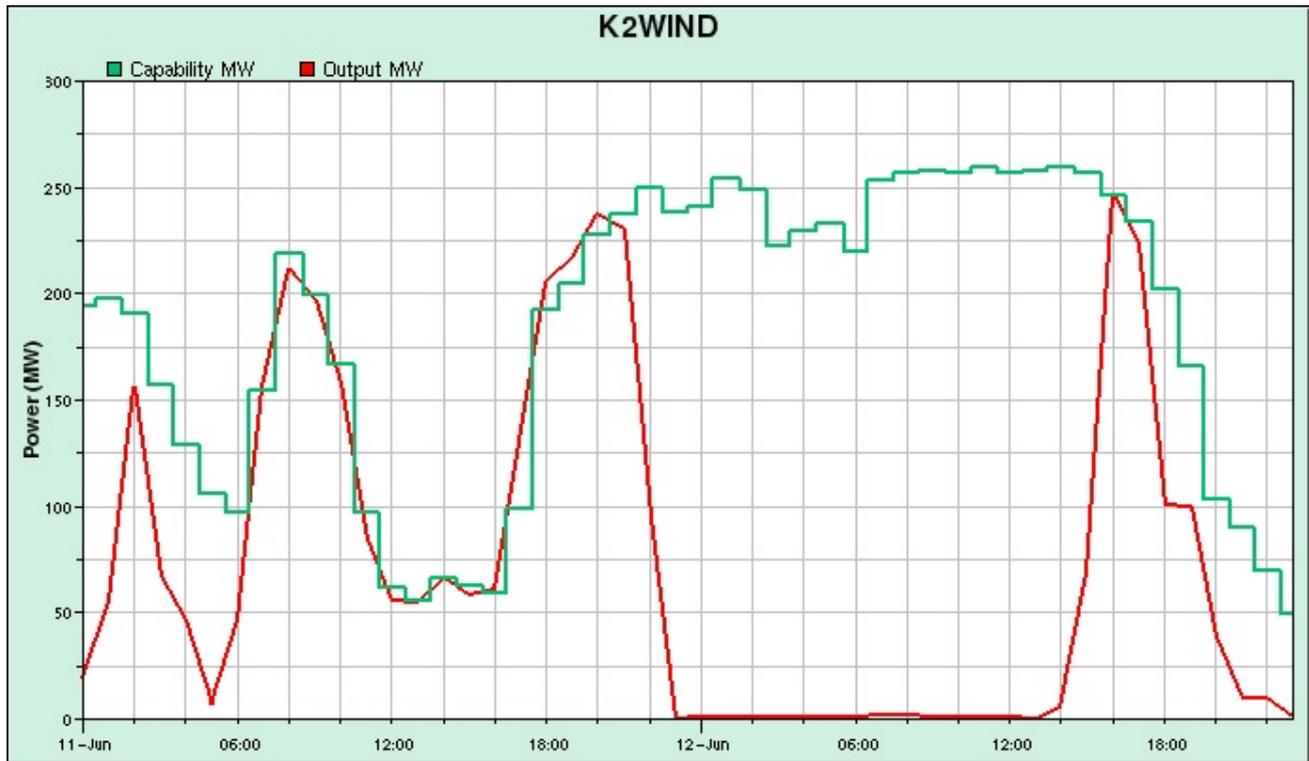


FIGURE 11 – K2 Wind Capacity and Output for June 11 & 12

Although the Ministry did not provide calibration files for their sound recordings they did provide in their report their assessment of the sound pressure level for each sample. Using the Electroacoustics Toolbox, and working backwards to set the given sound pressure level for a number of the recordings provided as the calibration level, permitted a “Quasi Calibration” of the Ministry data, and from that a calibrated FFT analysis was made. The result of that analysis is presented in Figure 12.

Again, it was seen that when the residents described adverse effects in their comments filed with their initiation of recordings, FFT analysis of the sound recordings taken at those times clearly show a tonal condition occurring at about 450 Hz. Reference to the Output curve in Figure 11, shows that the tonality occurred just before the turbine output was curtailed. As noted earlier, the output curves derived from the Independent Electricity System Operator give the average output for the hour preceding each hourly data point, and do not necessarily show the exact time of the change. However, it was clear that the tonal condition again corresponded to the onset of curtailment.

In Figures 9 and 12, the traces representing the “Threshold of Audibility” from ISO 226:2003 and the associated “20 phon” threshold have been included as an indicator that the sound pressure levels seen were well above the thresholds. However, adding data from another source to a chart of FFT results presents a problem. As one who has experience with FFTs can testify, the value shown on an FFT chart is not as important as the indication of frequencies they give. In fact, as FFT’s are prepared with larger sample sizes (of smaller width) the frequency resolution improves, but the indicated sound pressure level falls. This is shown in Figure 13.

**Quasi Cal MOECC Data June 7 to 11**  
**Focusing on Audibility of 145Hz Tonality**

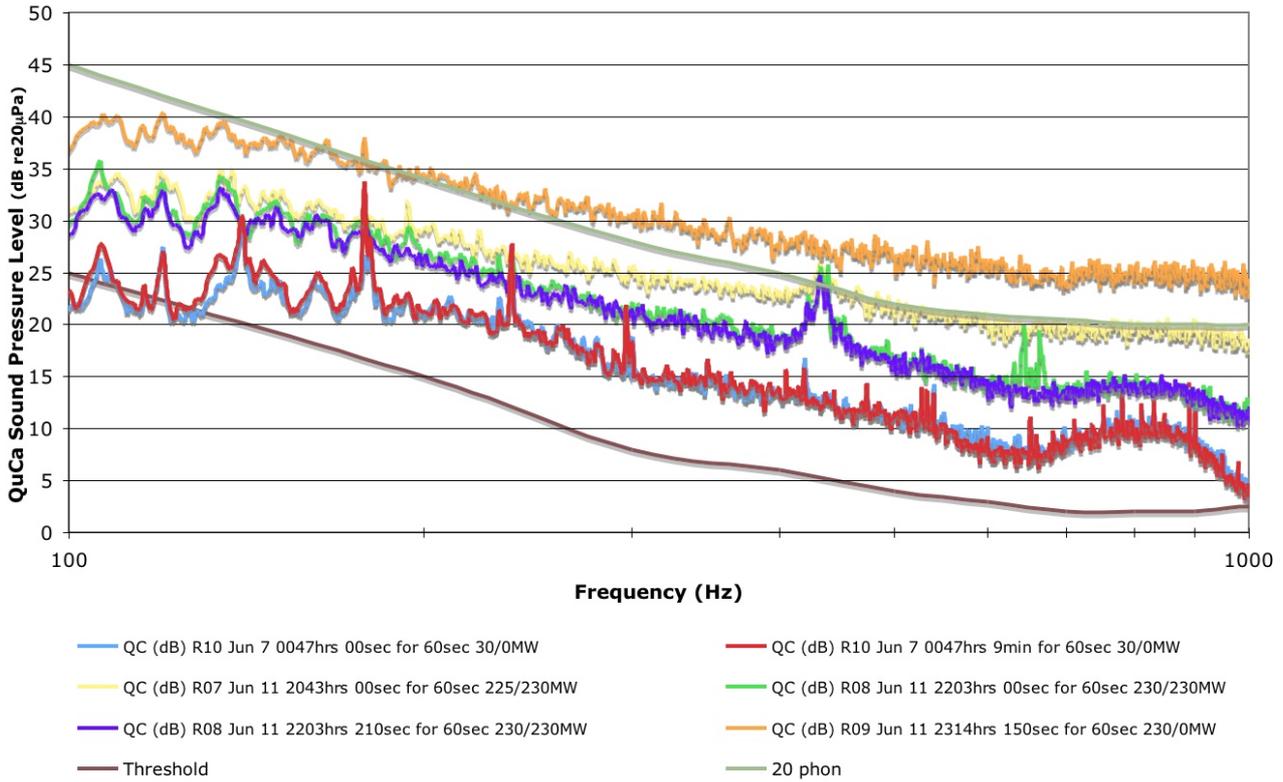


FIGURE 12 – Quasi-Calibrated MOECC Data for June 7 through 11

**The "Cost" of Increasing Sample Number in FFTs**

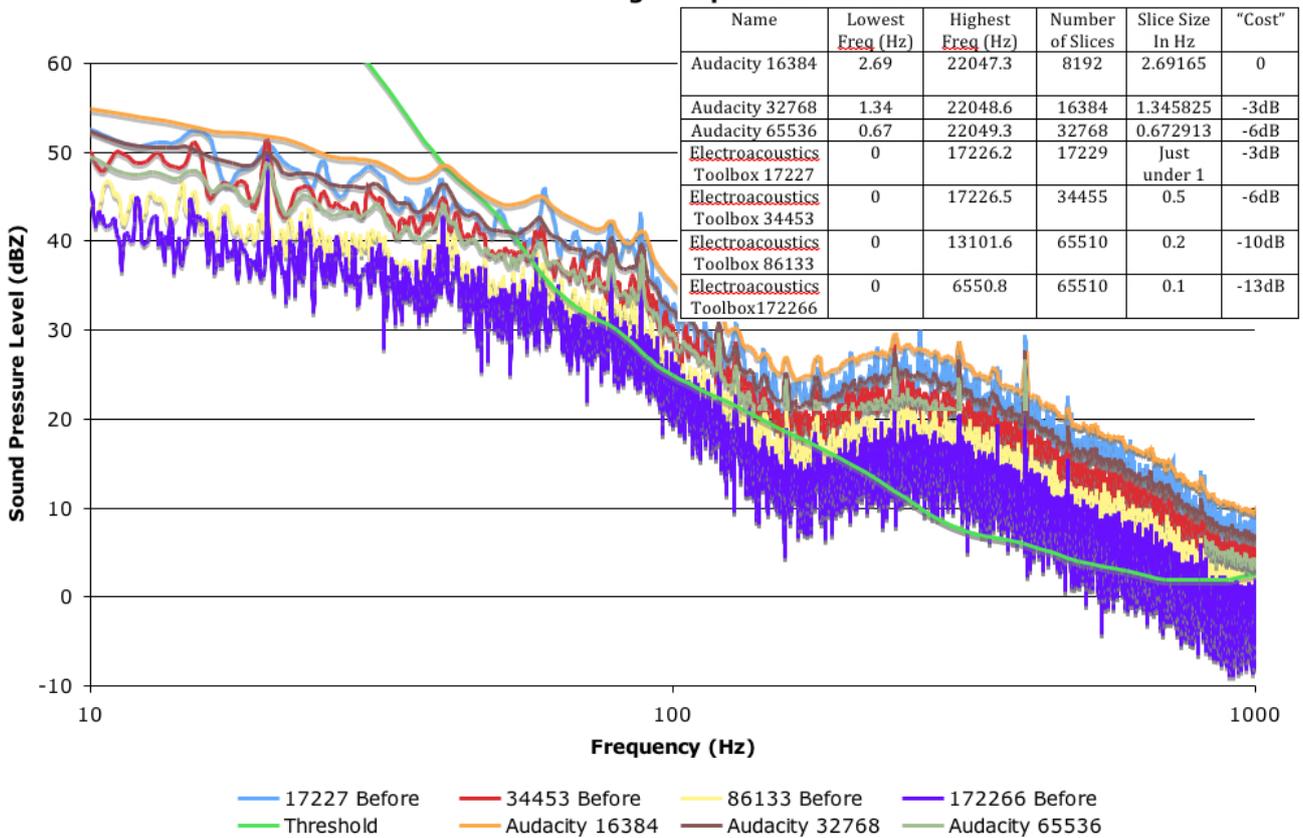


FIGURE 13 – A Caution When Plotting FFTs

Figure 13 would seem at first glance to show that the 7 traces displayed must show very different sound samples, as some are well below the Threshold of Audibility while others are well above it. Yet, the FFT's were prepared for exactly the same sound sample.

Four of the seven FFTs of the same sample were performed by the Electroacoustics Toolbox and three by Audacity, with different sample sizes. A table on Figure 13 shows the “cost” of increasing the number of samples. As an example, doubling the number of samples results in decreasing the indicated Sound Pressure Level by about 3 dB. In fact the chart shows that over the different FFT's, there is a reduction in the indicated Sound Pressure Level of about 13 dB.

The caution here is that displaying the “Threshold of Audibility” on a FFT display may not be an accurate determination of whether a sound is audible or not. The FFT's in this report were prepared generally using the Audacity tool, with 65,536 sample lines, for a sample slice width of 0.69 Hz. This presents an indicated Sound Pressure Level some 6 dB below the first tool in the list, which uses 16,384 sample lines, for a sample slice width of 2.69 Hz. Thus, showing the “Threshold of Audibility” trace might be misleading, as for example in this case, the sample was very definitely audible as it showed the case of all turbines in an array in service surrounding a home only 453 m from the nearest turbine. Yet, the 65,536 Audacity sample shows that the indicated Sound Pressure Level was only slightly above the Threshold of Audibility. The Sound Pressure Level presented on an FFT can only be considered as an indication for comparison purposes, while the strength of an FFT is showing frequency specifics such as tonality.

### 3.3 Conducting Measurements at the Underwood Wind Power Development

Measurements made on November 7 & 8, 2016 will be used as an example. On these days, the wind turbine output and capability is shown in Figure 14.

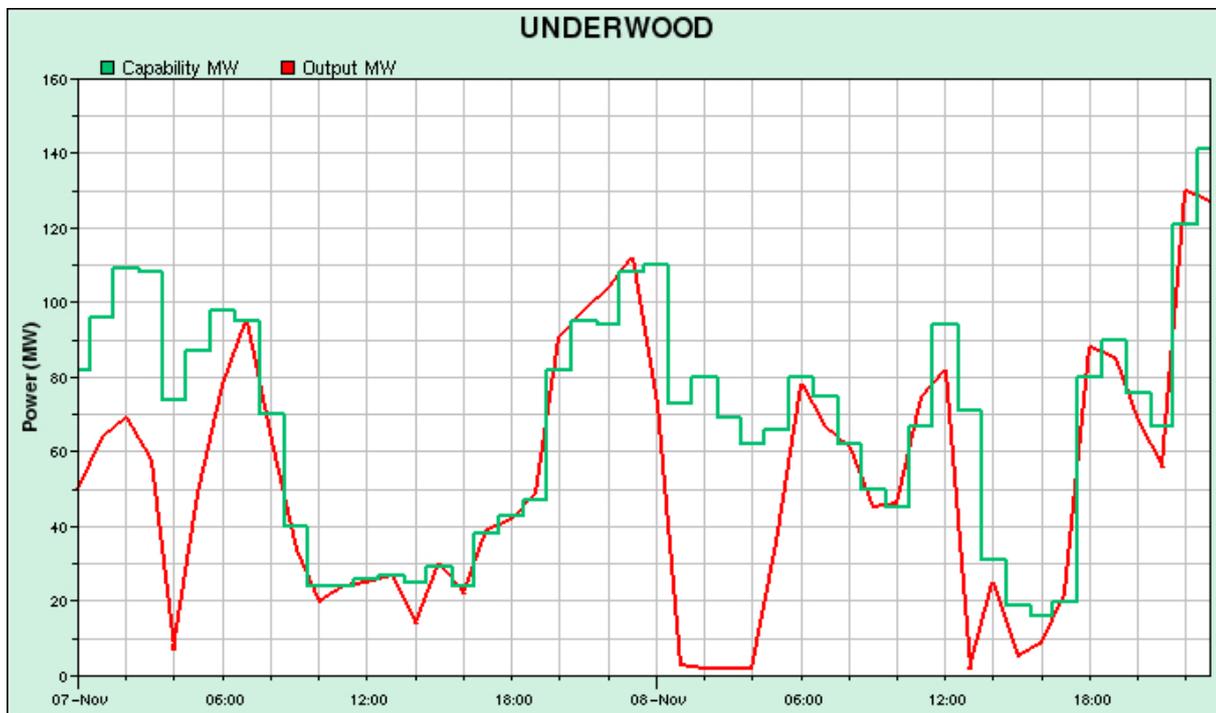


FIGURE 14 – Underwood Wind Power Development Output and Capability Nov 7 & 8

The figure shows that near midnight on Nov. 7, the turbines changed from about 110 MW to near zero. In fact, what physical presence in the field conducting monitoring showed was that the turbines continued at an unchanged power level until about 0030 hours on Nov 8, when the turbines were heard to stop quickly, with a very abrupt transient as all turbines in the array

received a stop signal. Monitoring was carried out outdoors at 4 sites soon before the turbines were shut down, at one of the 4 sites during the transient, and soon after at all 4 sites again.

**Impact of Curtailing Wind Turbines on Sound at Test Site 1**

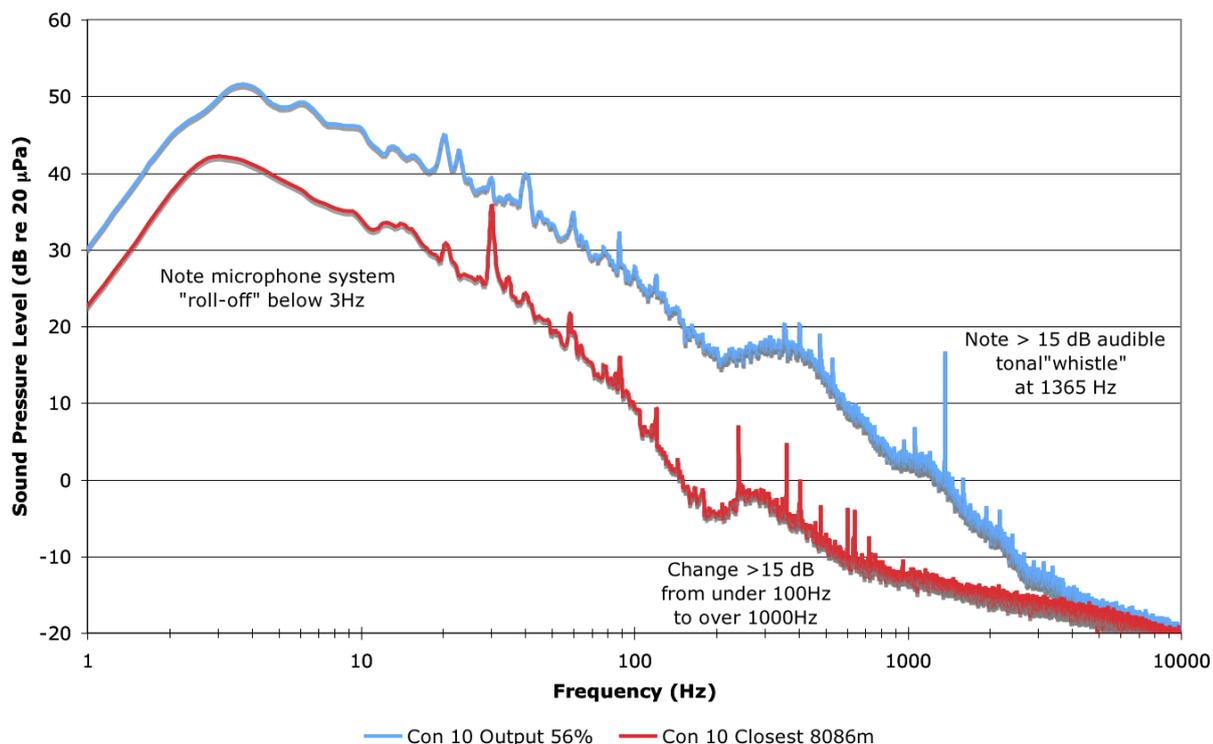


FIGURE 15 – Impact of Curtailing Wind Turbines on Sound at Test Site 1

The FFTs of the Sound Pressure Levels before and after the turbine operation was curtailed, at the first site on Bruce Concession 10, a roadway with little nighttime traffic, are shown in Figure 15. The Figure shows the microphone “roll-off” below 3 Hz, that there was a change of about 15 dB from under 100 Hz to over 1000 Hz with the wind turbines shut down, and that when the turbines were operating, the FFT shows a very clear tonal “whistle” at about 1365 Hz indicated as 17 dB higher than the Sound Pressure Levels at frequencies just below and just above the tonal condition.

A premise of the Ministry of the Environment and Climate Change wind turbine monitoring protocol is that monitoring to show compliance must be conducted over a long period. The protocol requires the initial acoustic monitoring by residents to produce at least a 10-minute sample for each complaint period, and the final compliance protocol requires a minimum of 120 one-minute measurement intervals for each integer of wind speed. During each of those one-minute intervals there must be no changes in wind speed or direction. A further 60 samples are required for each integer wind speed with the turbines not operational. So far data collection has taken years to obtain a sufficient number of samples, and in at least one array, initial reports showed that over 90% of samples taken were discarded as non-compliant. All samples are logarithmically combined to determine the Leq produced by the facility, which eliminates any short-term change effects. This appears to be precisely the sort of monitoring that was cautioned against by Genuit and Fiebig described in Section 1 when they noted, “By relying on sound pressure levels averaged over long time periods and suppressing all aspects of quality, the specific properties of environmental noise situations cannot be identified, because annoyance caused by environmental noise has a broader linkage with various acoustical properties such as frequency spectrum, duration, impulsive, tonal and low-frequency components, etc. than only with SPL [Sound Pressure Level]. In many cases these acoustical

properties affect the quality of life.” The annoyance aspects that impact the quality of life of impacted residents are not being assessed.

For this facility as an example, where the turbines first went into operation in November 2008, and citizen complaints occurred soon after, it has not yet been possible to complete a report to demonstrate compliance. The monitoring is still in progress, over 8 years later, with the turbines continuing in operation, and residents continuing to complain. The hypothesis is that individual samples are not representative due to variation. As a test of this hypothesis, two test samples were taken in the first minute of a 3-minute monitoring sample and in the last minute of the 3-minute test record, and the FFTs were compared to see if there was indeed any correspondence. The two traces for this first location are shown in Figure 16. They would appear to be very nearly identical, and the differences would not be adequate to dismiss either one as unrepresentative. Similar compliance was seen at another site when tested. The rigorous testing method described in this paper is showing indications of some of the special acoustical properties that are affecting the quality of life, as the testing method independently verifies that the conditions described by residents do indeed exist.

**Case 1 - Comparing 60 second sound samples separated by 60 seconds**

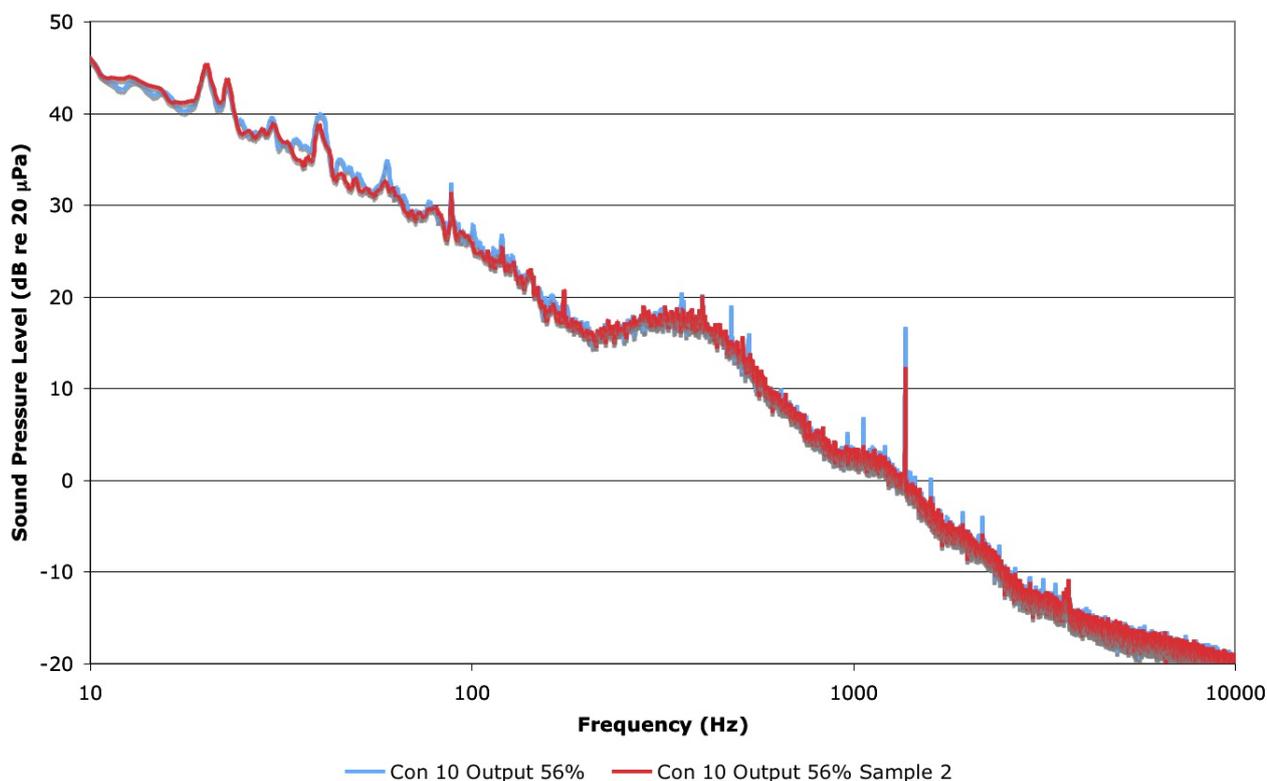
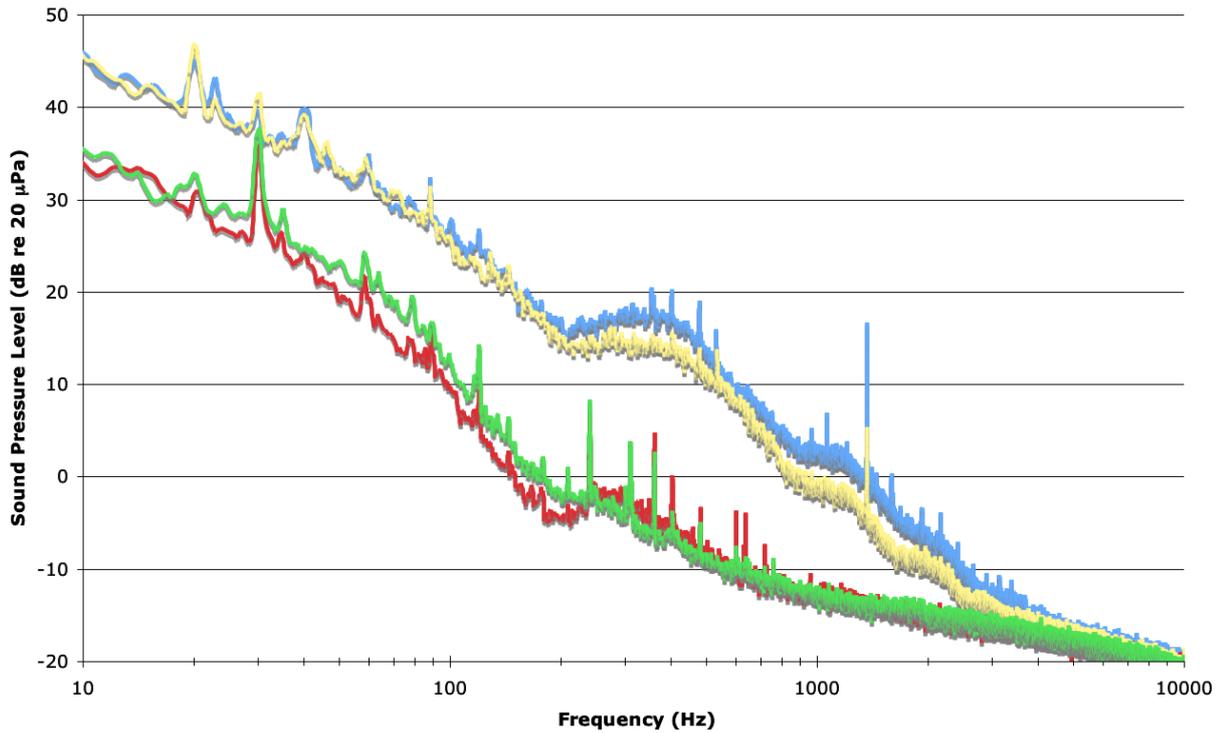


Figure 16 – Comparing Two Samples at First Monitoring Site shows Remarkable Correlation.

Figure 17 shows the comparison between the first two test sites, which are separated by about 1.5 km, for the case of the readings with the turbines in service and the turbines shut down. The samples at each location are separated by some 30 minutes, yet still show a very similar pattern. The troubling conditions are not only localized to one turbine, but are distributed through the array with minor variation in amplitude.

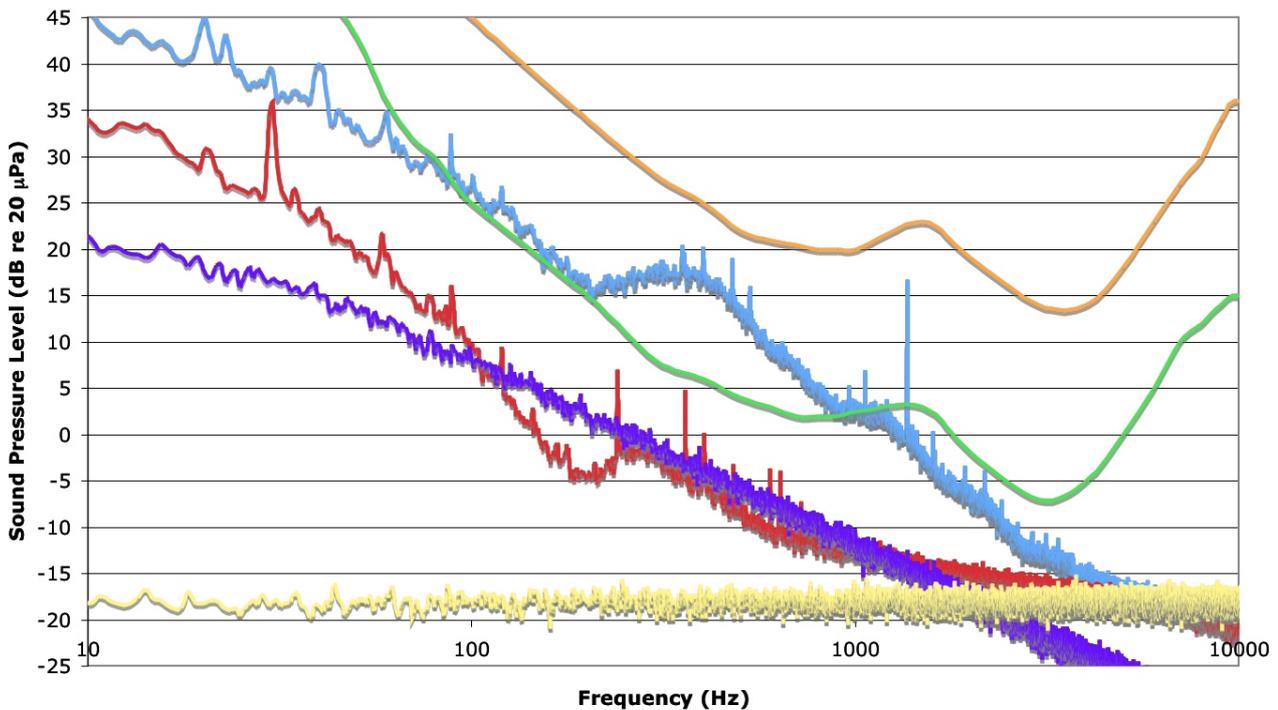
**Impact of Turbines on Audibility and Annoyance  
Note Similarity of Pattern at Sites 1.5 km apart**



— Con 10 Output 56%    — Con 10 Closest 8086m    — Bruce Twp Hall Output 56%    — Bruce Twp Hall Closest 6800m

FIGURE 17 – Comparing Two Test Sites 1.5 km Apart Shows Similarity

**Impact of Microphone Self Noise Floor**



— Con 10 Output 56%    — Con 10 Closest 8086m    — 22 dBA Brownian Noise  
— 22dBA White Noise    — Threshold    — 20 phon

FIGURE 18 – Demonstration of the Impact of Microphone Self Noise Floor

As a further consideration, the FFT Sound Pressure Level for the first test site was compared in Figure 18 to the manufacturer’s suggested noise floor of 22 dBA for the Earthworks microphone using both a 22 dBA White Noise trace, and a 22 dBA Brownian Noise trace. The MSc Thesis in Acoustics by Benjamin Russo at The Pennsylvania State University (2013) shows that some components in a microphone system will display a fairly flat noise response with frequency, (like white noise) while others will show a 1/f characteristic (like Brownian noise). Figure 18 shows that for either case, neither the noise floor nor the threshold of audibility will prevent the microphone from being effective as the sound pressure level is above these limits, even if it shown low on the FFT analysis.

The results before and after the turbines are shut down at the second test site, outside the Bruce Township Hall (R285) are shown in Figure 19. The difference from before to after is seen to be in the order of 20 dB, and again an audible tonal signal is displayed on the FFT at 1365 Hz. Ontario regulations require that if tonality of wind turbines is detected as it has been at the K2 turbines and at the Underwood turbines a 5 dB penalty is to be applied. The MOECC issued approval for the K2 turbines in their “Renewable Energy Approval” issued July 23, 2013 on the basis of an application that said the turbines were not tonal, and similarly the “Certificate of Approval Air” for the Underwood turbines was issued July 4, 2007 on the basis that they were not tonal. The rigorous monitoring method demonstrates evidence that both are indeed tonal.

**Impact of Curtailing Wind Turbines - shutting down due to excess generation  
Monitored at Test Site 2**

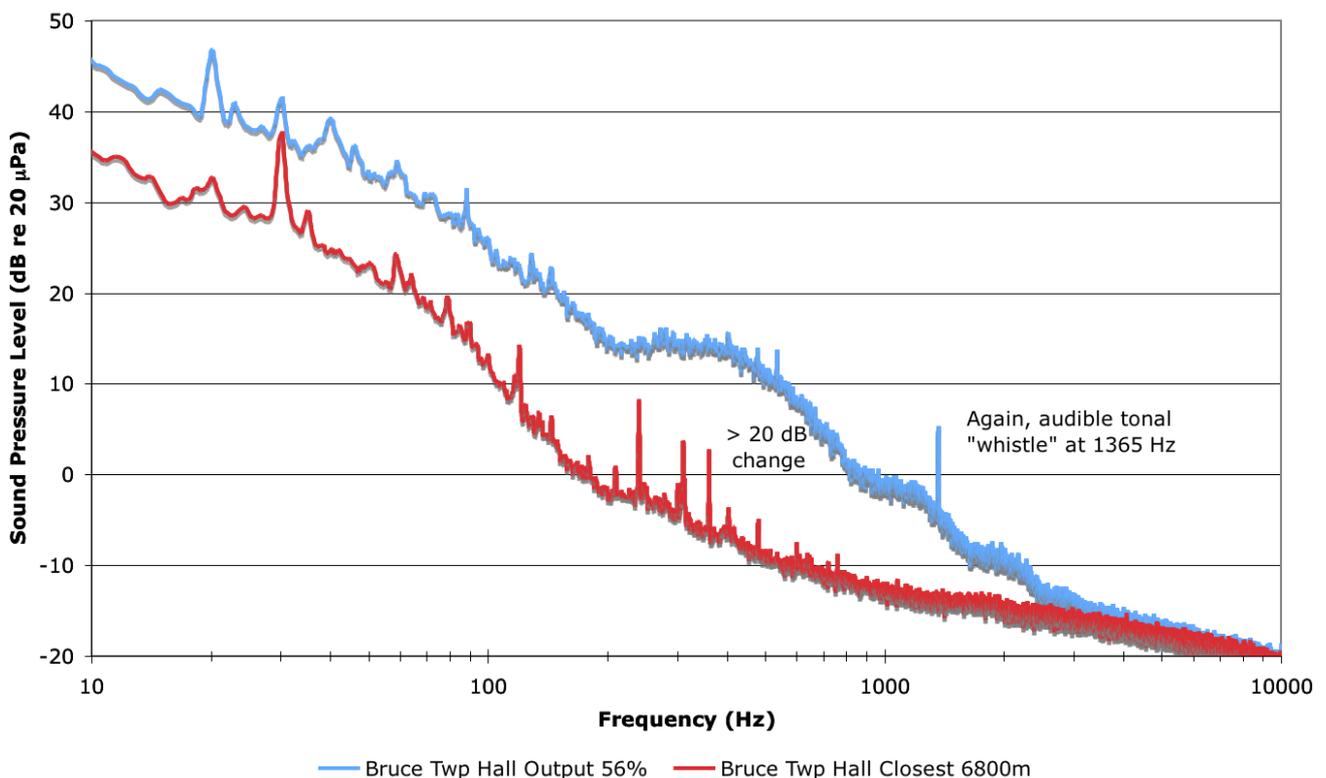


FIGURE 19 – Impact of Curtailing Wind Turbines at Test Site 2 – Bruce Township Hall

Figure 20 shows the case of the monitoring before and after curtailing of operation at the third test site. Again, with the turbines operational, the Sound Pressure Level displayed by the FFT (recognizing that it may well be low) shows to be very near to the 20 phon annoyance level. When the turbines are not in operation, the sound level is reduced by some 20 dB. Again, a very significant tonality is detected. In this case, there is some residual tonality detectable even with the local turbines shut down. While carrying out the monitoring with the turbines shut

down, it was possible to hear a repetitive slapping sound, as if cables in the turbine tower were slapping the tower, exciting it to ring. This may be a cause of the indicated tonality even when shut down.

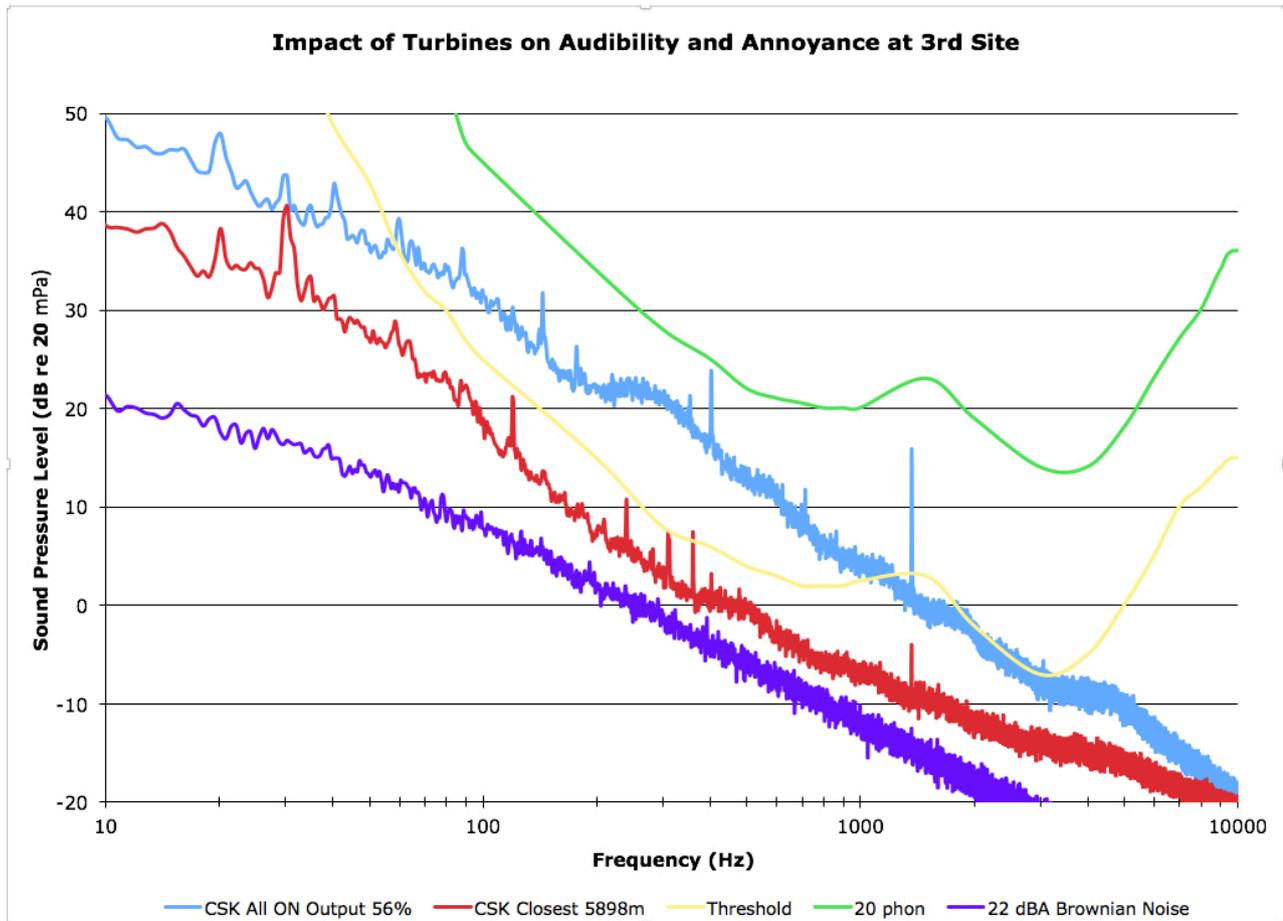


FIGURE 20 – Impact of Turbine Audibility and Annoyance at Test Site 3

At the fourth monitoring site, monitoring was set up and in service when the turbines shut down at about 00:30 AM. However, at this site, the closest turbine to the home, WT045, continued in operation. There is a sound monitoring site near this wind turbine, which may be a factor in why this turbine continued in operation, even when the others were shut down so that a lower sound recording could be made. At this site shown in Figure 21, the condition both before and after the transition remained above the threshold of audibility. Here too, tonality was detected at 1365 Hz.

The shut down transient itself generated a significant impact, as all of the surrounding turbines but this one received a stop signal, and the blades rotated to the feathered position from full speed operation. The recording of the transient itself will be available for the poster based audio listening test to give an indication of the sort of transient that is occurring routinely day after day, with the curtailment of wind turbines, that often occurs about midnight, just after residents may have gotten to sleep as the electrical load drops and the need to reduce generation manifests itself.

**Impact of Curtailing all Turbines except closest on Audibility and Annoyance  
Considering Audibility Threshold and Noise Floor, Site 4**

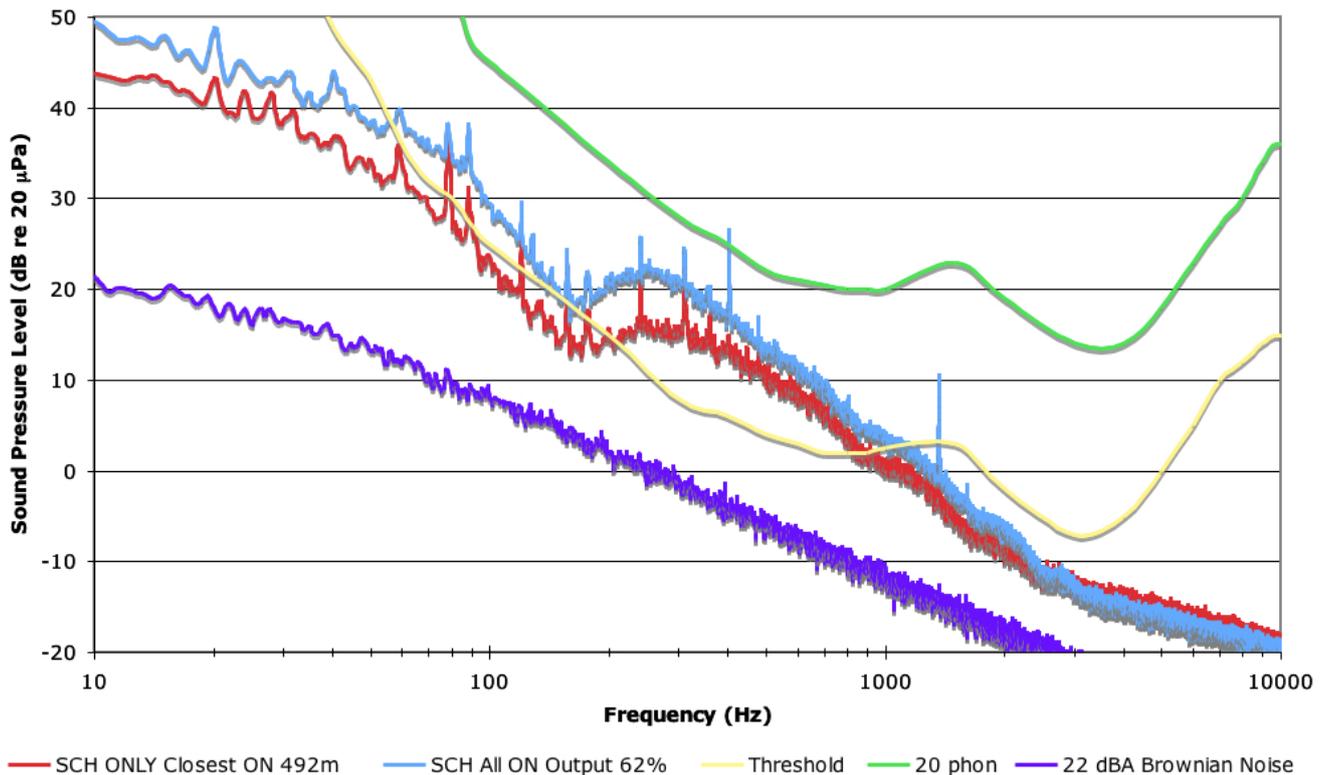


FIGURE 21 – Impact of Curtailing All Turbines But One (the Closest) at Monitoring Site 4

### 3.4 Comparing Measured Vs Predicted Sound Pressure Levels at Two Sites

Earlier in Section 2.2, the calculation of the Predicted Sound Pressure Levels was described. Following the measurements made in Section 3.3, it was possible to compare the measurement results to the predictions. To do this, a calculation of the third-octave sound pressure levels was carried out by “binning” the outputs of the FFT performed on the sound recordings and logarithmically adding them together as relevant to each third-octave. The overall A-weighted and Z (unweighted) sound pressure levels were also calculated. It is recognized that using the FFT results does allow the same vulnerability as described before for the FFT display, in that the higher the resolution of the FFT, the lower is the indicated sound pressure level. Thus, the indicated sound pressure levels may be lower than exist in reality.

The measured vs predicted Sound Pressure Levels for R145 is shown in Figure 22 (the 4th monitoring site where one turbine was left in operation) and for R285 in Figure 23, (the 2<sup>nd</sup> monitoring site at Bruce Township Hall).

The sound measurements shown in Figure 22 and Figure 23 were derived by separating the FFT results into one-third octave bins as described above, and then these were converted to octaves. The predicted results were from the Wind Turbine Sound Calculator in Section 2.2.

**Measured vs Predicted Sound at R145 (Test Site 4)**

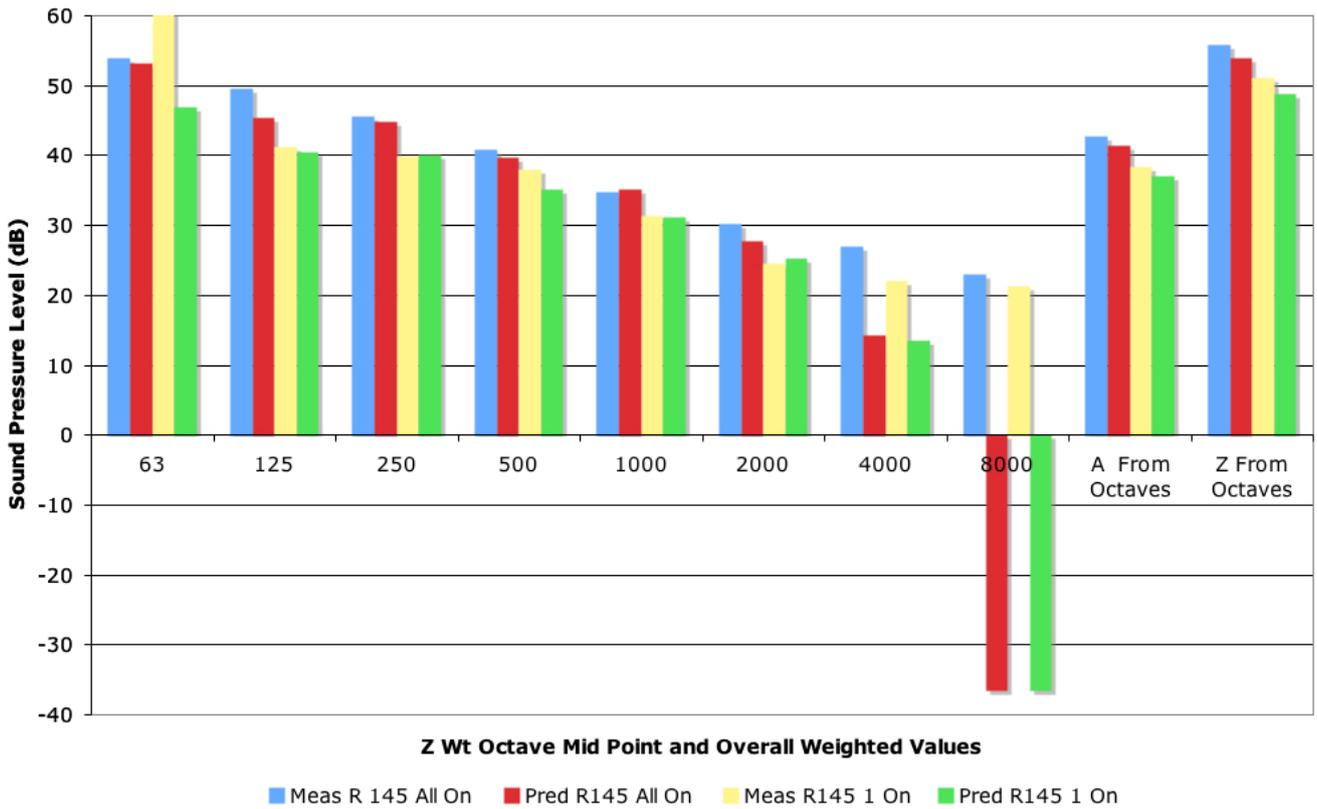


FIGURE 22 – Measured vs Predicted Sound at R145, the 4<sup>th</sup> Test Site

**Measured vs Predicted Sound at R285 (Test Site 2)**

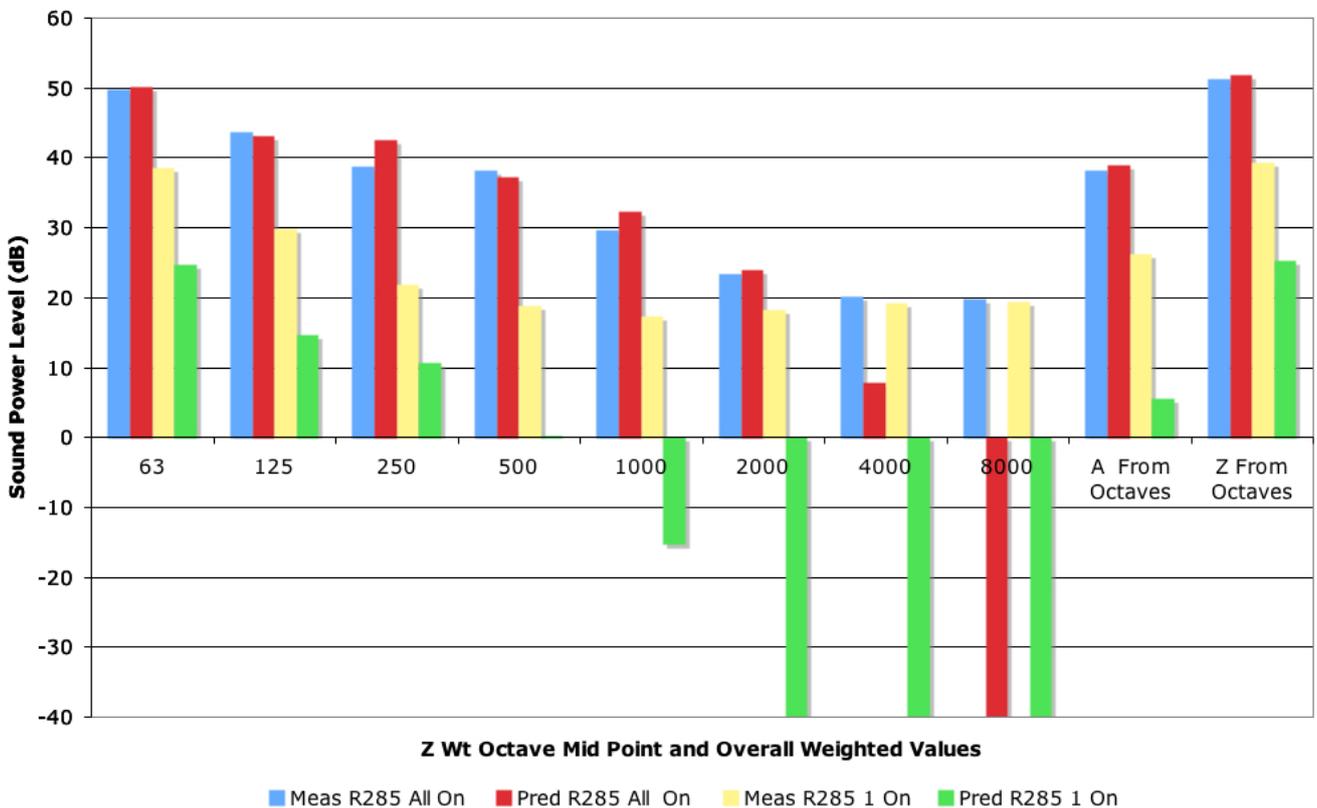


FIGURE 23 – Measured vs Predicted at R285, the 2<sup>nd</sup> Test Site

Figures 22 and 23 make several observations possible.

- At Test Site 4, for the all turbines “on” monitoring condition, the overall dBA measured sound pressure level exceeded the predicted value from the calculator in section 2.3 by 42.8 dBA vs. 41.4 dBA. For all but one octave (at 1000 Hz) the measured sound pressure level was greater than the predicted level. This may be accepted for the 4000 and 8000 Hz octaves, where the atmospheric attenuation of the higher frequencies from the turbines reduces them well below ambient, to make the predicted value very low. However, when the measured value is greater than the predicted value for octaves 2000 Hz and lower it suggests that the Sound Power Level for the turbines is higher than the value provided by the manufacturer, or the attenuation is less than predicted by the ISO 9613-2 code.
  - As the code itself is generally well verified for the attenuation factors, the error would appear to be in the turbine Sound Power Level. A number of possible conditions for this were identified earlier. These turbines have been in service for 8 years now, and the blades are wearing, and dirtier than new. The turbines are not individually located as at a test site, but are spaced at about 5 rotor diameters apart, so may influence each other. The temperature when the monitoring was conducted was below 10 °C, so the greater air density may have impacted each turbine output. However, it is not the requirement of the monitoring program to identify the actual cause of the measured sound being over the predicted sound, it is only to be able to show that the actual sound pressure level at the receptor was above the licence value. These turbines were licensed on the basis that the sound pressure level would be 39.2 dBA at R145 when the wind speed 10 metres above ground was 6 m/sec. On the night of the monitoring, the wind speed at R145 was well below 6 m/s, but the measured sound pressure level exceeded 40 dBA by nearly 3 dB when calculated from the octaves from 63 to 8000.
- At Test Site 4, for the 1 turbine “on” monitoring condition, the overall measured dBA exceeded the predicted value by 1.3 dBA at 38.4 vs. 37.1. A possible cause for the reduction from the excess in the all turbine state would be that as the other turbines were stopped and producing less turbulence than when operating, there would not have been the same inter turbine interaction.
- At Test Site 2, the predicted sound pressure for the all turbines “on” monitoring condition at 38.9 dBA, exceeded the measured value at 38.1 dBA. The probable cause for this can be seen from the wind output chart in Figure 11. For both the R145 and the R285 site, the predicted value was based on the maximum shown output before the turbines were shut down at 110 MW, while the chart shows that the output was actually rising in the time before the shut down, so it may have been less than 110 MW when the monitoring was carried out at Test Site 2. Thus, the predicted sound power level would have been estimated high, while the measured value would have been what was actually occurring.
- At Test Site 2, for the 1 turbine operating state, the sole turbine WT045, at 6772 metres distant was well beyond the propagation estimation specifications for ISO 9613-2. The fact that the measured sound pressure level exceeded the predicted value is not remarkable since the predicted contribution from the distant turbine (at 5.5 dBA) to the ambient was minimal. The measured value at 26.2 dBA is an expected ambient condition at night, showing the significant excess above ambient caused by the operating wind turbines.

#### **4. A Reproducible Manner of Producing Listening Tests**

In the “poster” presentation for this paper, a repeatable model for the prediction of the cyclic sound of a wind turbine will be demonstrated. Further, a demonstration of a repeatable model

for modelling the tonal characteristics observed at both the K2 array and the Underwood array will be demonstrated. The demonstrations will help to understand that even if sounds have the same A-weighting, they do not have the same annoyance. The listening test will show that suppressing special characteristics of sound quality in some current acceptance criterion can fail to identify real problems faced by residents in the area of a wind power development. Figure 24 gives a brief overview of how the signal generator function of the Audacity program can be used to create a replica of a modulated cyclical signal using the envelope tool to modify a basic Brownian noise signal. In a similar manner, the tone generator function on Audacity was used to overlay onto a modulated cyclical signal to simulate a tonal wind turbine. Samples such as these were demonstrated to a number of residents with experience living near wind turbines. Interesting remarks were made such as, “That is exactly what it sounds like!”

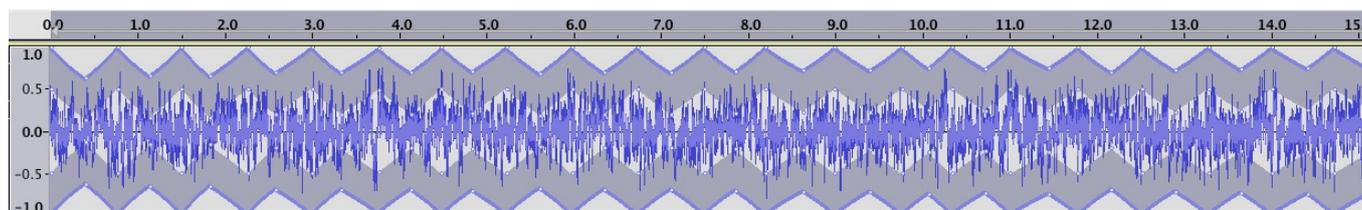


FIGURE 24 – A Demonstration of how to Simulate a Modulated, Cyclical Wind Turbine Signal

## 5. Conclusions

This paper has demonstrated a method for rigorous monitoring of wind turbine sound. The goal of the method was to establish evidence for the condition noted by Karl D. Kryter: “The most direct, and perhaps most valid, insight into the possible presence and magnitude of stress reactions in general living environments is probably that which has been obtained from attitude surveys and real-life behaviour of people.” Behaviours such as walking away from an unsold loved home to live at the home of a family member, or when normal people become activists in trying to communicate their concerns provide such valid insights. The rigorous method had to consider the present acceptance criterion for wind turbines, in light of the insight given by those who study the quality of noise and its relation to annoyance. Those who study the subject identify that, “Current acceptance criterion relying on sound pressure levels averaged over long time periods and suppressing all aspects of quality cannot identify the specific properties of environmental noise situations.”

A repeatable and transparent method of predicting the expected sound pressure level was presented. A rigorous method of monitoring the actual sound conditions was described. This was used to conduct assessments at two different wind power developments with two different turbine types. Using the method it was possible to generate reproducible evidence of some of the special acoustical properties that are affecting quality of life. Thus it could verify that conditions identified by residents as troublesome do exist, when the current acceptance criterion was unable to detect problems.

The paper outlines a method of preparing reproducible sounds to permit a “jury-test” at the poster session in a repeatable manner of special acoustical qualities such as modulated cyclical sound, or tonality. The demonstration will show evidence that two sounds with the same A-weighting, in the absence of consideration of the special characteristics of the sound, are not equal in annoyance.

## 6. Acknowledgements

Many have contributed to the development of this monitoring protocol, and this list of acknowledgments will be incomplete, but representative of some who helped, even without knowing of their influence:

- Residents permitted the intrusion of allowing monitoring inside and around their home, both occupied and vacant, and visits at any hour of the day or night to collect data. The locations reported in this paper are only indicative of many where residents have permitted monitoring at their homes. In some cases residents even got up during the night to plug in the monitoring computer to ensure the battery would be recharged when needed. Thanks for your tolerance, and for discussions to outline what your observations were as to what you found most bothersome. They were invaluable at making sense of a mystery.
- Werner Richarz provided the initial thinking for an Excel spreadsheet used to evaluate the third-octave contributions from FFT results.
- Discussions with Kristen Persson Waye were instrumental in clarifying the issue of cyclical sound as bothersome.
- Discussions with Jo Solet were useful in helping to understand sleep disturbance issues.
- Speaking face to face with Mathias Basner and Wolfgang Babisch at a special Acoustical Society of America presentation honouring the work of Karl D. Kryter was a big factor in focusing on “The Effects of Noise on Man”.
- Discussions with, and listening to papers presented by Klaus Genuit, André Fiebig, and Brigitte Schulte-Fortkamp were very helpful in understanding the issue of the quality of noise and it’s relation to annoyance.
- The understanding of my wife, Jean, to permit me to focus almost single-mindedly on a subject for over 10 years allowed this work to happen.

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