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Health-based Audible Noise Guidelines Account for Infrasound and Low Frequency Noise Produced by Wind Turbines

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Summary

Setbacks for wind turbines have been established in many jurisdictions to address potential health concerns associated with audible noise. However, in recent years it has been suggested that infrasound (IS) and low frequency noise (LFN) could be responsible for the onset of adverse health effects self-reported by some individuals living in proximity to wind turbines, even when audible noise limits are met. The purpose of this paper was to investigate whether current audible noise-based guidelines for wind turbines account for the protection of human health, given the levels of IS and LFN typically produced by wind turbines. New field measurements of indoor IS and outdoor LFN at locations between 400 m and 900 m from the nearest turbine, which were previously underrepresented in the scientific literature, are reported and put into context with existing published works. Our analysis showed that indoor IS levels were below auditory threshold levels while LFN levels at distances >500 m were similar to background LFN levels. A clear contribution to LFN due to wind turbine operation (i.e., measured with turbines on in comparison to with turbines off) was noted at a distance of 480 m. However, this corresponded to an increase in overall audible sound measures as reported in dB(A), supporting the hypothesis that controlling audible sound produced by normally operating wind turbines will also control for LFN. Overall, the available data from this and other studies suggest that health-based audible noise wind turbine siting guidelines provide an effective means to evaluate, monitor, and protect potential receptors from audible noise as well as IS and LFN.

1. Introduction

Wind power has become the fastest growing source of new electric power generation, with several countries achieving high levels of wind power capacity and overall penetration (Wiser and Bolinger 2013). Public support for the use of wind energy is typically high; however, acceptance of projects at the local level does not always reflect this trend. While support is found in some locations, strong opposition stemming from concerns of visual aesthetics, health risk perception and noise levels can be found in others (Baxter et al. 2013; Jobert et al. 2007; McCallum et al. 2014; Wolsink 2000).

Currently, there exists an ongoing debate surrounding the relationship between wind turbines and human health within both the public and the scientific communities (Knopper and Ollson 2011). This debate is driven by the fact that some people that live near wind turbines have reported adverse health effects such as (but not limited to) ringing in ears, headaches, lack of concentration, vertigo and sleep disruption that they attribute to the wind turbines. Some argue that reported health effects are related to wind turbine operational effects (e.g., electromagnetic fields [EMF], shadow flicker from rotor blades, audible noise, low frequency noise and infrasound); others suggest that when turbines are sited correctly, reported effects are more likely attributable to a number of subjective variables, including nocebo responses, where the etiology of the self-reported effect is in beliefs and expectations rather than a physiologically harmful entity (Chapman and St George 2013; Crichton et al. 2013a; 2013b; Pedersen and Persson Waye 2004; 2007).

It is well known that exposure to excessive levels of audible noise, regardless of the source, can cause annoyance, sleep disturbance, cognitive impairment and other serious health effects. According to the World Health Organization (WHO), nighttime exposure to noise levels above 55 dB(A) outdoors averaged over the year is considered increasingly dangerous for public health and a sizeable proportion of the population will be highly annoyed and sleep-disturbed (WHO 2009). As a result, jurisdictions across the globe have developed noise regulations specific to wind turbine projects to protect the public from potential noise-related health effects. Though some variability exists among jurisdictions, the majority of the guidelines center around an outdoor limit between 35-45 dB(A). This limit coincides with the WHO Europe nighttime noise guideline of 40 dB(A) outdoors, a health-based value derived to “protect the public, including the most vulnerable groups such as children, the chronically ill and the elderly, from the adverse health effects of night noise” (WHO 2009).

Even when these health-based noise limits are met, some people living near wind turbines self-report a variety of adverse health effects that they attribute to living near the wind turbines (Knopper and Ollson 2011; Knopper et al. 2014). As a result, the etiology of these health effects has been hypothesized by some to stem from exposure to low frequency sounds, including infrasound (IS; 0.01-20 Hz) and low frequency noise (LFN; 10-200 Hz) (Møller and Pedersen 2011; Salt and Hullar 2010; Salt and Kaltenbach 2011), both of which are known components of the broadband sound associated with normal wind turbine operation (Leventhall 2006; Pedersen and Persson Waye 2004; Persson Waye and Öhrström 2002). In response to these concerns, a number of investigations have measured IS and LFN associated with modern wind turbine operation at a variety of distances, operating scenarios, and geographic and meteorological conditions. Collectively, these reports suggest that sound associated with well-functioning wind turbines has measurable energy within the IS and LFN spectra. However, IS levels, which are often described in dB(G), are consistently well below auditory perceptual levels (Boczar et al. 2012; Evans et al. 2013a; Evans 2013; O'Neal et al. 2011; Turnbull et al. 2012) and LFN is below available guidelines (O'Neal et al. 2011). Furthermore, IS levels at relatively close distances to wind turbines are equivalent to or less than those produced by a number of natural or engineered sources that individuals are exposed to on a regular basis (Evans et al. 2013a; Evans et al. 2013b; Turnbull et al. 2012). The physical characteristics of sounds emitted from wind turbines have been recognized to influence the perception and

annoyance to wind turbine associated sounds; however, this generally refers to sounds that are above the auditory level of perception (Bolin et al. 2011; Pedersen and Persson Waye 2007; van den Berg 2013).

It has been suggested that wind turbine noise limits set in dB(A), which simulates the sensitivity of human hearing and perception, may underestimate the contribution of IS and LFN from wind turbines (Salt and Kaltenbach 2011). Alternative sound weightings, including G-weighting (dB(G)) and C-weighting (dB(C)), have been proposed as more appropriate metrics for noise limits when LFN and IS are present, respectively (Salt and Kaltenbach 2011; Sloven 2005). However, Health Canada recently suggested that there was “no additional benefit in assessing LFN as C- and A-weighted levels were so highly correlated (r=0.94) that they essentially provided the same information” (Health Canada 2014). Accordingly, the purpose of this paper is to examine further IS, LFN and overall sound levels typically produced by wind turbines and provide discussion as to whether concerns regarding wind turbine associated IS and LFN are warranted. Field measurements of outdoor LFN and overall sound levels and indoor IS at locations between 400 m and 900 m from the nearest wind turbine, which were previously underrepresented in the scientific literature, are reported. The results of these measurements are put into context with existing published works and current available guidelines based on dB(A) to provide a weight-of-evidence conclusion.

2. Experimental design

2.1. Indoor Infrasound Measurements

Sound measurements were conducted in three residences, two at 450 m and one at 900 m from the nearest wind turbine. These turbines were part of an operating wind farm with over 40 turbines, each with a power capacity of 1.5 MW. The measurements were carried out using Class 1 instrumentation with sufficiently low frequency range and noise floor. Measurements were carried out on a ground plane fitted with a double windscreen. The double wind screen consisted of the thin hemispherical wireframe (450mm diameter) covered with a thin layer (approx. 10mm) of open cell foam. This setup is consistent with that defined in IEC 61400-11 with the exception that the measurement location was at a dwelling rather than close to a wind turbine. Although not in a windy environment, a double windscreen helps protect very low frequency and infrasonic measured levels against pressure fluctuations within a dwelling caused by moving air from ventilation and opening/closing doors.

For these measurements, access was not available to turbines in order to conduct on/off tests for quantifying ambient levels. Additionally, turbine power performance was not made available during the study. In order to identify whether the turbines in the facility were operating, an autocorrelation technique was used in the signal analysis in order to detect characteristics in the sound signal attributable to the turbine operation. This autocorrelation technique (Richarz et al. 2011) exploits the periodicity in the signal attributable to the wind turbine operation and uses this feature to detect when the turbines were operating. Infrasound levels measured during wind turbine operation were compared to those when the wind turbines were unlikely to be operational (i.e., at wind speeds below turbine cut-in at 3 m/s). Data were collected from 1 to 1000 Hz and subsequently weighted using dB(G) to focus the analysis on the IS component, and allow for comparison to other studies.

The data presented in this report represent the periods where 1-minute interval recordings showed the existence of the wind turbine noise (i.e., characteristic blade passage frequencies) the clearest out of the entire measurement period which was 3-4 weeks. Because the nature of the signal detection mechanism, and the averaging over a minute, the Type A uncertainty for the measured value is difficult to quantify. The Type B uncertainty of the measurement is that of a Class 1 instrumentation which is typically ± 1 dB.

2.2. Outdoor Low Frequency Noise and Overall Sound Measurements

Sound levels were measured near two different wind turbine facilities, both with more than 30 wind turbines each. The turbines had a power capacity between 1.5-2.4 MW. Measurements were carried out outdoors at 4.5 m height, and at a distance between 400-800 m. Meteorological data were also recorded at a height of 10 m at the same location. The sound measurements were carried out using Class 1 instrumentation with sufficiently low noise floor. A large 450 mm diameter spherical secondary windscreen was employed in addition to a commercially available 7 cm primary wind screen to minimize pseudo-noise from wind flowing over the microphone. Field sound measurements of wind turbines are highly susceptible to contamination from extraneous noise such as from human activity, fauna, insects, and wind-induced noise. To control for these sources of contamination, the following methods were used:

- sound measurements were only collected during nighttime, between 10 PM and 5 AM;
- measurements were conducted in one minute intervals;
- measurements were binned by wind speed for each one minute interval;
- intervals within one hour of rainfall or snowfall were not used; and
- intervals with gusty winds (>2 m/s above the mean wind speeds) were not used as these periods are more susceptible to wind-induced pseudo-noise.

Measurements were carried out in the vicinity of the wind facility during wind turbine operation as well as with the turbines off. The same filtering and data quality management methods were applied to both data sets. A minimum of 60 data points in each wind bin were gathered. To isolate only the LFN portion of the spectrum, data between 20-200 Hz were analyzed and summed. Once tallied, the mean spectrum for the 3 and 6 m/s integer wind speeds was calculated. For each of those cases, the calculation was made from spectra where the mean wind speeds were within 0.5 m/s of the stated value and was relatively steady during the entire interval. The gust filtering ensures that no gust was more than 2 m/s above the mean. The mean spectrum was calculated by computing the energy averaged sound level for each 1/3rd octave band between 20-200Hz, and then computing an A-weighted sum of the spectrum.

The self-noise emitted by the system itself was assessed using the measurements conducted during periods when the wind turbines in the vicinity were not operating. The mean spectrum at various wind speeds was compared to those found in other literature comparing measured ambient levels with respect to wind speed. The most applicable study, conducted by the Japanese Ministry of Environment and reported by Tachibana (2013) compared sound levels measured with various windscreens ranging from naked microphone to a specialized dodecahedron double windscreen. Measured low frequency levels were at or below those reported in the double windscreen case in the Japanese study for most wind speeds and locations. It should be noted that although the measured ambient levels are consistent with those measured with high degree of windscreen protection, pseudo-noise contamination of the signal cannot be fully avoided.

Based on the measurements conducted, the typical measured standard deviation for the A-weighted level was ±3 dB for the turbines ON, and ±2dB when the turbines were OFF. The standard deviation was higher at lower wind speeds and decreased with increasing wind speed. This is due to wind induced ambient noise (which is fairly steady) dominating the signal at the higher wind speed. At lower wind speeds, because the ambient levels are lower, individual non-turbine related events such as vehicular traffic, faunal noise, or other intermittent noises increase the variability in background noise. Additionally, during lower wind speeds, the wind turbine noise source would be more susceptible to changes in wind speed at the hub. For example, for two cases where the ground level wind speed is 3 m/s, the hub height wind speed could be 4m/s in one case and 8m/s in another. This would result in a difference in the amount of noise produced by the turbine. It is the authors' view that given the above variability, wind

turbine noise measurements at far field distances should carry a nominal uncertainty value of ±3 to ±5dB.

3. Results and Discussion

3.1. Indoor Infrasound Measurements

Infrasound levels in the homes at 450 m were relatively similar, measuring 59 and 58 dB(G) (Table 1). Infrasound measured at the furthest location of 900 m was comparable to the measurements at 450 m, measuring 60 dB(G). These data indicate that IS levels were relatively constant with increased distance from the nearest wind turbine and were approximately 25 dB below the level of human perception (approximately 95 dB(G) (Watanabe and Møller 1990)), which may be indicative of non-wind turbine associated distant sources of IS. The results reported here are consistent with previous measurements at varying distances (Boczar et al. 2012; Evans et al. 2013a; Evans 2013; O'Neal et al. 2011; Turnbull et al. 2012). For instance, IS measurements from 290-323 m from wind turbines were 20 to 30 dB below the human auditory threshold levels (O'Neal et al. 2011). Additional measurements of IS in the 1-30 Hz range at a distance of 200 m from the wind turbines also remained below the human auditory threshold (Boczar et al. 2012). Other investigations have shown that at further distances (1.5 km) indoor IS levels in two residences were between 49-61 dB(G), with no reported difference between operational and shutdown periods, also suggesting that there are other sources of IS contributing to these results (Evans et al. 2013a). The same group (Evans and Cooper 2012) also showed that indoor IS levels were between 50-70 dB(G) at distances of 1.8 and 2.7 km from the nearest wind farm. In conjunction with these reports, the results from the current field investigation indicate that wind turbines are a source of IS; however, sound levels are well below the human auditory threshold.

Table 1 Indoor infrasound measured at three homes at two different distances to 1.5 MW turbines.

WT Rated Power (MW)	Distance (m)	IS Level (dB(G))
1.5	450	59
1.5	450	58
1.5	900	60

Only two jurisdictions have developed clear guidelines for IS and neither is specific to wind turbine noise. The Queensland Department of Environment and Resource Management's Draft *ECOACCESS Guideline- Assessment of Low Frequency Noise* proposed an interior IS limit of 85 dB(G) (Roberts 2004). This value was derived based on a 10 dB protection level from the average 95 dB(G) hearing threshold (Watanabe and Møller 1990) and previous Danish recommendations for IS limits (Jakobsen 2001). The Japanese Handbook on Low Frequency Noise provides an IS reference value of 92 dB(G) at 10 Hz and 1/3 octave bands up to 80 Hz (Kamigawara et al. 2006). These values were derived from investigations that monitored complaints of mental and physical discomfort from healthy adults exposed to low frequency sounds in a room (Kamigawara et al. 2006). Though the Japanese guidelines were derived through short-term monitoring experiments and are not equivalent to the long term exposure associated with living in proximity of wind turbines, the levels of IS measured as part of this current study (Table 1) are 20-30 dB below these guidelines.

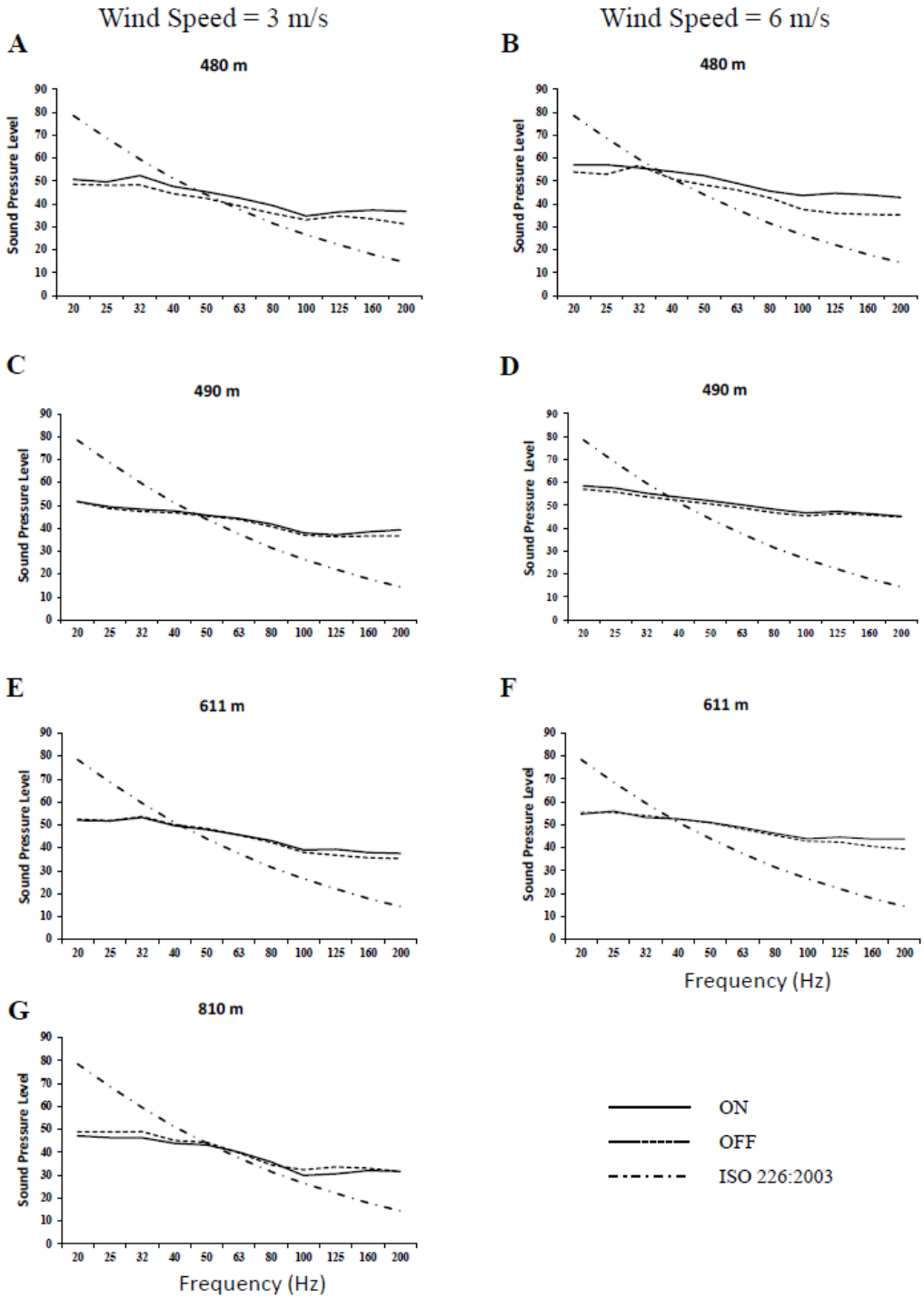
A limited number of reports have suggested that the IS component of wind turbine noise is the cause of self-reported adverse health effects (Ambrose et al. 2012; Rand et al. 2011; Walker et al. 2012). Mechanisms within the inner ear that are sensitive to low levels of IS stimulation have been proposed to be associated with adverse health responses (Pierpont 2009; Salt and Hullar

2010; Salt and Kaltenbach 2011). However, functional magnetic resonance imaging has provided powerful evidence that IS is perceived via similar auditory pathways as audible sounds when above the level of perception with no indication of cortical activation at sub-threshold values (Dommes et al. 2009). Furthermore, exposure to IS is known to originate from other engineered or natural processes, including wind and weather systems (Goerke and Woodward 1966), volcanic (Goerke et al. 1965) and auroral activity (Wilson 1967), and mountain ranges (Bedard Jr 1978); this would arguably also induce stimulation of the inner ear. Recent outdoor measurements have provided an indication of IS levels from a number of natural sources, including sea waves at 25 m from the coast (75 dB(G)), 250 m from a coastal cliff face (69 dB(G)) and 8 km inland from the coast (57 dB(G)) (Turnbull et al. 2012). The authors reported that wind turbine IS levels, that were between 61-72 dB(G) at distances of 85-360 m, were lower than many of the natural sources measured (Turnbull et al. 2012). Infrasound is also generated in urban environments as a result of human activity and engineered sources such as industrial processes, ventilation systems and vehicles (Evans et al. 2013a; Turnbull et al. 2012). Measurements of IS in a typical urban setting have been reported to be up to 70 dB(G) during the daytime and 63 dB(G) at night (Evans et al. 2013a). In comparison, studies reporting biological responses to infrasound exposure were at sound pressure levels that were above the level of auditory perception, much higher than those produced by wind turbines (e.g., 145 dB and 165 dB (Leventhall et al. 2003; Yuan et al. 2009)). Collectively, these reports and the measurements from the current investigation indicate that humans are regularly exposed to IS from several natural and engineered sources at levels that exceed those produced by wind turbines. Although sounds with impulsive characteristics (e.g., wind turbines) generate greater levels of annoyance than non-impulsive sources, annoyance levels have only been associated with noises that are above the threshold of auditory perception (Berglund et al. 1996; Pedersen and Persson Waye 2004). Our measurements of IS, and those from the literature, are all well below the threshold of auditory perception.

3.2. Outdoor Low Frequency Noise and Overall Sound Measures

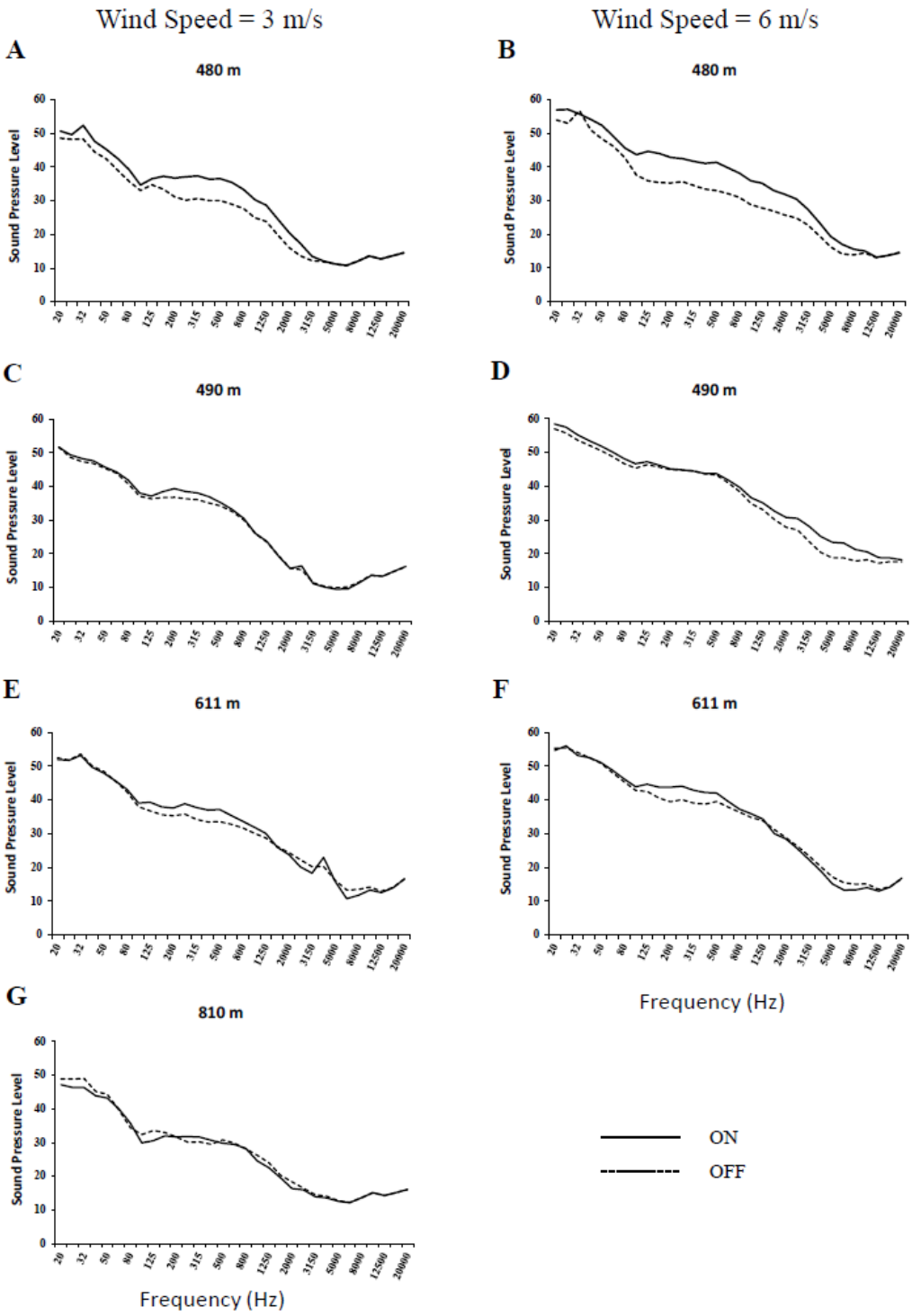
Outdoor LFN levels were assessed through 1/3 octave band measurements with wind turbines operational (on) and during scheduled shutdown periods (off) at distances of 480, 490, 611, and 810 m (Figure 1). At all locations, measured LFN levels with wind turbines on and off (ambient) were similar between 20-100 Hz. At frequencies greater than 100 Hz, a deviation was noted between the ‘on’ and ‘off’ conditions, particularly for measurements taken nearest to the turbines (Figure 1A and 1B). As distance from the turbines increased, the amount by which LFN levels measured with turbines on and off differed decreased in comparison to the measurements reported at 480 m. At all distances and wind speeds, irrespective of wind turbine operation, LFN exceeded the ISO-defined audible threshold at frequencies greater than 40-50 Hz (ISO 2003). These results indicate that the observed increase in LFN during wind turbine operation was found primarily in the frequency range consistent with the audible range of hearing, namely 20-20,000 Hz, and not in the IS range (<20 Hz). It is also noted that the same applies to ambient noise levels, namely that the levels cross the auditory threshold at frequencies between 40-50 Hz and higher.

Figure 1. Outdoor low frequency noise measurements at 480 m (A and B), 490 m (C and D), 611 m (E and F), and 810 m (G) from 1.5 MW wind turbines with wind speeds of 3 m/s (A,C, E, G) and 6 m/s (B,D, F) with turbines on and off. Hearing threshold (ISO 226:2003) are also provided.



Through the 1/3 octave band analysis of overall sound levels (20-20,000 Hz; Figure 2) it was apparent that the increase in LFN from wind turbine operation was accompanied by increased sound levels at higher frequencies (i.e., >200 Hz). This was particularly evident at 480 m where wind turbine associated sound levels continued to be above ambient levels until approximately 3150 Hz (Figure 2A and 2B). At further distances, sound levels were above ambient levels at frequencies between 125-1000 Hz, but not easily distinguishable from ambient levels below 125 Hz, or above 1 kHz (Figure 2C-2F). These results indicate that though there was an observed increase in LFN levels during wind turbine operation at the 480 m location this increase was accompanied by an increase in sound levels up to 3 kHz.

Figure 2. Outdoor sound measurements at 480 m (A and B), 490 m (C and D), 611 m (E and F), and 810 m (G) from 1.5 MW wind turbines with wind speeds of 3 m/s (A, C, E, G) and 6 m/s (B, D, F) with turbines on and off.



At closer distances where the LFN component can be measured above the ambient conditions, the mid frequency sound levels were also above ambient levels. In those cases, the signal-to-noise ratio of the mid frequency sound levels was higher than that below 125 Hz, indicating that the most audible portion of the frequency spectrum was between 125-3150 Hz. At further distances, it was evident that the signal-to-noise ratio decreased, such that only acoustic energy between 125Hz and about 800-1000 Hz was above background, with the

highest signal-to-noise ratio between 200-500 Hz (Figure 2C-2F). The single measurement point at 810 m showed no measurable increase in any of the mean sound levels. This indicates that a presence of LFN in the signal from wind turbines was accompanied by a presence in mid frequency sound levels. For instances where the LFN levels were considerably above ambient levels, the mid frequency sounds levels were also considerably increased. This indicates that, at the distances of interest, it is the mid frequency region that is the most audible portion of the noise from the turbines. Only at closer distances, where the mid frequency components would be clearly audible (6 to 9 dB signal-to-noise ratio), would the low frequency components from the turbines start to be audible above ambient levels. The overall A-weighted sound pressure level was significantly affected by the mid frequency component. As a result, it would be expected that by controlling the overall sound pressure level (dB(A)) from normal functioning wind turbines, that the LFN component would also mitigated.

When the wind turbines were operating, the highest mean LFN level (dB(A)) was observed at 480 m (Table 2). At the other locations >480 m from the wind turbines, the measured difference between wind turbines on and off was between 1-3 dB, at least half of that observed at 480 m. The mean overall sound levels reported in dB(A) showed very similar trends to those reported in the LFN analysis. Critically, the increase in mean sound levels at the closest location (480 m) reported in the LFN spectrum and overall sound in the 1/3 octave band analysis was maintained. In addition, the observed trends at 490, 611, and 810 m, also remained consistent. From these results it is evident that during wind turbine operation, the increased sound levels that began in the LFN spectrum, at approximately 160 Hz and continued to 1000 Hz, were above auditory threshold levels and represented in the mean dB(A) sound measures. The consistency between the mean dB(A) measurements and trends observed in the 1/3 octave band analysis suggest that the contribution of the LFN component and overall sound levels were accounted for in the calculation.

Table 2 Low frequency noise (LFN) and overall sound levels with turbines on and off (i.e. background) in dB(A).

Wind Speed (m/s)	Distance (m)	LFN "On"	LFN "Off"	Overall Sound "On"	Overall Sound "Off"[1]
3	480	30	26	41	35
	490	32	30	40	39
	611	31	30	42	40
	810	25	26	36	36
6	480	36	30	47	40
	490	39	38	49	48
	611	37	34	49	45

[1] Ambient noise at this location, with turbines off, is influenced by wind speed (3 and 6 m/s) and movement of vegetation in the measuring location.

Similar LFN levels in the proximity of wind turbines have been reported elsewhere (Evans et al. 2013b; O'Neal et al. 2011). Furthermore, the results showing LFN levels passing the auditory threshold between 40 and 50 Hz are similar to those that have been previously reported (Botha 2013; O'Neal et al. 2011). For instance O'Neal et al. (O'Neal et al. 2011) measured indoor and outdoor LFN levels from wind turbines at a distance of 300 m and found the levels were below the United Kingdom's (UK) Department for Environmental and Rural Affairs (DEFRA) and Japanese guidelines and became audible at approximately 50 Hz (O'Neal et al. 2011). Elsewhere, LFN levels were only marginally higher and remained well below guidelines even though measurements were taken as close as 104 m from the nearest wind turbine (Botha 2013). Low frequency noise measured at 1.8 and 2.7 km from the nearest wind farm was comparable during pre-operational and operational periods of development, though small increases at frequencies above 63 Hz were reported (Evans 2013). At a greater distance of 1.5 km from wind turbines, Evans et al. found LFN levels were similar to those measured at

distances of 10 and 30 km from the turbines (Evans et al. 2013b). Further, organized shut downs of the two wind farms showed that the contributions of the turbines to LFN measurements were negligible or relatively small contributions at 100 Hz and above (Evans et al. 2013b). As shown with IS, LFN is also produced by natural and common engineered sources: in urban environments, including offices and residences, LFN levels often exceed available guidelines and are greater than those measured 1.5 km from the nearest wind turbine (Evans et al. 2013b).

The sound characteristics and associated fall off with distance have been extensively measured by Tachibana in the range from 0.8 Hz to 5 kHz at 164 locations around 29 wind farms, using one third octave analysis. The average of the measures fell with a slope of 4 dB/octave over the whole range. The average passed through 55 dB at 10 Hz and crossed the hearing threshold at about 50 Hz (Tachibana et al. 2014). Other, less detailed measurements on individual turbines have shown slopes of 5dB/octave to 6 dB/octave (O'Neal et al. 2011). A spectrum which falls at 5dB/octave and passes through, for example, 60 dB at 10 Hz has an A-weighted level of 39 dB(A), which is mainly determined by a broad peak in the A-weighted spectrum in the region of 200 Hz to 630 Hz. Any shift in the level at 10Hz is reflected in the A-weighted level. Similarly this spectrum has a C-weighted level of 58 dB(C). The difference between dB(A) and dB(C) levels depends only on the spectrum shape and is independent of overall level, indicating that for similar spectrum shapes, the dB(A) and dB(C) levels are highly correlated.

There are currently no widely accepted international health-based limits for LFN specifically derived for wind turbines. A number of jurisdictions have developed both indoor and outdoor LFN limits to address potential issues associated with industrial noise emissions. The majority of the limits are for indoors and utilize 1/3 octave sound pressure level measurements between 5-200 Hz. This analysis enables assessors to identify tonal components within the spectrum that may be problematic. The 1/3 octave band limits vary significantly between jurisdictions. In Poland, LFN limits are around 10 dB(A) across 1/3 octave bands between 10-250 Hz (Mirowska 2001). In Denmark, LFN is limited to a total level of 20 dB(A) between 10-160 Hz (Jakobsen 2012), while in the UK, guidelines are generally between 10-25 dB(A) depending on the frequency between 10-100 Hz (Moorhouse et al. 2005). Indoor LFN limits provide a basis to address specific complaints from local residents; however, for wind farm development, regular monitoring of outdoor sound levels presents a more practical option.

Only a small number of jurisdictions, including the province of Alberta, Canada (AUC 2013), Japan (Kamigawara et al. 2006), and the Australian States of South Australia and New South Wales (New South Wales Planning and Infrastructure 2011), have introduced outdoor LFN noise limits. Several of these guidelines determine the difference between C- and A-weighted sound measurements. This calculation can provide an indication of an unbalanced spectrum; a difference greater than 20 dB between two weightings may warrant further investigation based on those regulations (Broner and Leventhall 1983; Leventhall 2004). The ability of this calculation to predict LFN issues is limited, particularly when there are low levels of background noise that result in a large difference between the A- and C-weighted sound levels that are not associated with increased levels of annoyance (Broner 2011). In the current investigation the difference between wind turbine operational scenarios (i.e., on and off) was <5 dB at the 490 and 611 m locations at both wind speeds. Measured background levels at 490 and 611 m were also high, measuring 48 and 45 dB(A) respectively. A number of noise guidelines, including those in the UK (Barclay 2012), New Zealand (NZWEA 2010) and several of the Australian states (Department of Planning and Community Development 2012; New South Wales Planning and Infrastructure 2011; South Australia Environmental Protection Authority 2009; Western Australian Planning Commission 2004), take into account the potential for high levels of background noise by suggesting that the contribution of wind turbines to be limited to <5 dB above background. In the current investigation, the 480 m location was the only one observed to be ≥5 dB above background levels (6 dB at 3 m/s and 7 dB at 6 m/s).

4. Conclusion

Data from the current investigation indicate that wind turbines produce noise that is broadband in nature, which includes energy within the IS and LFN spectrums. Based on the data presented here, the indoor IS component of wind turbine noise measured as dB(G) at distances of 450 and 900 m, was well below the levels of human perception (Watanabe and Møller 1990), providing further support to previous reports (Boczar et al. 2012; Evans et al. 2013a; Evans 2013; Leventhall 2006; 2013; O'Neal et al. 2011; Turnbull et al. 2012). Infrasound is produced at levels comparable or greater than those shown here by natural and engineered sources (Leventhall 2013; Turnbull et al. 2012). There is no scientific evidence to indicate that exposure at these G-weighted levels of IS can directly impact human health. Recent studies have indicated that psychological factors (Crichton et al. 2013a; 2013b) and the manner in which information is presented from media reports and non-scientific sources may influence the perception and expectations associated with wind turbine sounds (Deignan et al. 2013). These reports suggest that subjective variables may be a more likely etiology for self-reported effects than from exposure to IS associated with normal wind turbine operation.

The LFN analysis showed that when the turbines were both on and off sounds above 40-50 Hz exceeded the threshold for auditory perception as defined by ISO 226:2003 (ISO 2003). A clear contribution from the operation of the wind turbines was only observed at the closest location of 480 m when compared to background levels. Increases in LFN observed between 100-200 Hz corresponded to increases in overall sound measures reported in dB(A). The use of alternative sound weightings (i.e., dB(C)) may have utility in instances where there are significant increased levels of LFN, particularly when a tonal component is present. However, the results from the current investigation indicate that increases in LFN associated with wind turbine operation are correlated with increases in overall sound levels. These results, in conjunction with those of previous reports, suggest that controlling for overall sound levels produced by normally operating wind turbines will inherently control for LFN (Møller and Pedersen 2011; Parnell 2012; van den Berg 2013). The results reported here are in agreement with a recent report issued by Health Canada, which concluded that following over 4,000 hours of wind turbine noise measurements, there was "*no additional benefit in assessing LFN as C- and A-weighted levels were so highly correlated (r=0.94) that they essentially provided the same information*" (Health Canada 2014). Given the low levels of IS and the correlation between LFN and overall sound levels from wind turbines, the development and enforcement of suitable outdoor guidelines and limits, based on dB(A), provide an effective means to evaluate, monitor, and protect potential receptors.

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