Wind farm noise – what is a reasonable limit in rural areas?

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ABSTRACT

Wind farms are a rapidly growing source of renewable energy, but can be a source of persistent noise complaints, despite compliance with the relevant wind farm noise regulation being achieved. This paper presents a review of wind farm noise assessment criteria and methodology with a focus on the South Australian guidelines. The results of this review indicate that the noise limits may not be appropriate for some locations which are characterised by very low background sound levels at night time. The assumption in the guidelines that background noise is capable of reducing annoyance from wind farm noise is also not necessarily borne out in reality. Measurements of the outdoor-to-indoor noise reduction for a typical dwelling, with the window open, show that the reduction is slightly lower than assumed by the guidelines, and varies significantly with frequency. Measured low frequency noise and infrasound complied with all criteria addressed in the literature with the exception of one. Reliable compliance measurements are often difficult to achieve for wind farm noise, therefore it seems appropriate to adopt a conservative approach in setting noise limits and predicting noise emissions.

INTRODUCTION

Noise from wind turbines is often raised as a serious issue by residents in the vicinity of existing wind farm developments, and concerned residents near proposed developments. Most countries and jurisdictions with extensive wind energy programs have implemented regulations in response to these concerns, with the general aim of enabling wind farm development while protecting the health and amenity of surrounding communities. The most up-to-date comprehensive regulation in Australia is the South Australian EPA *Wind Farms: Environmental Noise Guidelines* (2009). The *Draft National Wind Farm Development Guidelines* produced by the Australian Federal Government were released in 2010 but the EPHC standing committee has decided not to proceed with further development. The *Draft NSW Planning Guidelines: Wind Farms* was released for consultation in early 2012. Australian Standard AS4959 *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators* (2010) provides guidance for the formulation of wind farm noise regulations but does not set objective criteria or noise limits.

However, vigorous complaints from residents regarding annoyance and adverse health effects due to wind turbine noise emissions continue to occur in Australia and worldwide, despite new wind farms being established in accordance with the relevant guidelines (Pedersen *et al.*, 2009; The Senate Community Affairs References Committee, 2011). The persistence of these complaints suggests that the guidelines are not resulting in adequate protection of the amenity of communities in the vicinity of wind farms.

There are a number of studies that provide commentary on various wind farm noise regulations, both for Australia and elsewhere (Chiles 2010; Colby *et al.* 2009; Sonus 2010). There is also a wealth of literature on individual aspects of wind turbine noise, which are of relevance to regulation, including appropriate noise limits; prediction methodology; and compliance measurements, but no comprehensive, peer reviewed critique of Australian regulations exists.

The purpose of this paper is therefore to provide a critical review of the assessment of the impact of wind farm noise on rural communities, with a focus on Australian regulations, and in particular, the South Australian guidelines. It is expected that many aspects of this review will be relevant to other Australian guidelines (in particular the draft NSW guidelines) and international regulations. An analysis of the apparent method of derivation of the guideline noise limits is undertaken, considering assumptions related to appropriate noise limits for rural areas, masking by background noise, and noise attenuation provided by a dwelling façade. Results of detailed measurements comparing outdoor and indoor wind turbine noise levels and character for a typical rural dwelling are presented, including measurements at low frequencies down to 0.8 Hz. The prediction methodology set out in the guidelines is also reviewed, along with the problems and challenges associated with compliance measurements.

FIELD MEASUREMENT ARRANGEMENT

Measurements were undertaken both indoors and outdoors at a typical rural residence approximately 2km from the nearest wind turbines at Waterloo wind farm. The local wind speed and direction were monitored concurrently. All outdoor microphones were equipped with 90mm diameter wind shields and mounted at a height of 1.5m on star-droppers to minimise wind noise interference associated with the more conventional method of tripod mounting. To investigate the potential masking effects of wind noise on the outdoor microphones, a comparison was made between a low frequency underground microphone located in a 400mm^3 plywood box and a similar low frequency microphone located at 1.5m above the ground. The microphone in the box was mounted on a small tripod and equipped with a 90mm windshield and the box had an acoustic foam lid, 50mm thick. The top of the lid was flush with the surrounding ground to minimise the formation of eddies that would generate extraneous noise. This method of locating a microphone in an underground box to minimise wind noise was also implemented by Sonus (2010).

The indoor measurements were carried out in a small bedroom with a window facing the wind turbines. The window was open so as to simulate a worst case scenario. Four microphones with 70mm wind shields were placed at various, randomly-chosen positions in the room. A microphone measurement at a single position would not have been sufficient to properly characterise the noise in the room due to the existence of standing waves, which are particularly significant at low frequencies below 200 Hz (Pedersen *et al.*, 2006). One microphone was located in the corner of the room, at the junction of 2 walls and the floor (where all room modes have anti-nodes).

The walls of the residence were 70mm thick brick with 10mm thick internal gypsum plasterboard lining on 90mm timber framing. The window was 4mm single float glass and the roof consisted of 16mm concrete tiles, with a 13mm gypsum plasterboard ceiling and 75mm fibreglass batts in the cavity.

A summary of the instruments and the transducers, with their respective A-weighted noise floors and approximate location is provided in Table 1, while Figure 1 shows a schematic depicting a more accurate representation of the transducer locations and a simplified overview of the room layout.

Table 1. Instruments, transducers and their locations.

No.	Instrument	Transducer Type	Location	Noise Floor (Manufacturer)
1	6 Channel Brüel & Kjær (B&K) Pulse System	B&K 4955	outdoors	6.5dBA
2		B&K 4955	indoors	6.5dBA
3		B&K 4955	indoors	6.5dBA
4		B&K 4943	Outdoors (near façade)	15.5dBA
5	4 Channel Svantek 958	GRAS 40AZ / SV 12L	outdoors	17dBA
6		GRAS 40AZ / SV 12L	Outdoors (in box)	17dBA
7		GRAS 40AZ / SV 12L	Indoors (in corner)	17dBA
8	1 Channel Svantek 979	GRAS 40HL	indoors	6.5dBA
9	Jaycar Weather Station	-	outdoors	-

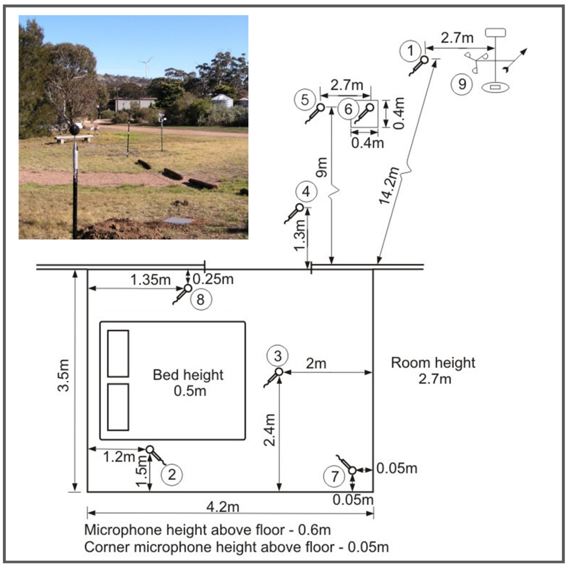

Figure 1. Schematic of residence and top left: outdoor microphones with wind turbines visible in the distance.

NOISE CRITERIA

Base noise limits

The SA EPA guidelines require that the predicted equivalent wind farm noise level ($L_{Aeq,10}$) does not exceed:

- 35 dB at relevant receivers in localities which are primarily intended for rural living, or
- 40 dB at relevant receivers in localities in other zones, including rural industry zones, or
- the background noise ($L_{A90,10}$) by more than 5 dBA.

It is not entirely clear from the guidelines how the respective base noise limits of 35 and 40 dB $L_{Aeq,10}$ were derived. The guidelines refer to Part 7 of the *Environmental Protection (Noise) Policy 2007*, which in turn refers to the now superseded 2003 *Wind Farms: Environmental Noise Guidelines*. This latter document sets a base noise level of 35 dB $L_{Aeq,10}$ for wind turbine noise, regardless of receiver locality.

Some indication as to the source of distinction between ‘rural living’ and other localities may come from statements in the 2009 guidelines which note that “a ‘rural living’ zone is a rural-residential ‘lifestyle’ area intended to have a relatively quiet amenity” while “some rural zones are intended for rural industry or primary production/general farming, where the amenity of the area may include noise from industrial sources.” Many wind farms in South Australia are located in rural areas which are not zoned ‘rural living’ but are nevertheless characterised by relatively low ambient noise levels (excluding wind farm noise), particularly during night-time. Typically, noise from primary production or agriculture is present during the daytime only, except for short periods during harvesting. A higher base noise limit for these areas does not therefore seem warranted. Background noise levels measured at each receiver location prior to operation of the wind farm are likely to be the most reliable indicator of acoustic amenity, rather than zoning. This is a slightly different concept than that introduced by the NZS 6808:2010 standard, which defines “high amenity areas” that have a 35dB(A) limit. Finally, it should not be assumed that background noise is capable of effectively ‘masking’ wind turbine noise in all cases.

In addition to the pre-existing ambient noise levels, guidance as to the appropriate noise criteria for new wind farm developments may come from dose response studies, which aim to determine the relationship between noise levels and community response in terms of the proportion of public annoyed or highly annoyed. Janssen *et al.* (2010) found that the proportion of people annoyed by wind turbine noise within their homes is higher than for most other stationary sources of industrial noise and the three most common sources of transportation noise (road, rail, and aircraft) for a given external noise level. This may be due to characteristics of wind turbine noise such as amplitude modulation, temporal variability, and lack of night-time abatement. This could also be attributed to a negative attitude toward the visual impact of turbines on the landscape, although it should be noted that wind farms are not unique as an industrial noise source that provokes strong reactions in regard to visual impact.

It is difficult to arrive at a robust conclusion as to the appropriate base limit for wind farm noise in rural South Australia on the basis of the above-mentioned dose response study, since they do not include detailed information about background sound levels, which may be relatively high in densely populated European countries where the measurements were taken. Also, the Janssen study was based on predicted noise levels received outside dwellings, while most respondents reported being most annoyed indoors. The outdoor noise predictions reported by Janssen (2010) were not verified with measurements, and indoor noise levels were neither predicted nor measured. Furthermore, the wind turbines investigated were significantly smaller (generally in the order of 1MW or less) than turbines typically used in new wind farm developments today (3MW).

Although there have been a number of studies comparing predicted and actual noise levels in Australia, including South Australia, there have been no extensive studies relating both indoor and outdoor wind farm noise levels to community response. This type of dose response study would therefore be useful in informing the selection of a suitable noise limit.

Background noise levels

Masking potential of background noise

The EPA guidelines (2009) state that wind turbine noise increases with increasing wind speed, with a corresponding increase in background noise that can mask noise from the wind farm. The guidelines allow wind farm noise levels to exceed the base noise limit at receiver localities, provided it does not exceed the local background noise level at a given wind speed, by more than 5 dBA. This rule may be problematic for several reasons. For example, the authors of this paper have viewed no conclusive evidence that supports the idea that background noise is capable of effectively 'masking' or reducing annoyance from wind turbine noise at levels of up to 5 dBA greater than the former. Bolin (2006) found that the masking potential was dependent on signal-to-noise ratio as well as the source of ambient noise; with coniferous vegetation having the greatest masking potential at equivalent levels (out of the sources considered). Listeners were able to detect wind turbine noise at levels 3 dBA below noise from coniferous vegetation, and perceived wind turbine noise as approximately 50% of the total noise when levels were 3 dBA above coniferous vegetation noise.

The masking potential of ambient noise may also be less than Bolin's work indicated in many cases because his study is based on wind turbine noise recorded at 400 metres from a wind farm. Wind turbine noise at greater distances is expected to have a relatively higher proportion of energy at low frequencies because high frequency noise is more effectively absorbed by the atmosphere and ground with increasing distance. Noise from vegetation contains the most energy at mid and high frequency and is therefore expected to have a reduced ability to mask this low frequency noise

This is illustrated in Figure 2, which shows a comparison of A-weighted spectra for wind turbine noise at a distance of 2 km, and vegetation noise. The wind turbine noise spectrum was determined using the sound power level spectrum of a Vestas 90 turbine operating in Mode O at a wind speed of 11.1 ms^{-1} at hub height (Delaire 2011). ISO 9613-2 was used to calculate the spectrum at 2km, assuming flat topography with no obstacles, and a fully reflective ground surface. The vegetation noise spectrum was adapted from measurements taken by Von Hunerbein *et al.* (2010) of deciduous vegetation at a wind speed of 8 ms^{-1}. Both spectra have been normalised to a total level of 0 dBA for comparison and it is assumed that the spectra of wind turbine noise and vegetation noise do not vary significantly with different wind speeds.

As the ability of most building materials to attenuate noise is reduced at lower frequencies, the level of wind turbine noise relative to vegetation noise is likely to be higher indoors than outdoors. To demonstrate this concept, the outdoor-to-indoor noise reduction of a typical bedroom has been calculated in accordance with EN 12354-3:2000. This calculation is based on the construction materials described above, and requires input of the above spectra for wind turbine noise and vegetation noise. The internal acoustic absorption was determined based on a carpeted floor and plasterboard walls, and some additional absorption provided by furnishings. The window was assumed to be fully closed. The noise reductions calculated using EN 12354-3:2000 are also shown in the figure.

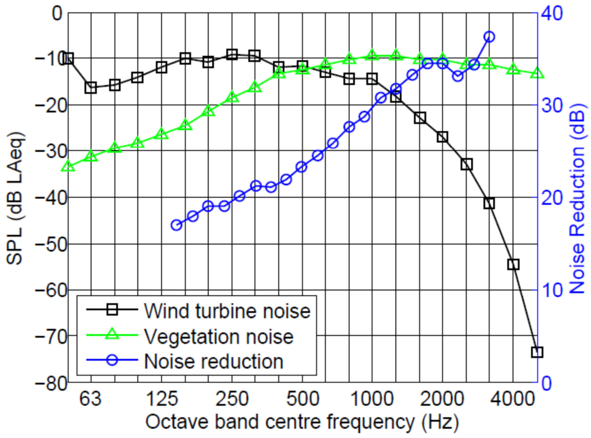

Figure 2. Comparison of calculated outdoor wind turbine noise spectrum at 2km with vegetation noise spectrum.

For an external wind turbine noise level 5 dB higher than the external vegetation noise level, the internal wind turbine noise level was calculated to be approximately 14 dB higher than the indoor vegetation noise level.

Based on the above results, it appears that there are critical problems with the assumption that background noise is capable of masking wind farm noise at external levels 5 dB higher than the background. However, further work including the analysis of the masking potential of background noise in relation to typical indoor wind turbine spectra, is needed to determine a suitable threshold.

Background noise regression analysis

The EPA guidelines (2009) require that at least 2,000 measurements of background noise (dB $L_{A90,10}$) at representative receiver locations be taken, along with simultaneous measurement of wind speed at hub height. The data are then plotted for each receiver location and a regression analysis used to determine the line of best fit. The allowed wind farm noise limit in dB $L_{Aeq,10}$ is 5 dB above this regression line, or the base noise limit of 35 or 40 dB, whichever is greater.

However, the background noise level at a receiver location at a given hub height wind speed is often highly variable depending on many factors including the time of day, wind direction, and agricultural or other activity taking place in the area at the time of measurement. As van den Berg (2005) notes, stable atmospheric conditions that typically occur during the evening or night-time result in a high wind shear; causing low wind speeds at ground level relative to the wind speed at hub height. The regression analysis effectively 'averages' the range of background noise levels for a given wind speed, and therefore may over-estimate the actual background sound levels occurring at a receiver location during stable atmospheric conditions, which usually occur during night-time when annoyance and sleep disturbance effects are also likely to be most critical.

Where conditions resulting in low background levels coincide with conditions resulting in worst case noise generation and propagation from the wind farm, wind farm noise levels are able to exceed background noise levels by significantly greater margins than the 5 dB anticipated in the guidelines. Figure 3 shows an example from Delaire (2011) where the wind farm would theoretically be permitted by the guidelines to generate noise levels 30 dB greater than the background noise levels in some circumstances. In addition, the actual background level (in dBA L90) is much less than assumed by the regression analysis during approximately half of the measurements (which are most likely the night-time ones).

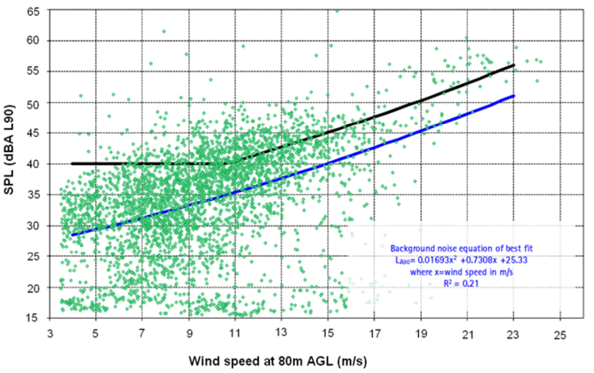

Figure 3. Example of background noise regression analysis (adapted from Delaire (2011)).

A more detailed regression analysis method is outlined in NZS 6808:2010, which requires that separate scatter plots be generated for day-time and night-time, and different wind directions, if a strong regression relationship is not evident in the overall scatter plot. If a regression relationship is not evident in the sub-plots, further analysis including wind flow modelling is required. However, this analysis is likely to be time consuming and expensive. In the absence of such an analysis, a conservative approach would be to *use the lowest measured background levels at each wind speed*. This would ensure that the background noise level is unlikely to fall below that assumed in setting the wind farm noise limit, and therefore would consistently provide or exceed the anticipated level of masking.

Difference in noise levels outside and inside of a residence

Both the SA EPA guideline noise limits and NZS 6808:2010 are expressed in terms of an outdoor noise limit, but annoyance and sleep disturbance are most commonly reported indoors. Understanding the outdoor-to-indoor noise reduction is therefore a critical aspect of understanding the possible causes of annoyance. A typical outdoor-to-indoor reduction of 15dB is outlined by both standards. Considering the internal target of 30dB(A) for a room with partially open windows (WHO, 1999, 2009), and the 40dB(A) guideline for rural industrial areas, this only gives a 5dB safety margin to account for differences in housing construction. In addition, the 30dB(A) indoor level recommended by the WHO (1999, 2009) was determined from studies in suburban areas where traffic noise is the dominant noise source. As such, this value of 30dB(A) may be too high for an indoor rural environment where low frequency wind turbine noise is dominant and the ambient noise levels are much lower than in suburban areas.

Here, a series of 10 minute average noise levels, $L_{eq(10min)}$, are analysed to evaluate the relation between indoor and outdoor noise levels. Wind speeds of 0ms^{-1} and 1.1ms^{-1} (north-westerly) were selected for comparison since these wind conditions occurred most frequently during the night and enabled comparisons to be made at different measurement times. Vegetation near the house consisted of 10m high trees approximately 5m from the side of the house and at least 30m in front of the façade. During the measurements, a freezer was operating in the room across the hallway and may have contributed to the sound pressure level at 50Hz and its harmonics. Unfortunately, the hub height wind speed and operational data were not available. These data would have enabled a more accurate analysis, since the wind characteristics at hub height were most likely different for a given wind condition at the residence.

For each wind speed, 3 measurements were considered to determine the maximum, minimum and mean outdoor-to-indoor sound pressure level (SPL) differences. For the measurements at 1.1ms^{-1}, it was desirable to analyse data obtained when the wind direction was as westerly as possible since the residence is located east of the ridge where the wind turbines are situated. Figures 4 and 5 show the SPL measured by the indoor microphones.

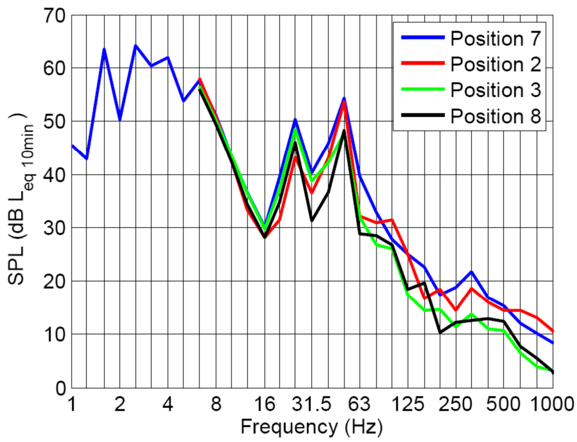

Figure 4. Comparison of indoor results for a wind speed of 0ms^{-1} at residence (2am). Note: Position 7 microphone is the only transducer rated to measure frequencies down to 0.8Hz.

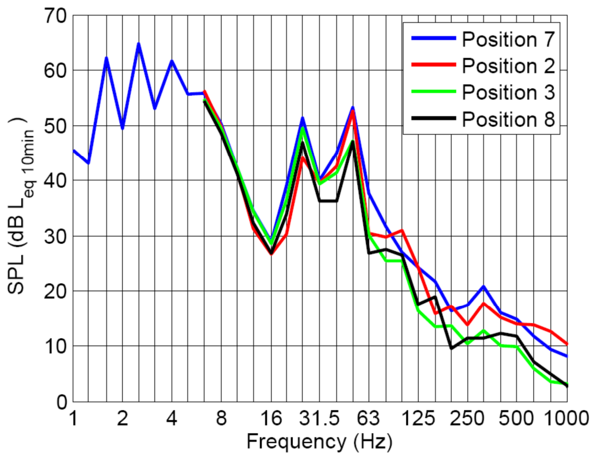

Figure 5. Comparison of indoor results for a wind speed of 1.1ms^{-1} in NW direction at residence (2:30am).

As the indoor measurements varied from one position to another, it was decided to analyse the differences between each outdoor microphone and the average SPL of the indoor microphones. It can be seen from the results shown in Figure 6 that the outdoor-to-indoor difference in SPL is highly dependent on the third octave band under consideration. The SPL difference can be anywhere between 0dB and 15dB above a frequency of 10Hz, depending on the third octave band of interest. In fact, below 10 Hz, the measured sound levels indoors are actually greater than they are outdoors. Hence, it appears to be more relevant to consider outdoor-to-indoor noise reduction for specific third octave bands along with the overall noise reduction.

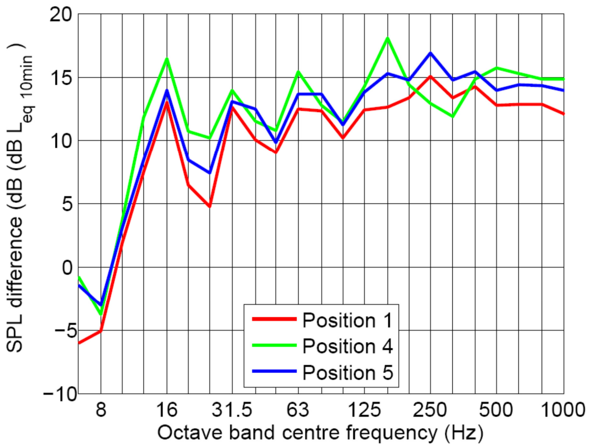

Figure 6. Comparison of outdoor results for a wind speed of $0ms^{-1}$ at the residence.

It can be seen from Figure 6 that reflections near the façade increase noise levels by between 1 and 3dB depending on frequency, except at 250 and 315 Hz when the microphone near the façade shows slightly lower levels. Figure 7 shows a comparison between measurements outdoors where one microphone is mounted at a height of 1.5m on a star-dropper (position 5) and the other is buried underground in a cubic box with an acoustic foam top and a side of length 400 mm (position 6 in Figure 1). It is evident in Figure 7 that a higher level of low frequency noise is measured by the microphone exposed to a northerly wind at $3.6ms^{-1}$, but this is not the case for the wind speed of $0ms^{-1}$. The figure indicates that measurement of infrasound with the underground microphone is more accurate below 50Hz, and that above 50 Hz, it does not produce useful results.

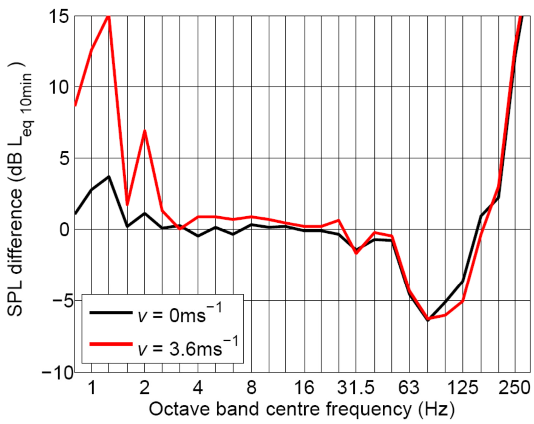

Figure 7. Difference in outdoor results for a microphone mounted at a height of 1.5m and microphone located underground in a box with a foam top for 2 wind speeds.

The maximum, minimum and mean outdoor-to-indoor differences of 3 selected 10 minute measurements at $0ms^{-1}$ and $1.1ms^{-1}$ for each third octave band are shown in Figures 8 and 9, respectively. For these figures, the indoor measurements were averaged over all four measurement positions before being compared with each outdoor measurement. The microphone located near the building façade as well as the underground microphone were excluded.

The difference in maximum and minimum outdoor-to-indoor SPL increases slightly with wind speed, however, results for both cases are reasonably consistent. Also included in Figures 8 and 9 are calculations for the outdoor-to-indoor SPL difference, which agree reasonably well with the measurements, except around 250 Hz where it is likely the acoustic absorption in the room was under-estimated. These results indicate that as the frequency of the noise is reduced the difference in results with the window open and closed becomes less pronounced. This implies that low frequency noise can effectively penetrate a dwelling whether the window is open or closed.

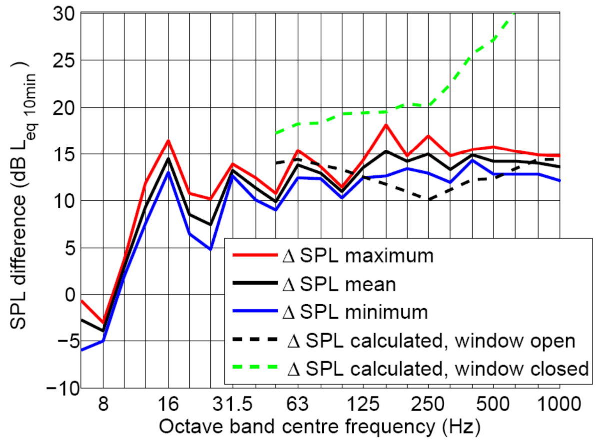

Figure 8. Maximum, mean and minimum SPL difference from outdoors-to-indoors with wind at $0ms^{-1}$.

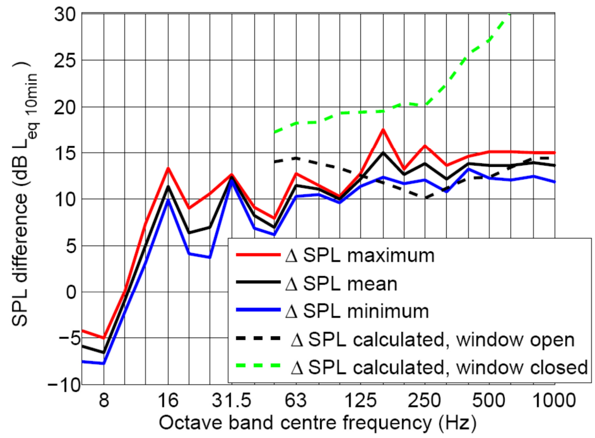

Figure 9. Maximum, mean and minimum SPL difference from outdoors-to-indoors with wind at $1.1ms^{-1}$.

The maximum outdoor-to-indoor overall A-weighted difference in sound pressure levels was found to be 9dB for both wind speeds. This is considerably lower than the assumed 15 dBA overall SPL outdoor-to-indoor reduction suggested in the 2009 SA EPA guidelines and in NZS 6808:2010.

Annoying characteristics

Wind turbine noise may exhibit tonality or amplitude modulation, which are known to make a noise subjectively more annoying than a noise at the same level which does not exhibit these characteristics (Wagner, Bareiss & Guidati 1996).

Tonality is likely to be the result of mechanical noise and may vary significantly between turbine models. Modern wind turbines generally have an isolated mechanical drive train such that the turbine does not generate noticeable tonal noise.

There have been cases where inadequate design or a mechanical fault have resulted in tonal noise from modern wind farms, however it is sometimes possible to retrospectively fix these problems.

Amplitude modulation is a fundamental characteristic of wind turbine noise, but may vary significantly depending on wind turbine design, wind farm design, topography, meteorological conditions, and distance from the wind farm. The causes of amplitude modulation are not well understood, but are thought to be related to the difference in wind speed over the swept area of the blade; and the directivity of aerodynamic noise sources (Oerlemans & Schepers 2009). A stable atmosphere results in a greater variation in wind speed with height, thereby potentially causing an increased degree of amplitude modulation during evening and night-time periods (van den Berg 2005). Noise from the leading edge is related to inflow turbulence and may therefore fluctuate with changes in the turbulence intensity and turbulence length scale (Wagner, Bareiss & Guidati 1996). These changes may be more significant in hilly topography, or when the turbine is in the wake of another turbine. Unlike trailing edge noise, which is modulated at the blade passing frequency (typically around 0.5 – 1.5 Hz for modern wind turbines), leading edge noise may fluctuate randomly.

It should be noted that a wind farm noise limit based on a comprehensive dose-response study would intrinsically take into account any annoying characteristics and an additional penalty to account for these characteristics would not be necessary.

The SA guidelines do not allow for any penalty to be applied for amplitude modulation, stating that the noise limits have been developed with this characteristic already taken into account. However, no additional information is given as to how this has been achieved.

The Draft NSW wind farm noise guidelines propose a 5 dB penalty where excessive amplitude modulation is measured. This is taken to be “a variation of greater than 4 dBA at the blade passing frequency”. While there is some ambiguity associated with this statement, it is assumed here to mean a variation in the A-weighted wind farm noise level within the interval between one blade and the next passing the tower.

This method of assessing amplitude modulation may not be appropriate for wind turbine noise since it is possible that the A-weighted overall level may not be significantly modulated while there is still significant modulation of certain frequencies. For example (Moorhouse *et al.* 2007) found that at a site where the A-weighted noise level was modulated by 3 – 5 dB, there was modulation of up to 10 dB in specific third-octave frequency bands. However, the relationship between annoyance and modulation of specific frequencies is not well understood.

Infrasound and low frequency noise

The frequency range of infrasound is generally considered to encompass frequencies below 20Hz, where the audible frequency range is taken to span 20Hz to 20,000Hz (Leventhall *et al.*, 2003). Frequencies between 10Hz and 200Hz are typically defined as in the low frequency range (Leventhall *et al*, 2003). There are several standards available that suggest suitable methods of assessment for low frequency noise (LFN) and infrasound. These methods are summarised below and include definitions of audible thresholds as well as identification of characteristics which indicate the potential presence of high levels of LFN.

According to ISO 389-7 (2005), the audible thresholds for 10Hz and 20Hz are 90-105dB and 75-85dB respectively. Broner *et al.* (2011) recommend an audible threshold of 65dB(C), and both ISO 7196 and DIN 45680 (1997) specify an audible threshold of 85dB(G). Both the C-weighting and G-weighting include a larger proportion of low frequency energy in a signal, which is appropriate where LFN is predicted to be problematic. The NSW draft guidelines (2011) specify 60dB(C) during the night-time and 65dB(C) during the day-time. It has been suggested by Broner and Leventhall (1983) and DIN 45680 (1997), that a simple method of determining the amount of low frequency noise present in a signal is to subtract the A-weighted SPL from the C-weighted SPL. Broner and Leventhall (1983) recommend that a difference of LCeq-LAeq of at least 20dB is necessary to indicate a LFN problem.

Tables 2 – 6 show noise levels measured in the current study and indicate compliance with all recommended standards except the LCeq-LAeq < 15-20dB. In this case, Broner and Leventhall (1983) and DIN 45680 (1997) would recommend a further investigation into the time-dependent low frequency noise characteristics including noise fluctuations, spectral balance and amplitude modulation.

Table 2. Measured SPL in the 10Hz 1/3 octave band.

SPL at 10Hz	Position 5	Position 6	Position 7	Position 8
Maximum (dB)	52	51	50	49
Average (dB)	45	44	44	43
Minimum (dB)	35	35	36	36

Table 3. Measured SPL in 20Hz 1/3 octave band.

SPL at 20Hz	Position 5	Position 6	Position 7	Position 8
Maximum (dB)	48	48	46	46
Average (dB)	43	43	39	39
Minimum (dB)	40	40	37	37

Table 4. L_{Geq}

L_{Geq}	Position 1	Position 2	Position 3	Position 4
Maximum (dB)	60	57	56	64
Average (dB)	59	57	55	63
Minimum (dB)	57	56	54	63

Table 5. L_{Ceq}

L_{Ceq}	Position 5	Position 7	Position 8
Maximum (dB)	60	55	55
Average (dB)	57	53	51
Minimum (dB)	52	47	43

Table 6. L_{Ceq} - L_{Aeq}

L_{Ceq}-L_{Aeq}	Position 5	Position 7	Position 8
Maximum (dB)	25	29	28
Average (dB)	22	26	26
Minimum (dB)	7	14	14

PREDICTION METHODS

The guidelines require that wind farm noise predictions are conducted using a noise propagation model, including allowances for noise attenuation due to air and ground absorption, topographical effects and meteorological effects. The specific model to be used is not specified, although typically either the ISO 9613-2 (1996) or CONCAWE models are used in Australia, while the NORD2000 model is used in Europe.

Evans and Cooper (2012) found that the ISO 9613-2 method, assuming completely reflective ground (G=0), and the CONCAWE method, assuming completely absorptive ground and Weather Category 6, were found to be the methods least likely to under-predict wind turbine noise levels. Average measured levels exceeded levels predicted by ISO 9613-2 at two out of 10 sites by up to 0.7 dB; and exceeded levels predicted by CONCAWE at one site by 1.2 dB. On the other hand, it has been stated that it is not uncommon for measurements to exceed predictions by 5 to 8 dBA (James, 2011), which suggests that there is some disagreement with regards to the accuracy of sound propagation models.

All sites where noise levels were under-predicted by Evans and Cooper (2012) were characterised by an initial steep downward slope from the wind farm towards the measurement site, becoming progressively shallower. The researchers suggested that topography may not have been well accounted for in the propagation models, possibly as a result of the unusually elevated noise source compared to other environmental noise sources. Another possibility is that this topography resulted in greater inflow turbulence which may have caused the wind turbine sound power to be higher than was input into the models.

Regardless of the propagation model used, the guidelines require that the wind turbine sound power level used as an input in the model is determined in accordance with IEC 61400-11 (2006), for all integer wind speeds between the cut-in wind speed and wind speed of rated power. This standard requires that sound pressure level measurements be taken at a distance of the hub height plus half of the rotor diameter downwind of a single wind turbine. The sound power levels in third-octave bands are then derived from these measurements. Typically these measurements are undertaken by the wind turbine manufacturer and the sound power level data supplied for the purposes of prediction. However, the accuracy of the data for application in situations where the topography differs significantly from the flat terrain used for the measurements is questionable. This is due to increases in in-flow turbulence caused by hilly terrain, which in turn results in significant increases in wind turbine noise generation. Turbulence from the wake of upwind turbines will also result in increased in-flow turbulence and could well explain the "pulsations" described by many residents. Currently the influence of topography and turbine layout on wind turbine noise generation is not well understood and more research in this area is needed. At present, it is not possible to predict the likelihood and magnitude of any amplitude modulation experienced by residents in advance of the wind farm being constructed.

COMPLIANCE MEASUREMENTS

A significant challenge associated with wind farm noise compliance measurements is that wind turbines are only operational in windy conditions, where background noise from wind in vegetation is often also present, especially during the day time when most compliance measurements tend to be made due to convenience considerations. When there is a significant amount of wind at the measurement location, it is difficult to separate wind farm noise levels from background noise levels for the purposes of checking compliance with the noise limits.

The SA guidelines require compliance measurements to be taken during operation of the wind farm, employing the same methodology as background noise monitoring. The wind farm noise level for each integer wind speed is determined by subtracting the background regression curve from the compliance monitoring regression curve. However, as noted by Delaire and Walsh (2009), this method assumes that the average background noise level during background noise monitoring and compliance monitoring is constant. However, in reality the background level is highly susceptible to change across seasons and years, particularly in a rural environment due to variations in noise from sources such as foliage, streams, livestock, insects, agricultural machinery, and other sources.

The guidelines recognise that compliance measurements in a windy environment are technically difficult and subject to variation, and recommend alternative compliance checking procedures such as those detailed in Clause 6 of the IEA recommended practices (1997), should the standard method fail to generate conclusive results. Alternative techniques include relocation of the microphone to a location less influenced by background noise sources, or closer to the wind farm; and approximation from measurements at reduced wind speeds only. However it is unlikely that measurements in a location other than the residence or not including the full range of operational wind speeds would provide confidence to residents concerned about possible non-compliances.

Another alternative technique is 'on/off' testing, which is described in AS4959:2010, and involves measurements at the 'critical wind speed' (the wind speed with the smallest predicted margin of compliance) both with the wind farm operating and shut down. This method requires attended measurements and it may therefore be time consuming to collect the required amount of data at the critical wind speed in the appropriate direction. A further option may be to undertake compliance measurements indoors. As noted previously, the level of wind induced vegetation noise relative to wind farm noise is likely to be lower indoors. However, to prevent interference from indoor noise sources, residents may have to vacate the dwelling for the duration of measurements, which may be disruptive.

Another method would be to take measurements during stable atmospheric conditions when there is sufficient wind at turbine height to drive the turbines but negligible wind at the measurement location and when the measurement location is in a downwind direction from the turbines. However, this would require monitoring over an extended period of night times, which would be expensive and time consuming.

Given the inherent difficulties associated with conducting conclusive wind farm compliance measurements, it seems appropriate to adopt a conservative approach for predictions so as to reduce the likelihood of any non-compliance occurring.

CONCLUSIONS

This paper has highlighted that the wind farm noise limits stated in the EPA guidelines (2009) do not ensure adequate protection of the amenity of rural communities. In addition, the concept of zoning has been challenged and background noise levels measured at each residence are proposed as a more suitable method for indicating acceptable noise limits at a given location. A dose response study specific to South Australian rural areas is considered pertinent to provide further guidance for selection of a suitable noise limit. This study should take into account annoying characteristics such as tonality and amplitude modulation, which are not adequately addressed in the EPA guidelines. The potential for background noise sources to mask wind turbine noise up to 5dB louder has also been questioned, particularly with respect to LFN. In addition, a more conservative method of predicting background noise for a given wind speed has been proposed, which is justified by highlighting the inherent difficulties associated with obtaining conclusive compliance measurements. The importance of separating out night-time and daytime background noise measurements for the purpose of establishing acceptable noise wind farm noise levels was also highlighted.

Measurements showed that consideration of the average noise level in a room is more accurate than relying on data from a single transducer. The transmission loss from outside-to-inside was found to be highly dependent on frequency. While the overall transmission loss is close to specifications in the EPA guidelines, in some 1/3 octave bands there is very little difference in noise level from outside-to-inside. The difference in LCeq-LAeq > 20dB suggests that further analysis of the data is required with respect to LFN.

This paper also highlighted the potential inaccuracy of using sound power level data from the manufacturer as an input for sound propagation models where the topography differs significantly from that used in the manufacturer's measurements. In general, the influence of the surrounding topography on noise generation of wind turbines is not well documented and further research is necessary.

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