COMPARISON OF PREDICTED AND MEASURED WIND FARM NOISE LEVELS AND IMPLICATIONS FOR ASSESSMENTS OF NEW WIND FARMS

Tom Evans[1] **and Jonathan Cooper**[2]
[1]**AECOM, Level 28, 91 King William Street, Adelaide, SA 5000**
[2]**Resonate Acoustics, 97 Carrington Street, Adelaide, SA 5000**

To maximise the energy output of wind farms whilst still meeting the relevant noise regulations, it is important that an accurate environmental noise prediction method be used during the planning stage. This paper presents a comparison of predicted noise levels from four commonly applied prediction methods against measured noise levels from the operational wind farm conducted in accordance with the applicable guidelines in South Australia. The results indicate that the methods typically over-predict wind farm noise levels but that the degree of conservatism appears to depend on the topography between the wind turbines and the measurement location.

INTRODUCTION

An environmental noise assessment is an important component of the planning stage for new wind farms located near to noise sensitive receivers. Noise criteria defined by regulatory authorities will often constrain the layout and number of turbines within the wind farm.

A key part of the assessment is the environmental noise prediction method used to predict wind turbine noise levels at nearby sensitive receivers. A prediction method that under-predicts noise levels, even marginally, could lead to turbines being shut down during the operational phase in order to achieve compliance with the noise criteria. Conversely, a prediction method that over-predicts noise levels could result in available land for wind energy production being under-utilised.

This paper presents a comparison of predicted noise levels from commonly applied noise prediction methods against measured operational wind farm noise levels from 13 sites at six wind farms. Noise levels from each of the sites have been analysed in accordance with the South Australian *Wind Farms Environmental Noise Guidelines* (SA Guidelines) [1].

In order to minimise the effect of other factors that could result in a difference between predicted and measured noise levels, predictions have been carried out using:

- measured sound power levels for the installed turbines
- topographical contours for each wind farm
- GPS-determined co-ordinates for measurement sites
- hub height measured wind speeds.

Similarly, the measurement sites and analysis processes have been selected to minimise the contribution of background noise to the measured noise levels.

The findings of this paper complements those of the authors' other paper in this issue [2]. The noise measurement and analysis process, outlined briefly in this paper, is discussed in more detail in the other paper.

PREVIOUS INVESTIGATIONS

A number of investigations into the accuracy of environmental noise prediction methods for wind farms have been undertaken both in Australia and internationally, with key ones discussed briefly in this section.

Bass et al. [3] conducted a study into the development of a wind farm noise propagation prediction model by measuring noise levels from a loudspeaker of known sound power level across three different sites. The loudspeaker was situated at a height between 15 to 30 metres above ground, with measurements conducted up to 900 metres away. It was concluded that the prediction model defined by International Standard ISO 9613-2:1996 [4] provided "impressive" accuracy between the predicted and measured noise levels but that this could be improved through the application of corrections depending on topographical conditions. Following this, Bullmore et al. [5] conducted measurements around three European wind farm sites and found the ISO 9613-2 prediction method provided an upper limit of measured noise levels under downwind conditions. This modelling assumed either completely reflective ground or 50% absorptive ground depending on the particular site.

A comparison of measured and predicted noise levels for two wind farms as part of the Portland Wind Energy Project has also recently been carried out [6]. For this assessment, post-construction L_{95} noise levels were measured in accordance with New Zealand Standard NZS 6808:1998 [7] and compared to the sum of the predicted noise levels and the average pre-construction background noise levels. It was found that the ISO 9613-2 prediction method, using 50% absorptive ground, provided the best correlation to the measurement data across the two wind farms. However, the paper identified potential concerns regarding the contribution of background noise levels to the overall measured noise levels.

A number of standards and guidelines also provide recommendations on prediction methods to be used for wind farms. NZS 6808:1998 and the updated 2010 version [8] both outline acceptable methods. A stakeholder review of NZS 6808:1998 [9] concluded that:

> *In cases where the distances between turbines and receivers are significant and have significant terrain features, the ISO9613 model produces more accurate results. As typical setbacks to NZ wind farms are 800 metres or more, ISO9613 would appear to most accurately predict measured sound levels.*

The SA Guidelines recommend the use of either the ISO 9613-2 or CONCAWE [10] prediction methods.

The discussed previous studies have typically focussed on comparing individual attended measurements (under known conditions) with predicted noise levels, or on assessing whether prediction methods provide an upper limit for any measured noise level at the site. This limits the ability to directly compare the results from these studies with the compliance measurement procedures typically carried out for Australian wind farms, as these procedures involve determination of an average noise level across a number of data points at each integer wind speed.

While the Portland Wind Energy Project study was carried out based on the NZS 6808:1998 assessment methodology, this method has only been used within Victoria and has recently been superseded by the NZS 6808:2010.

In our study, measured noise levels from wind farms in South Australia and Victoria have been determined in accordance with the SA Guidelines, or the earlier 2003 SA Guidelines [11] which use the same measurement process. This requires determination of an average measured noise level under all downwind periods. For future wind farms assessed in this manner, it is important that the accuracy of the environmental noise prediction method be understood to both improve the planning of the wind farm and to address concerns about noise prediction accuracy.

SITE DESCRIPTIONS

Six wind farm locations and 13 measurement sites have been selected for comparison in this paper as measurements collected at these sites appear to be controlled by noise from the wind turbines across a reasonable wind speed range.

The measurement sites were selected based on their higher than typical exposure to noise from the wind farms, or due to the low background noise levels at the site. They are typically representative of the closest receivers to wind farms in South Australia, although several of the measurement sites were not actually at a residence. However, one measurement site has been selected that is located approximately 3,000 metres from the nearest turbine.

For commercial reasons, the names and locations of the wind farms have not been disclosed and the wind farms will be designated as Wind Farm A through to F. The turbines at the farms are rated between approximately 1.5 MW and 2 MW. Based on compliance monitoring conducted at each site, all of these wind farms are in compliance with the environmental noise criteria.

Wind Farm A

Wind Farm A involves a line of turbines stretching about 10 kilometres along the top of a range of hills. The turbines are spaced approximately 400 metres apart. Three noise measurement sites have been considered as part of this comparison (A1, A2 and A3). Each site is located between 800 and 1000 metres from the nearest turbine, and situated 50 to 70 metres lower than the base height of that turbine.

The ground between Sites A1 and A2 and the nearest turbine to each site slopes steadily down from the turbine, with a slight rise in the ground relative to the straight line between the turbine base and the measurement site within about 100 metres of the receiver location. The ground between Site A3 and the nearest turbine slopes sharply down from the turbine initially, reaching a height of 5 metres above the measurement point less than 400 metres from the turbine before sloping gently for the remainder of the distance.

Wind Farm B

Wind Farm B also involves a line of turbines stretching about 10 kilometres along the top of a range of hills. The turbines are spaced approximately 300 metres apart. Four noise measurement sites have been considered as part of this comparison (B1, B2, B3 and B4). B1, B2 and B3 are located approximately 1,000 to 1,500 metres from the nearest turbine, with B4 located approximately 3,000 metres away. All sites are situated 130 to 200 metres lower than the base height of the nearest turbine.

The ground between Sites B1 and B3 and the nearest turbine to each site initially slopes sharply down from the turbine to the measurement site, with an 80% decrease in elevation before the midpoint between is reached. The topography between Site B4 and the nearest turbine is similar to that of B1 and B3, but the 80% decrease in elevation occurs within 800 metres of the turbine (approximately 25% of the total horizontal distance to the measurement point). The ground between Site B2 and the nearest turbine slopes relatively evenly down for the entire distance, with a slight concave nature to the slope.

Wind Farm C

Wind Farm C involves a group of turbines distributed over about 20 square kilometres, and spaced approximately 350 metres apart. Three measurement sites have been considered as part of this comparison and have been designated C1, C2 and C3. The measurement sites are located between 300 and 700 metres from the nearest turbine.

The ground around the wind farm is relatively flat, with no change in elevation from the turbine base to the measurement site greater than 10 metres.

Wind Farms D, E and F

Wind Farms D and E both involve turbines arranged in a line, while the turbines at Wind Farm F are arranged into a group. One noise measurement site has been selected for each wind farm and designated D1, E1 and F1 respectively. The distance from each site to the nearest turbine is 300 metres for D1, 1,200 metres for E1 and 700 metres for F1.

The ground between the nearest turbines and the measurement site at each of these wind farms is relatively flat, with no change in elevation from the turbine base to the measurement site greater than 10 metres.

Summary

Table 1 provides a general description of the topography for each site. At none of the measurement sites was the line of sight from receiver to the nearest turbine hubs and blades (controlling the overall noise levels) interrupted by the local topography.

MEASURED NOISE AND SOUND POWER LEVELS

Environmental Noise Measurements

A-weighted $L_{90,10min}$ noise levels from the wind farms were measured at each site over a period of three to four weeks. Both the measurements and subsequent data analysis were undertaken in accordance with the 2009 SA Guidelines [1]. The measured noise levels were correlated with wind speeds for the period, measured at the most representative hub height meteorological mast. A single 'measured' noise level value for each integer wind speed was determined by fitting a polynomial regression line to the data.

Only those measured noise levels that coincided with wind directions within 45° of the worst case wind direction (i.e. the direction from the nearest wind turbine to the measurement site) were considered for the analysis. Measurements that were obviously affected by extraneous noise sources or that did not coincide with wind speeds between the cut-in and cut-out of the turbines were excluded from the analysis. At eleven of the locations, over 500 valid data points remained in the worst case wind direction. At the other two locations (C1 and C2) approximately 200 valid data points remained although these were confined mainly to the small range of wind speeds where measured sound power data for the installed turbines was available.

A significant issue that can affect measurement results from operational wind farms is the contribution of the background noise environment. While this can be somewhat overcome by subtracting the measured pre-construction noise levels, Delaire and Walsh [12] showed this method is susceptible to error as background noise levels can change across seasons and years. The pre- and post-construction measurement locations may also be different, another possible inaccuracy with this method. To address this, each measurement site was selected such that it was as far away as possible from potential sources of background noise (e.g. trees, occupied dwellings), and such that the noise level at the site was typically controlled by turbine noise. In addition, only wind speeds where the L_{A90} noise level appears to be consistently controlled by turbine noise were considered in our analysis. These wind speeds have been selected based on analysis of the measurement data and supported by observations made on site during the measurements. Wind speeds where there was a significant spread in the measured noise levels were excluded, as observations on site indicated this variation was the result of extraneous noise sources affecting measured levels.

As an example, Figure 1 presents measurement results for Site B3, indicating a wind speed range of 4 to 12 m/s where the measured noise level is controlled by turbine noise. This is evident due to the small spread of the measurement data when compared to wind speeds above 12 m/s where background noise causes significant variation between measured noise levels at the same integer speed. At lower wind speeds, there are also a number of measurements where the turbine clearly cut-out due to low wind speed during the measurement period. These have been excluded from further analysis. For each measurement site, between three and six integer wind speeds were identified as being in the turbine-controlled wind speed range.

Table 1. General description of topography

Site	Topographical description	Approximate distance to nearest turbine
A1	Steady downward slope	1000 m
A2	Steady downward slope	800 m
A3	Concave downward slope	800 m
B1	Concave downward slope	1500 m
B2	Slight concave downward slope	1000 m
B3	Concave downward slope	1000 m
B4	Concave downward slope	3000 m
C1	Flat	600 m
C2	Flat	300 m
C3	Flat	700 m
D1	Flat	300 m
E1	Flat	1200 m
F1	Flat	700 m

Sound Power Level Measurements

Sound power levels for typically two of the turbine models installed at each site were measured in general accordance with International Standard IEC 61400-11 Edition 2.1 [13]. Minor deviations from IEC 61400-11 Edition 2.1 at each site were not considered likely to affect the measured sound power levels. There was generally little difference between the measured sound power levels for different turbines at the same site but the average measured sound power level has been used for this comparison.

The measured sound power levels were compared against the measured compliance noise levels at each of the sites. At every site, the change in measured compliance noise level across the turbine-controlled wind speed range demonstrated good correlation with the change in sound power level across that range. This suggests that there is no noticeable change in the propagation of noise from the turbines to the measurement locations due to changes in the wind speed.

Figure 2 compares the measured noise levels for Site B3 against the measured sound power levels (reduced by approximately 60 dB) for the turbines at that wind farm. Similar results were obtained for all of the measurement sites.

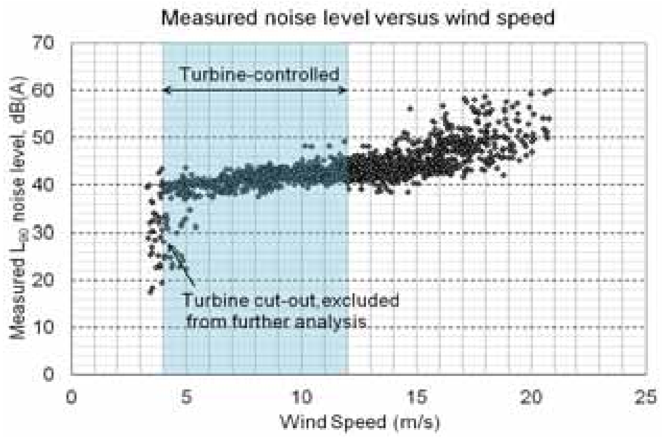

Figure 1. Example of measured noise levels versus wind speed with turbine-controlled wind speed range

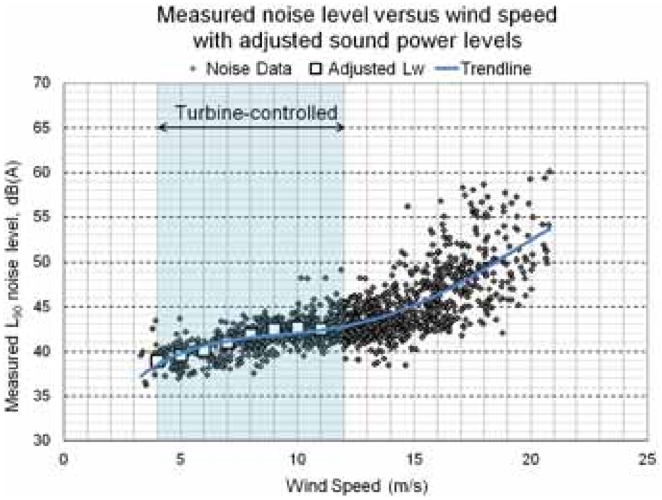

Figure 2. Comparison of measured noise levels and measured sound power levels

ENVIRONMENTAL NOISE PREDICTION METHODS

ISO 9613-2

The ISO 9613-2 prediction method, as implemented in the SoundPLAN Version 7.0 software (produced by Braunstein + Berndt GmbH), has been selected for comparison with the measured noise levels in this paper. It is recommended by both NZS 6808:2010 and previous investigations as providing appropriate accuracy for predictions of wind farm noise levels. ISO 9613-2 states a prediction accuracy of ± 3 dB for sources of heights up to 30 metres above ground and for distances up to 1000 metres from the source. However, outside of these conditions, no indication of accuracy is provided.

Two different ground absorption values (G=0 and G=0.5) have been adopted for the ISO 9613-2 method. No meteorological correction factor has been applied, such that the predicted levels can be considered to reflect the typical downwind noise level.

CONCAWE

The CONCAWE prediction method, as implemented in the SoundPLAN Version 7.0 software, has also been selected. It was developed based on sources of heights up to 25 metres above ground and is typically applied up to distances of 2,000 metres from the source.

Predictions with the CONCAWE method have been carried out assuming worst case meteorological conditions (Weather Category 6) apply from all wind turbines to each measurement site. Completely absorptive ground (G=1) has been assumed as the use of reflective ground has previously been found to result in significant over-predictions with the CONCAWE methodology [9]. The air absorption values specified by ISO 9613-2 have been used for the CONCAWE predictions.

NZS 6808:1998 method

The simplified hemispherical prediction method outlined in NZS 6808:1998 has been widely used in Australia and New Zealand, has also been used in this paper. The method is independent of topography and the noise level (L_R) at a height of 1.5 metres and distance R from each turbine is calculated based on Equation (1):

$$L_R = L_W - 10\log(2\pi R^2) - \alpha_a R \qquad (1)$$

L_W is the sound power level of the turbine and α_a is the attenuation of sound due to air absorption in dB(A)/m. Two different air absorption values have been used to calculate noise levels using this method:

- a constant value of 0.005 dB(A)/m as recommended by NZS 6808:1998
- the octave band air absorption values outlined in ISO 9613-2.

Nord2000 method

The Nordic environmental noise prediction method, referred to herein as the Nord2000 method, has been validated for the prediction of wind turbine noise [15]. This method, as implemented in the SoundPLAN Version 7.0 software, has been selected for comparison. The Nord2000 method represents the only prediction method used where the wind speeds have been altered accordingly to predict noise levels at each speed within the turbine-controlled wind speed range. This is as the Nord2000 method allows for specific wind speeds to be input at particular heights, which can vary the propagation. Other inputs specific to the Nord2000 prediction method included:

- average roughness length of 0.05 metres
- downwind conditions
- average temperature gradient of +5 K/km (temperature inversion), with standard deviation of 1 K/km
- turbulence constants: C_V^2 of 0.012 $m^{4/3}s^{-2}$ and C_T^2 of 0.0008 Ks^{-2}
- average ambient pressure measurements for the meteorological masts at each site
- flow resistivity for the site of 80 $kNsm^{-4}$
- medium roughness class.

Further information on each of these inputs and how they affect the predicted noise levels from the Nord2000 method can be found in the *Nordic Environmental Noise Prediction Methods, Nord 2000 Summary Report* [15].

Additional Model Inputs

Each noise model within the SoundPLAN software included the measured sound power levels for the installed turbines, topographical ground contours, turbine co-ordinates provided by the site operator and measurement site co-ordinates determined using a handheld GPS unit. The search radius in the SoundPLAN calculation module was set to 20 kilometres.

At Wind Farms A and B where the topography varied considerably between turbine and receiver, one metre elevation contours were used to develop the digital ground model. For Wind Farms C, D, E and F, 10 metre contours were used as this was the most accurate topographical data available. However, given the relatively flat nature of these sites, this was considered unlikely to affect the predictions. For the simpler NZS 6808:1998 method, only the measured sound power levels and the turbine and receiver co-ordinates were used as additional inputs. Based on the 2009 SA Guidelines, an average temperature of 10°C and average humidity of 80% was assumed for each site.

COMPARISON BETWEEN MEASURED AND PREDICTED NOISE LEVELS

Table 2 summarises the average difference between the predicted and measured noise levels at each site. A positive difference indicates over-prediction of the noise levels, while a negative difference indicates under-prediction. The differences have been averaged across the turbine-controlled wind speed range for the site, but the variation between differences at each wind speed is typically less than 0.2 dB(A) due to the good agreement between the change in measured sound power levels and the change in measured noise levels. The results indicate that, except for concave topographies, nearly all of the prediction methods over-predict wind farm noise levels at receivers when the measured levels are assessed in accordance with compliance methodology specified by the SA Guidelines.

Based on the comparison for the thirteen different measurement locations, it appears that topography plays an important role in the accuracy of predicted noise levels. This is most clearly evident at Wind Farm A where measurement sites A2 and A3 are located on different sides of the same small group of wind turbines. The only significant difference between the two sites is the topography from the nearest turbines to the measurement site.

As an example of the effect of topography, the ISO 9613-2 method with 50% absorptive ground is typically within ±1 dB(A) of the measured noise levels at Wind Farms C, D, E and F where the topography is relatively flat. Yet at Wind Farm B, where the topography is concave between the nearest turbines and receivers, this method can under-predict noise levels by up to 4 dB(A).

Considerable under-predictions appear to occur only at sites with concave slopes, with the NZS 6808:1998 (constant αa) and ISO 9613-2 (G=0.5) methods typically under-predicting by 2 to 5 dB(A). The exception is at B4, where the NZS 6808:1998 (constant α_a) method resulted in an under-prediction of approximately 15 dB(A). This is considered to be an effect of the significant distance to the measurement site (over 3,000 metres) at which the assumption of constant air absorption across the entire frequency range does not hold.

However, the relatively commonly used ISO 9613-2 (G=0) method only marginally under-predict noise levels at these locations. This finding is consistent with that of Bass et al. [3] who stated with reference to the ISO 9613-2 method:

> *Where the ground falls away significantly between the source and receiver ... it is recommended that 3 dB(A) be added to the calculated sound pressure level.*

IMPLICATIONS FOR ASSESSMENTS OF NEW WIND FARMS

Effects of Topography

The comparison between measured and predicted noise levels suggests that the topography between the turbines and the assessment location can be an important factor in the accuracy of particular prediction methods. The difference in accuracy of a particular method between a site with a steady slope to the nearest turbine and one with a concave slope can be 6 to 7 dB(A), even where the turbine hub is still clearly visible from the receiver.

Figure 3 shows the topographical cross-section for Site A2 (steady slope) from the nearest turbine, with the line of direct sight from the turbine hub to measurement site shown in red and the line from the turbine base to the measurement base shown in blue. Figure 4 shows the same cross-section for Site B1 (concave). It is clear that the line of sight from both measurement sites to the turbine is not broken despite the significant variance in the prediction accuracies at both sites.

A number of different factors based on the topographical cross-section have been calculated and compared to the differences between measured and predicted noise levels for each method in order to determine a correction factor that could be applied to predicted noise levels.

For Wind Farms A and B, dividing the area beneath the topographical cross-section by the area beneath the line connecting the turbine base to the measurement base appears to provide a reasonable correlation to the differences obtained

Table 2. Average difference between predicted and measured noise levels at sites (turbine-controlled speeds only)

Prediction method	**Predicted - measured noise levels, dB(A)**			
Wind Farm A	**A1 - Steady**	**A2 - Steady**	**A3 - Concave**	
ISO 9613-2 (G=0)	5.8	5.4	-0.4	
ISO 9613-2 (G=0.5)	2.2	2.2	-3.5	
CONCAWE (G=1)	6.2	6.5	1.3	
NZS 6808:1998 (constant α_a)	2.5	3.1	-1.9	
NZS 6808:1998 (ISO 9613 α_a)	6.2	6.5	1.2	
Nord2000	3.7	4.5	-0.8	
Wind Farm B	**B1 - Concave**	**B2 - Slight concave**	**B3 - Concave**	**B4 - Concave**
ISO 9613-2 (G=0)	-0.7	1.0	-0.4	-0.3
ISO 9613-2 (G=0.5)	-3.8	-2.4	-3.4	-4.8
CONCAWE (G=1)	-1.2	1.6	0	-5.2
NZS 6808:1998 (constant α_a)	-5.4	-2.5	-2.9	-14.7
NZS 6808:1998 (ISO 9613 α_a)	-0.1	1	-0.4	-1.2
Nord2000	-1.4	0.4	-1.4	-2.2
Wind Farm C	**C1 - Flat**	**C2 - Flat**	**C3 - Flat**	
ISO 9613-2 (G=0)	2.9	2.9	2.6	
ISO 9613-2 (G=0.5)	1.0	0.1	-0.6	
CONCAWE (G=1)	3.5	3.6	2.5	
NZS 6808:1998 (constant α_a)	2.5	1.8	0.1	
NZS 6808:1998 (ISO 9613 α_a)	3.2	3.4	2.5	
Nord2000	1.4	0.6	-0.3	
Wind Farm D, E and F	**D1 - Flat**	**E1 - Flat**	**F1 - Flat**	
ISO 9613-2 (G=0)	3.2	2.5	2.1	
ISO 9613-2 (G=0.5)	0	-1.2	-1.0	
CONCAWE (G=1)	3.7	1.8	2.6	
NZS 6808:1998 (constant α_a)	1.6	-2.5	-0.6	
NZS 6808:1998 (ISO 9613 α_a)	3.2	3.1	3.3	
Nord2000	1	0.2	2.0	

with the ISO 9613-2 prediction method. However, this relationship does not hold for the flat topography of the other wind farms.

At this stage, no single topographical correction factor has been identified that can be applied to each of the situations. Additional reliable measurement data from other sites with varying topography is still required to determine an appropriate correction factor for the standard prediction methods.

Uncertainty

The predictions and measurements in this paper have been undertaken in an attempt to reduce potential uncertainty as much as possible. Some of these, such as uncertainty associated with the accuracy of measurement equipment, will be reduced due to the large number of measurements used to determine an overall ‘measured’ noise level. Similarly, slight topographical changes that are not accounted for in the noise models are unlikely to affect predicted noise levels at distances of over 300 metres. Nonetheless, some uncertainty in both the prediction and measurement of noise levels still remains.

A key source of uncertainty relates to the wind shear and variance of wind speed across a wind farm. To minimise this, all wind speeds have been based on hub height wind speeds and taken at a nearby meteorological mast or the nearest turbine to each measurement site. However, some uncertainty remains with regard to the difference between the measured wind speed and the actual wind speed at each wind turbine contributing to the overall measured noise level.

Measurement of the sound power level included calculation of an uncertainty value which is typically less than 1 dB(A) at those speeds considered for this comparison. While this can affect the actual difference between predicted and measured noise levels, most noise assessments undertaken at the planning stage of a new wind farm will use guaranteed sound power levels for turbines provided by the manufacturer. Guaranteed sound power levels are typically higher than actual sound power levels as the uncertainty is sometimes added to them by the manufacturer as a safety factor. For new assessments using guaranteed sound power levels, any prediction method will therefore be more likely to over-predict actual noise levels.

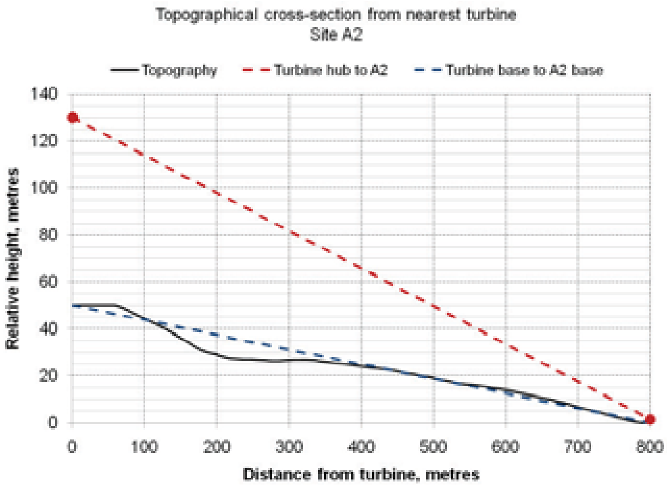

Figure 3. Topographical cross-section from nearest turbine to Site A2 (steady slope)

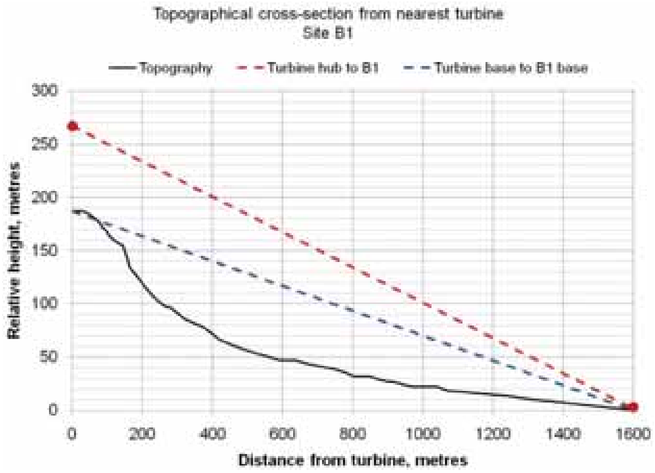

Figure 4. Topographical cross-section from nearest turbine to Site B1 (concave)

The contribution of background noise to the measured noise levels also requires consideration. Although this paper has identified wind speed ranges where turbine noise appears to control overall noise levels, there will still be some contribution to the measured noise levels from background noise. No attempt has been made to correct for the influence of background noise, such that actual turbine noise levels would have been slightly lower than the levels used in this assessment.

Similarly, the noise monitor at Site A3 was located approximately 10 metres from a building structure. This was the only monitor to be located near to a structure, and the measured noise levels may have included a relatively small contribution from reflected noise caused by the presence of the building.

However, any contribution to the measured noise levels from either background noise or reflected noise would lead to an underestimate of over-predictions (and an overestimate of under-predictions) of the different methods. Hence, the analysis provided here may be considered slightly conservative.

Overall Prediction Accuracy

The results in Table 2 indicate that none of the considered prediction methods can be considered suitably accurate for all wind farms. None of the methods appear to appropriately account for effects caused by topographical changes between the turbines and the measurement sites. While the ISO 9613-2 method with completely reflective ground may provide a typical upper limit for the measured noise level across all of the considered sites, it will also significantly over-predict noise levels at sites with flat topography or steady downward slopes.

The CONCAWE method (with G=0) also appears to provide a typical upper limit for the measured noise levels at each site, with the exception of B4 where it under-predicted noise levels by approximately 5 dB(A). B4 is the furthest measurement site from a turbine at a distance of over 3,000 metres and the measured noise levels are in the order of 30 dB(A), considerably below applicable noise criteria. The CONCAWE method therefore seems suitable for predicting noise levels to distances up to approximately 2,000 metres from a wind farm but not for accurately predicting noise levels at distances further than this.

Overall, the comparison of prediction methods in this paper indicates that predicted noise levels for wind farms are generally conservative. None of the measurement results from the sites indicate that the most commonly used methods in South Australia would under-predict noise levels by more than 1 dB(A).

It should also be noted that wind farms represent a relatively rare situation where the noise source is located greater than 60 metres above the ground height. Prediction methods such as CONCAWE and ISO 9613-2 have generally not been developed or tested considering noise sources at these heights, which may explain why they do not appropriately account for topography in this situation.

It is also important to note that the predicted noise levels are A-weighted $L_{eq,10min}$ noise levels which are being compared to measured A-weighted $L_{90,10min}$ noise levels. Our other paper [2] finds that the typical difference between L_{eq} and L_{90} noise levels for wind farms is approximately 1.5 dB(A). This indicates that both the ISO 9613-2 method (with G=0) and the CONCAWE method (with G=1) provide quite accurate predictions of L_{eq} noise levels for wind farms where the topography is relatively flat. Yet for Wind Farms A and B, where the topography varies more significantly, these prediction methods appear to either under- or over-predict L_{eq} noise levels by approximately 2 dB(A).

Recommended Prediction Methods For New Wind Farms

For many other noise sources, exceedances of the noise criteria of 1 to 2 dB(A) are often considered acceptable as humans do not generally perceive a change of 1 to 2 dB(A) in field conditions. However, a 1 dB(A) exceedance of the criteria for a wind farm could often result in a regulatory authority requesting mitigation and it could be considered important should wind farm noise levels be under-predicted by even 1 dB(A) during the planning stage.

Based on the comparisons presented in this paper, the prediction methods that would minimise the risk of a potential exceedance of the criteria would be the ISO 9613-2 method with completely reflective ground or the CONCAWE method with completely absorptive ground and Weather Category 6. However, care should be taken with both of these methods when considering turbines on a raised ridgeline where the ground slopes sharply down from the turbines to the receiver. The analysis in this paper has shown that these methods could under-predict noise levels in this scenario by up to 1 dB(A).

The NZS 6808:1998 method using the ISO 9613 air absorption factors may also be suitable to provide a prediction with minimal risk but is overly conservative on sites with a flat topography or steady downward slope from turbine to receiver.

It is also important to recognise that, in scenarios where the topography is relatively flat or there is a steady slope away from turbines located on a hill, these methods can over-predict noise by up to 6 dB(A) even where line of sight from the receiver location to the turbine hub is not broken. An understanding of the topography is therefore important for any environmental noise assessment of new wind farms.

It appears that the other common prediction methods presented in this paper (NZS 6808:1998 with constant α_a, ISO 9613-2 with 50% absorptive ground and Nord2000) should only be used with due consideration as they can result in considerable under-predictions of noise levels in certain situations.

Due to the relatively large number of possible inputs required for the Nord2000 method to determine meteorological conditions, it may be possible to improve the accuracy of this method through appropriate variation of these inputs. However, this would require further investigation and would also require the environmental noise assessment for a wind farm to analyse much more detailed meteorological data than is currently done.

Other Compliance Assessment Methodologies

The comparison in this paper has focussed on measured wind farm noise levels analysed in accordance with the methodology outlined in the SA Guidelines. For some other Australian and New Zealand wind farms, compliance measurements may also be required to be measured in accordance with NZS 6808:1998 or NZS 6808:2010. These standards require measurement of A-weighted L_{95} and L_{90} noise levels respectively and consider all wind directions. Cooper et al. [2] demonstrated that measured noise levels analysed under these Standards were typically 0 to 2 dB(A) lower than those measured under the 2009 SA Guidelines. This occurred as these other methods consider all wind directions and not only the worst case wind direction, and NZS 6808:1998 also requires measurement of L_{A95}, rather than L_{A90}, noise levels.

The implication of this is that, for wind farms assessed under NZS 6808:1998 or NZS 6808:2010, under-prediction appears unlikely even in the case of a concave slope. Similarly, where the topography is relatively flat around a wind farm or there is a steady downward slope between turbines on a hill and receivers below, the prediction methods considered in this paper would be expected to result in larger over-predictions than shown in Table 2.

Another compliance assessment method that may be used more extensively in the future is that contained in Australian Standard 4959-2010 [16], where the measured average L_{eq} noise level from the wind farm is required to comply with the noise criteria. The Standard assumes that the average L_{eq} noise level from a wind farm will be at least 1.5 dB(A) above the measured L_{90} noise level. The implication of this is that under-prediction of wind farm noise levels would become more likely for flat and concave topographies (unless this 1.5 dB(A) difference is taken into account during the assessment process) should the compliance assessment from AS 4959-2010 be required by regulatory authorities.

CONCLUSIONS

Measured noise levels from 13 measurement sites at six different wind farms have been compared to predicted noise levels using commonly applied noise prediction methods. The measurements and subsequent analysis have been carried out in accordance with the 2009 SA Guidelines. The sites and wind speed ranges have been selected to minimise the influence of background noise on the measured noise levels.

The comparison has indicated that the commonly used ISO 9613-2 (with completely reflective ground) and CONCAWE (with completely absorptive grounds) generally over-predict noise levels from the wind farm. However, the degree of over-prediction appears dependent on the topography around the wind farm. At sites with a relatively flat topography or a steady slope from the turbines to the measurement sites, the over-prediction can be in the order of 3 to 6 dB(A). However, at sites where there is a significant concave slope from the turbines down to the measurement sites, these commonly used prediction methods are typically accurate, with the potential of marginal under-prediction in some cases.

Other commonly used prediction methods, such as the NZS 6808 method with constant air absorption or the ISO 9613-2 method with 50% absorptive ground, can under-predict noise levels in some situations and should only be used with caution.

The implication of this for the assessment of new wind farms is that the topography around the site is an important consideration to estimate the degree of conservatism provided by the prediction method.

At this stage, no clear correction factor based on the topography has been identified that could be reliably applied across any wind farm site to improve the accuracy of noise prediction methods. Additional measured noise levels for wind farms with varying surrounding topography are required in order to improve the available data set.

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