Analysis of wind turbine low frequency noise prediction accuracy

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ABSTRACT

Some regulatory authorities in Australia have recently proposed low frequency noise assessment criteria for wind farms based on C-weighted noise levels. This involves the specification of an outdoor night time trigger level of 60 dB(C), above which further investigation may be required. While the accuracy of noise model predictions of A-weighted noise levels is well established for wind turbines, less information is available on the accuracy of low frequency noise predictions. This paper presents an analysis of approximately eight months of low frequency noise measurements at a location near a wind farm, conducted using appropriate windshields and at locations away from extraneous noise sources. The measured low frequency noise levels are compared to predicted levels to assess the accuracy of conventional noise modelling techniques for low frequency wind farm noise. Changes in low frequency noise levels with wind direction, wind speed and wind shear are also analysed.

Keywords: Wind Turbines, Low Frequency   I-INCE Classification of Subjects Number(s): 14.5.4

1. INTRODUCTION

Wind turbines produce noise over a wide range of frequencies, with the noise being relatively broadband in nature when near to the turbine. However, as noise sensitive locations in Australia are typically located further than one kilometer from the turbines, lower frequency components of the noise tend to contribute to a higher proportion of the overall noise level at residences.

Recently, some regulatory authorities in Australia have proposed low frequency noise assessment criteria for the assessment of new wind farms based on C-weighted noise levels. In NSW (1), for example, an outdoor night time trigger level of 60 dB(C) is specified above which further investigation may be required. This criterion requires acoustic consultants to have an understanding of the accuracy with which predictions can be made about low frequency from new wind farm projects. While the overall accuracy of standard noise prediction methods for A-weighted noise levels from wind farms is well documented (2, 3), less information is available regarding the accuracy of low frequency noise predictions.

This paper presents measured low frequency noise levels over an extended period at a site located 1.2 kilometres from the nearest turbine at a relatively large operational wind farm. The measurements were conducted over a period of eight months to capture a large range of operating conditions. The measured noise levels are compared to predicted noise levels for wind farm to assess the accuracy of low frequency noise prediction methods for wind turbine noise.

2. BACKGROUND

2.1 Low Frequency Noise Criteria in Australia

In 2011, the *Draft NSW Planning Guidelines: Wind Farms* (Draft NSW Guidelines, 1) were released, including guidance for the assessment of noise from wind farms in NSW. The Draft NSW Guidelines specify that, if it is shown that C-weighted noise levels (measured from 20 Hz upwards) regularly exceed 65 dB(C) during the day and 60 dB(C) during the night, then “a more detailed assessment of low frequency noise should be undertaken”. This more detailed assessment takes the form of an assessment against the indoor low frequency noise criteria proposed by the UK Department for Environment, Food and Rural Affairs (4), which apply a different assessment criterion to each

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one-third octave band from 10 Hz to 160 Hz.

In 2012, EPA Victoria released a draft wind farm noise guidance document (5) to members of the Australian Acoustical Society for comment. It has not been finalised but the aim of this document was to give guidance as to the way that the relevant wind farm noise standard for Victoria (New Zealand Standard 6808:2010, 6) should be applied. Where a low frequency assessment is considered appropriate, the draft document included a low frequency noise screening criterion of 65 dB(C) L_{90} during the daytime, 60 dB(C) during the night time and an additional requirement that the C-weighted L_{90} level must be more than 20 dB higher than the A-weighted L_{90} level. As for the NSW guideline, the C-weighted noise level is only measured based on frequencies of 20 Hz and above. If the screening criterion is exceeded, then an internal assessment is to be undertaken against the DEFRA criteria.

While neither the Draft NSW Guidelines nor the EPA Victoria guidance document have been finalised, planning stage environmental noise assessments for new wind farms in NSW now generally include a prediction of low frequency C-weighted noise levels at noise sensitive receivers (7, 8). As the secondary DEFRA criteria are assessed indoors, it is difficult to assess compliance with them at the planning stage of a wind farm. Therefore, accurate assessment against the initial C-weighted screening criteria is important.

Recently, wind farm opposition groups have also stated (9) that assessments should consider research undertaken by Kelley in the 1980s. This research was focused on turbines where the blades were located downwind of the tower and which resulted in impulsive low frequency noise as the blades passed through the wake of the tower. While the level of low frequency noise is significantly lower for modern wind turbines where blades are positioned upwind of the tower, it is informative to consider the low frequency noise criteria recommended for the assessment of low frequency noise annoyance by Kelley in 1987 (10). Kelley found a good relationship between the C-weighted indoor noise level and annoyance, recommending annoyance thresholds of 67 dB(C) to 76 dB(C) L_{eq} depending on whether the noise is impulsive or not. By contrast, the criteria being considered in NSW and Victoria appear conservative.

2.2 Previous studies

The A-weighted prediction accuracy of noise models for wind farms is relatively well understood, when assessment is conducted according to the methodologies used in Australia and the UK. Both the UK Institute of Acoustics (2) and Evans and Cooper (3) demonstrate that the ISO 9613-2 prediction methodology (11) provides accurate results for A-weighted wind turbine noise levels with due consideration of topographical effects.

Less information is available regarding the accuracy of prediction methods for low frequency noise, whether that be assessed using the C-weighted level or another low frequency metric. In a recent study Brown et al (12) analysed data collected at 11 sites from three Australian wind farms and reported that both the ISO 9613-2 and CONCAWE (13) methodologies tended to over-predict C-weighted low frequency noise levels as long as completely reflective ground was assumed for the ISO 9613-2 methodology and completely absorptive ground assumed for the CONCAWE methodology. However, this study acknowledged certain limitations including that the measurements were conducted using a 90 mm diameter windshield, which may not be sufficient to prevent wind-induced noise influencing the measurement results.

Søndegaard and Sørensen (14) investigated the accuracy of low frequency noise predictions conducted using the Nord2000 methodology based on a site in undulating terrain and with more than 40 wind turbines. An analysis was undertaken of predictions at three measurement positions between 2.5 and 3.5 kilometres from the wind farm, and good agreement was found between predicted and measured noise levels in the range of 20 to 200 Hz when predictions were carried out under the assumption that the wind speed was the same at all turbines. The paper reported measured noise levels from -2.9 dB below to +1 dB above the predicted noise levels for the A-weighted level calculated between 10 and 160 Hz, although the analysis presented was based on a single sample at each of the measurement positions.

3. SITE DESCRIPTION

3.1 Wind farm

This paper focusses on low frequency noise measurements conducted at a large operational commercial wind farm comprising wind turbines with a rated capacity of approximately 3 MW. The topography of the wind farm and the surroundings is essentially flat. Measurements of A-weighted noise levels at the wind farm indicates that relatively accurate predictions are obtained when assuming that the ground absorption in the ISO 9613-2 algorithm is set to 50% absorptive, providing good agreement with other studies (2,3). For reference, the measured A-weighted noise level at the measurement site for the maximum sound power output of the turbines is 39 dB(A) L_{90}.

The wind turbines at the site have a maximum measured A-weighted sound power level of approximately 105 dB(A) re 10^{-12} W and a maximum measured C-weighted sound power level of approximately 118 dB(C) re 10^{-12} W. Figure 1 presents measured one-third octave band sound power levels for the wind turbines at their maximum sound power output (hub height wind speed of approximately 10 m/s), determined in accordance with IEC 61400-11 Edition 2.1 (15).

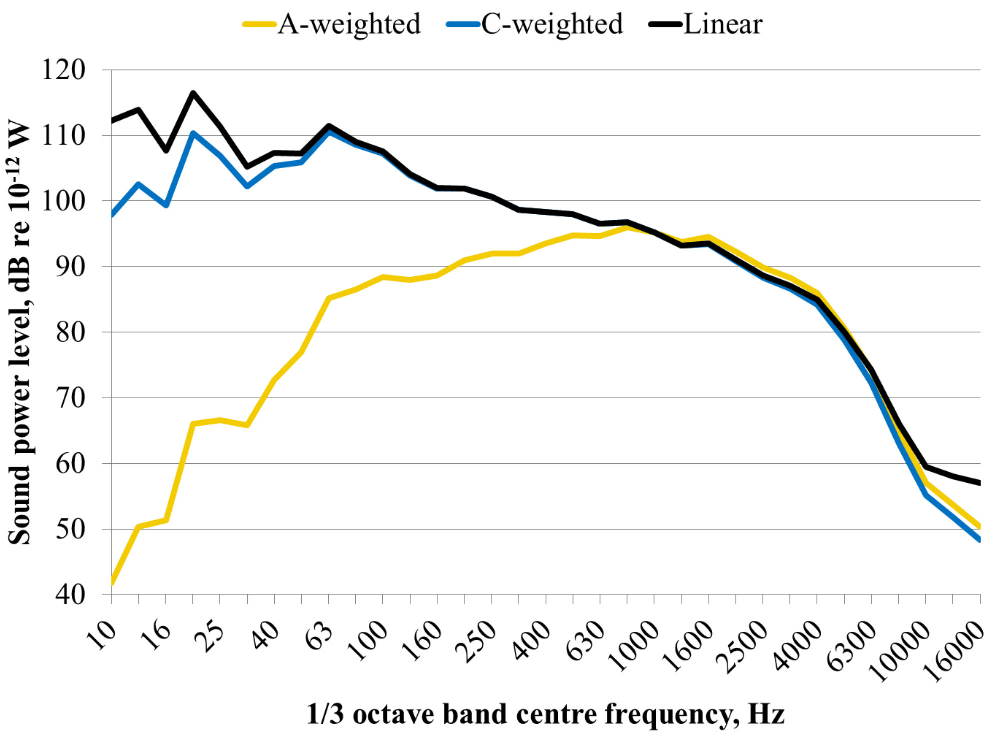

Figure 1 – Measured sound power level of wind turbine type installed at wind famr

3.2 Measurement location

Long-term noise measurements were conducted continuously for a period of eight months at an outdoor location approximately 1.2 kilometres from the nearest turbine. The measurement location was selected such that it was a significant distance from residences and not near significant vegetation other than the surrounding grass. The nearest road is approximately 350 metres away and carries negligible traffic.

The measurements of low frequency noise were conducted originally using a Rion NL-22 Class 2 sound level meter, configured to measure $L_{Ceq,10min}$ and $L_{C90,10min}$ metrics. After an initial period, the meter was removed from site and a Brüel & Kjær 2250 Class 1 sound level meter at the same measurement location was configured to measure $L_{Ceq,10min}$ and 10-minute averaged one-third octave band L_{eq} and L_{90} levels. The microphones at the site were housed within a 700 mm diameter multi-layered windshield that has previously been found to provide sufficiently accurate measurements of noise levels across a frequency range of 10-10,000 Hz (16).

The grid-like configuration of the wind farm meant that, when the location was downwind of the nearest turbines, the wind turbines were also in the wake of a considerable number of other turbines. Previous analysis has shown that there is an increase of 2 to 3 dB in low frequency noise from turbines when they are in the wake of other turbines (17). The measurement location is therefore considered to represent a worst case situation for low frequency noise measurements.

It is important to note that the measurement location was considerably closer to the wind farm than any other non-financially involved residence, and the measured noise levels presented within this paper are higher than those experienced at neighbouring residences.

4. MEASUREMENT RESULTS

4.1 Measured C-weighted noise levels

The measured C-weighted $L_{eq,10min}$ noise levels were correlated with hub height wind speed taken from the five nearest wind turbines to the measurement site as this was found to provide the clearest relationship to the noise source level. The C-weighted L_{eq} level was used in this case due to the lack of measured C-weighted L_{90} noise levels after the Rion was removed from the site and as, generally, the L_{eq} level could be relatively accurately measured at the site. Often this is not possible when measuring at a considerable distance from a wind farm due to the influence of extraneous noise.

To improve the overall accuracy of the measured data, some data exclusion was performed on the operational turbine noise data. Data was excluded where a sufficient number of turbines were not operating such that the predicted noise level decreased by more than 0.5 dB from the predicted level with all turbines operating. Data was also excluded for operational periods where the measured L_{Aeq} level was within 10 dB of the measured L_{Ceq} noise level. As the measured A-weighted sound power level of the turbines is typically 10 to 13 dB lower than the C-weighted sound power level, it is considered likely that these periods were influenced by an extraneous noise source. While it is not necessarily clear whether the extraneous source affected both the A- and C-weighted levels, it was considered reasonable to exclude these periods to improve the overall accuracy of the dataset.

Figure 2 presents the measured operational C-weighted L_{eq} noise levels referenced to hub height wind speed. Periods where there was an outage of the entire wind farm site are also shown for comparison. It can be seen that the measured noise levels are generally significantly higher during the operational periods, indicating that low frequency noise levels at the site are often controlled by wind turbine noise.

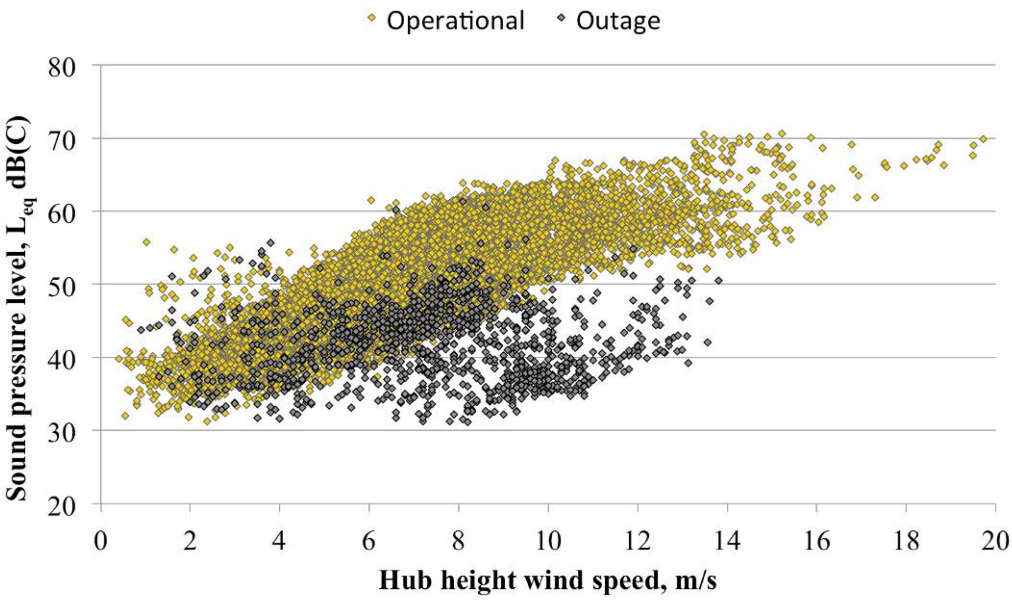

Figure 2 – Measured L_{Ceq} noise levels with hub height wind speed

There is considerable spread in the operational C-weighted dataset shown in Figure 2. Figure 3 separates the data into periods when the measurement position was downwind (±45˚) and upwind (±45˚) of the nearest wind turbines. The difference between the two wind directions is distinct, with the downwind levels approximately 10 dB higher than the upwind levels at the maximum sound power output of the wind turbines (10-12 m/s). Based on this data, as well as the data captured during crosswind conditions, which lay midway between the two datasets in Figure 4, the cause of the spread in the datasets is variations in wind direction.

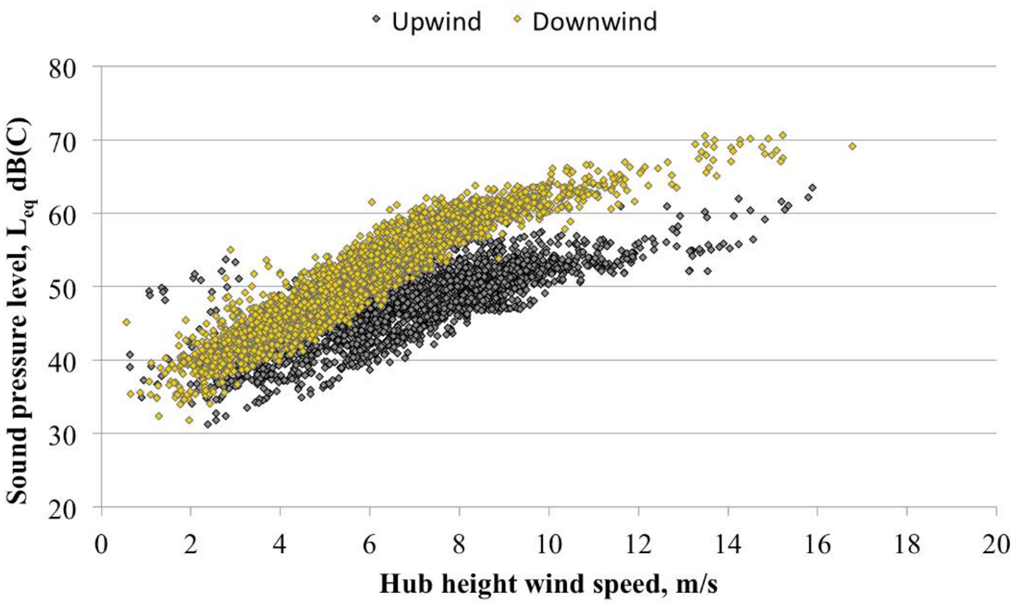

Figure 3 – Measured downwind and upwind L_{Ceq} noise levels with hub height wind speed

The measured downwind C-weighted noise levels reach a typical maximum of 61 – 64 dB(C) L_{eq} at the wind speeds at which the wind turbines reach maximum sound power (10 m/s). While the sound pressure levels do increase at wind speeds higher than this, this data is limited and measured sound power levels of the wind turbines do not show a corresponding increase. An analysis was undertaken of measured noise levels during periods of high wind speeds (> 12 m/s) and it was found that the C-weighted noise levels at the measurement site did not increase whether or not the nearest turbines to the site were operational. It is therefore considered that this increase from approximately 11 m/s is likely due to wind-induced noise rather than any increase in the wind turbine noise at the site.

4.2 Differences between metrics

The measurement data collected at the site provides an opportunity to analyse some common measures of interest to wind farm low frequency noise assessments. One measure commonly used to assess low frequency noise is the difference between the L_{Ceq} and L_{Aeq} noise levels. Figure 4 presents the differences at the measurement site for downwind conditions. Note that any differences below 10 dB were excluded from the dataset as previously stated.

It can be seen that the difference between the L_{Ceq} and L_{Aeq} levels typically varies between 14 and 22 dB. At higher wind speeds (above 9 m/s), the difference between the metrics actually appears to decrease, supporting the theory that these high wind speed measurements were affected by wind-induced noise which would also have an influence on A-weighted levels. It is common to use a difference of 20 dB to indicate a potential for low frequency noise annoyance, however it should be noted that this is often not considered to be applicable where the overall noise level is low and the C-weighted level is below 60-65 dB(C) (18).

The difference between the L_{Ceq} and L_{C90} measured over the two-month period when the Rion sound level meter was located on site is also of interest. It is documented that the difference between L_{Aeq} and L_{A90} wind turbine noise levels is approximately 1.5 dB (19) but less information is available regarding C-weighted noise levels.

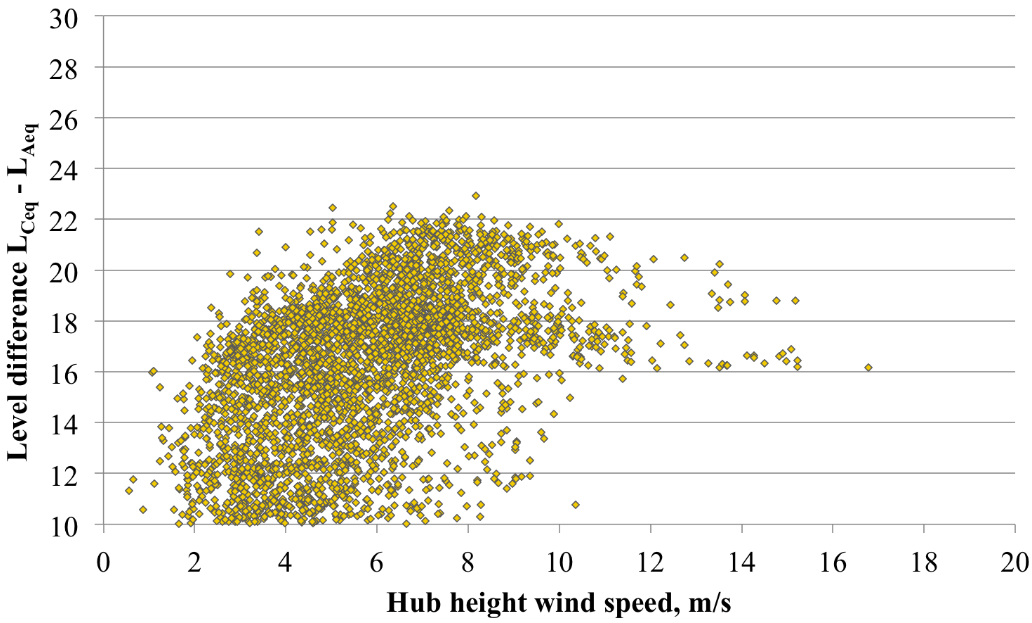

Figure 4 – Difference between measured L_{Ceq} and L_{Aeq} noise levels with hub height wind speed

Figure 5 presents the difference between the measured L_{Ceq} and L_{C90} noise levels over the period when the Rion sound level meter was on site. Only downwind (±45˚) noise levels are shown as there was more confidence that the measurements were wind turbine controlled, and the night-time period (11 pm to 5 am) is shown separately as it was considered that this would exclude more extraneous noise. It can be seen that the difference for C-weighted noise levels is also typically less than 2 dB with differences generally lower during the night-time period when extraneous noise was likely lower. While there are sometimes higher differences during the day (up to 6 dB) it is suspected that this is due to the presence of extraneous noise at these times.

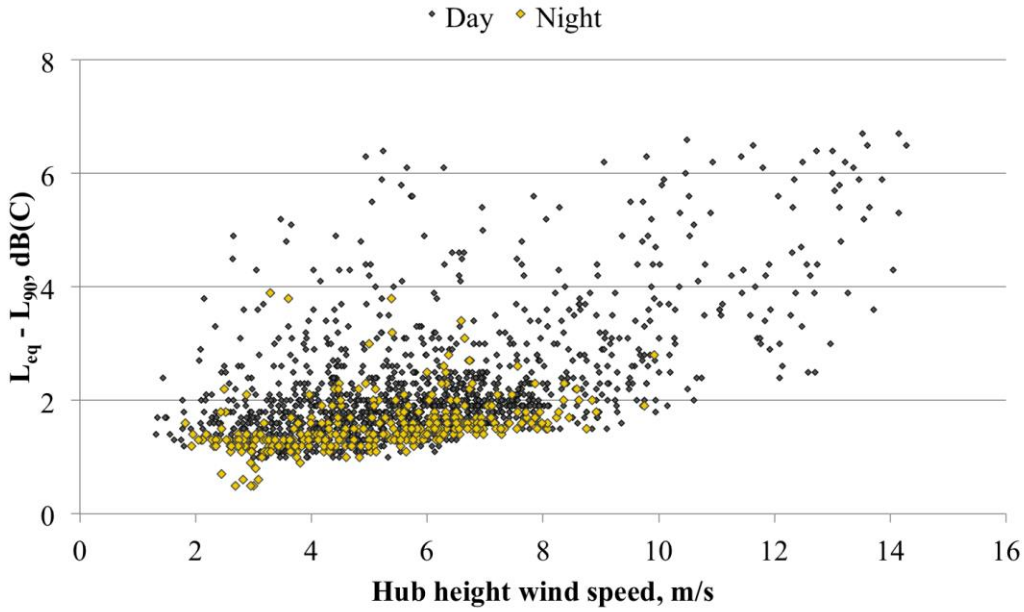

Figure 5 – Difference between measured L_{Ceq} and L_{C90} noise levels with hub height wind speed

Finally, it should be noted that the measurements conducted at the site and presented in this paper were based on the C-weighting filters applied by the sound level meters on site. On the Brüel & Kjær 2250 sound level meter, these filters do not exclude noise below 20 Hz as required by the Draft NSW and Victorian guidelines. Therefore a comparison was undertaken between the measured L_{Ceq} levels sourced directly from the sound level meter and the calculated L_{Ceq} determined from the measured one-third octave band sound pressure levels between 20 and 20,000 Hz. Over the wind speed range controlled by wind turbine noise, it was found that the measured overall L_{Ceq} level was typically less than 1 dB, and never more than 2 dB, above that measured when frequencies below 20 Hz were excluded.

5. COMPARISON TO PREDICTIONS

The C-weighted noise levels at the measurement site were predicted using three methods. The first was a SoundPLAN v7.3 (Braunstein + Berndt GmbH) computer noise model implementing the ISO 9613-2 algorithms, and the second the same noise model but implementing the CONCAWE algorithms. The third method was a simple spreadsheet implementing only the ISO 9613-2 distance attenuation and air attenuation algorithms but excluding topographical information.

All methods incorporated the turbine positions at hub height, the measured sound power levels for the wind turbines in octave bands, the measurement position at 1.5 m above ground, and ISO 9613-2 air absorption at 10˚C and 80% relative humidity. Both the SoundPLAN ISO 9613-2 model and the spreadsheet assumed completely reflective ground (G=0). The SoundPLAN model also incorporated an additional assumption of 50% absorptive ground (G=0.5) for the ISO methodology. The model implementing the CONCAWE algorithms assumed completely absorptive ground (G=1) and worst case weather conditions (Weather Category 6) for all noise sources to the receiver as these assumptions have previously been found to be broadly equivalent to the ISO 9613-2 methodology with completely reflective ground for predicting A-weighted noise levels (3). All SoundPLAN models included topographical information for the site and surrounds while the spreadsheet did not, although it should be noted that the site was essentially flat and the topography provided no shielding.

One key difference between the methods is that SoundPLAN only considers frequencies from the 31.5 Hz octave band and above. The spreadsheet methodology was able to incorporate the 16 Hz octave band. It should be noted that the ISO methodology is typically only applied to octave bands from 63 Hz and above, and certain factors such as ground attenuation and air absorption are not defined for frequencies lower than this. The spreadsheet methodology conservatively assumed no air absorption at octave bands lower than 63 Hz, while SoundPLAN assumes little or no air absorption for the 31.5 Hz octave band.

Table 1 compares the predicted and measured noise levels at the site for downwind conditions and a wind speed of 10 m/s. The predicted and measured A-weighted L_{90} noise levels at the site are also presented to provide context to the C-weighted predictions. The measured noise levels have been determined by fitting a third order regression curve to the measured downwind levels at the site between 5 and 10 m/s where there was confidence that the C-weighted noise level was turbine-controlled.

Table 1 – Predicted and measured downwind levels from ISO 9613-2 methodologies at 10 m/s

Method	Predicted, dB(A)	Measured, dB(A) L_{90}	Difference, dB(A)	Predicted, dB(C)	Measured, dB(C) L_{eq}	Difference, dB(C)
ISO 9613-2, G=0	42.9	39	+3.9	59.3	62.3	-3
ISO 9613-2, G=0.5	39.3	39	+0.3	58.5	62.3	-3.8
CONCAWE, G=0	41.8	39	+2.8	56.7	62.3	-5.6
Spreadsheet, G=0	44.5	39	+5.5	60.1	62.3	-2.2

Table 1 indicates that the predicted C-weighted L_{eq} noise levels are 2 to 4 dB below the measured C-weighted L_{eq} noise levels, excluding the CONCAWE methodology which predicts levels 5.6 dB below those measured. The SoundPLAN methodology is less accurate than the spreadsheet, likely due to the exclusion of the 16 Hz octave band in the prediction.

The SoundPLAN model assuming 50% ground absorption is also the least accurate of the methods for predicting C-weighted levels, which is interesting given that this is the most accurate method of predicting the A-weighted wind turbine noise levels. However, there was little difference in the predicted noise levels between the assumption of completely reflective and 50% absorptive ground, with a difference of only 0.8 dB(C). This contrasts with a difference in predicted A-weighted noise levels of 3.6 dB(A). This is a result of the ISO methodology ignoring the input ground absorption for calculating ground attenuation in the 63 Hz octave band, which controlled the overall predicted C-weighted noise level.

Some of the difference can be explained by the fact that we have measured the L_{eq} rather than L_{90} noise level. The L_{90} level is used for assessing A-weighted noise levels and the accuracy of predictions takes this into account. This would account for approximately 1.5 dB of the apparent under-prediction of C-weighted levels based on the difference between measured L_{Ceq} and L_{C90} levels presented in Figure 5.

Based on the current information available, it is not clear what accounts for the remainder of the difference but it may be due to a relatively small increase in the sound power level of the turbines at low frequencies when operating in the wake of other turbines. At the wind farm site used for the measurements, the nearest turbines to the measurement site were operating in the wake of up to 30 upwind turbines when the wind was blowing from the turbines to the measurement site. This was not accounted for in the predictions, which uses the sound power level measured at a test site with the turbine sound levels measured in wake-free conditions. As previous work has shown (17), while inflow turbulence does not appear to noticeably influence predictions of A-weighted noise levels, an increase of 2 to 3 dB is possible at low frequencies when turbines are operating in the wake of others and this would explain the remainder of the differences between measured and predicted noise levels.

It is also interesting to note that the findings are not in agreement with those of others (12, 14). This suggests that the 1 to 2 dB under-prediction of C-weighted noise levels (considering the L_{90} levels) at this site may be site specific and perhaps related to a slight increase in the turbine low frequency sound power levels when they were operating in the wake of other turbines. Further measurements are required at sites where inflow turbulence is not influencing the measurement results to confirm whether this is the case.

6. WIND SHEAR

The meteorological masts installed at the wind farm site measured wind speed at two sites enabling quantification of wind shear. Wind shear was determined using wake-free wind speed data obtained from the masts. Wind speeds measured at hub-height and approximately half this height were used to determine the wind shear power exponent for every 10-minute period during the measurements, with the wind shear exponent given by Equation (1).

$$V_1 = V_2 \left(H_1 / H_2 \right)^{\alpha} \qquad (1)$$

Where V_1 and V_2 refer to wind speed at height H_1 and H_2 respectively, and α is power law exponent.

To allow an examination of the influence of wind shear on the C-weighted noise level at the measurement location, a trend line was fitted to the dataset for the downwind direction between 5 m/s and 10 m/s where the noise level was expected to be turbine-controlled. The deviation of each data point from the trend line was calculated and plotted against the wind shear during that measurement. Figure 6 presents the deviation from the trend line with wind shear at the site.

It is apparent that there is a slight increase in the positive deviation from the trend line with wind shear, suggesting that wind shear at the site does increase measured C-weighted noise levels downwind of the wind farm. The increase is not significant but is measurable, with an increase in deviation of 3 dB between the minimum wind shear (0) and the maximum wind shear (0.6 – 0.7). Generally, wind shear at the site varies between 0.05 and 0.3 and across this range the relative increase in deviation is lower and only about 1.5 dB.

While this may be an effect of wind shear on propagation, it should be noted that no such effect was found on measured A-weighted noise levels at the site (20). An alternative explanation may be that wind shear exacerbates the differences in flow speed and therefore turbulence over the height of the rotor, marginally increasing low frequency noise generated by the wind turbines. This theory would agree with that expressed earlier regarding the difference between measured and predicted noise levels.

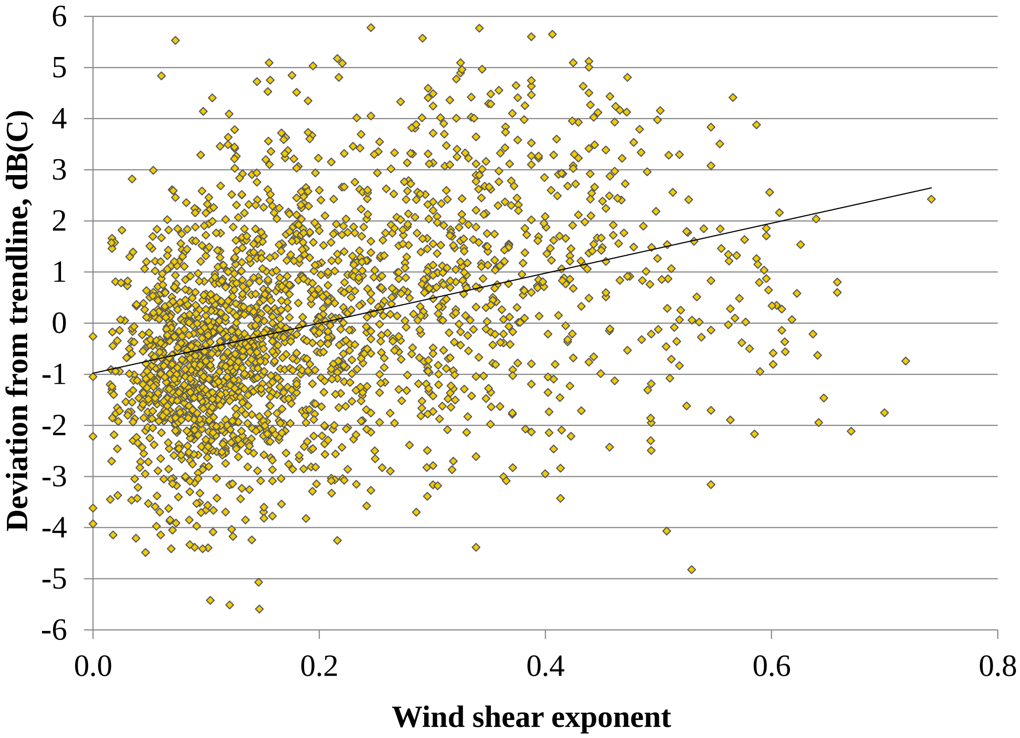

Figure 6 – Deviation of measured downwind noise levels from trend line with wind shear

As for the difference between predicted and measured noise levels, further measurements are required at sites where inflow turbulence is not influencing the measurement results to confirm whether this deviation with wind shear is a result of inflow turbulence or a result of propagation effects.

7. CONCLUSIONS

This paper presents an analysis of eight months of low frequency noise measurements conducted at a large commercial wind farm site, with wind turbines rated to approximately 3 MW. The measurements were conducted at a site approximately 1.2 kilometres from the nearest wind turbine and using appropriate windshields to reduce wind-induced noise up to the wind speed at which the turbines reach their maximum low frequency sound power level (11 m/s at hub height).

It was found that the measured C-weighted noise level at 11 m/s was 61 – 64 dB(C) L_{eq}, with the L_{eq} level typically 1.5 dB above the C-weighted L_{90} level. Of interest in low frequency noise assessments, the L_{Ceq} level was up to 22 dB above the L_{Aeq} level at the measurement site.

When noise levels were predicted using the standard noise prediction methodologies for A-weighted wind turbine noise, it was found that there was an under-prediction of 1 to 2 dB at the measurement site when known differences were accounted for. It is theorised that this difference may be due to an increase in the low frequency sound power levels of the wind turbines when operating in the wake of other turbines. The study site is in a grid configuration and the nearest turbines are operating in the wakes of many upwind turbines when the measurement site is downwind of the wind farm.

While this turbulence does not normally influence the A-weighted noise levels and therefore does not affect prediction accuracy for A-weighted levels, it is plausible that it would have a relatively small effect on the accuracy of C-weighted predictions. This may need to be considered in the planning stage of new wind farms where accurate predictions of C-weighted noise levels are required to achieve compliance with proposed low frequency noise criteria.

Wind shear was also found to have a small influence on measured C-weighted noise levels, although it does not influence A-weighted noise levels. This may also be a result of inflow turbulence, with turbine wake speed deficits tending to extend for longer distances under stable conditions.

It is important to note that this is only one site at one wind farm and further work is required to assess whether these findings are applicable to all wind farm sites, or whether the under-prediction noted here was a result of site-specific conditions.

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