# Influence of wind direction on noise emission and propagation from wind turbines

**Tom Evans and Jonathan Cooper**

Resonate Acoustics, 97 Carrington Street, Adelaide, South Australia 5000

## ABSTRACT

Noise predictions undertaken for wind farms generally seek to determine noise levels under worst case conditions, which are normally cited as being conditions when the receiver is located directly downwind of a wind turbine. In practice, it is rare for a receiver to be located directly downwind of all of the wind turbines that form a wind farm. In some cases, a receiver may be located between two groups of turbines, such that when it is downwind of one group of turbines it will be upwind of the others. This paper presents an analysis of noise measurements taken over two weeks at a range of distances from a modern wind turbine. The aim of the analysis is to determine the relative noise emissions from the wind turbine and propagation of the noise over distance under various wind conditions. Understanding the influence of wind direction on noise propagation allows for more accurate noise predictions, the assessment of noise exposure of receivers under various conditions and the potential suitability of wind sector management as a noise mitigation option for wind farms.

## INTRODUCTION

As one of the most cost-effective sources of renewable energy, a significant number of wind farms have been installed worldwide over the past decade. In April 2012, the total operating wind capacity in Australia was approximately 2.5 GW, with another 14,000 MW proposed (Clean Energy Council, 2012).

One of the most common community concerns related to wind energy projects is the potential noise impact, and environmental noise regulations imposed on sites often constrain the layout and number of turbines within a wind farm. Noise assessments conducted for proposed sites typically seek to determine the worst case conditions, conducive to the propagation of noise from the wind farm to the receiver. Worst case conditions are generally taken to be those conditions when the receiver is directly downwind of the nearest wind turbines, such as in the South Australian *Wind Farms Environmental Noise Guidelines* (SA EPA, 2009).

This paper seeks to determine the influence of wind direction on the relative emission and propagation of noise levels from a modern upwind wind turbine. Three sound level meters were installed for a period of approximately two weeks at various distances of up to 1000 metres from a turbine. The measurement results have been analysed against wind speed and direction data measured at the turbine to determine the difference in noise levels under different wind directions.

An understanding of the changes in noise emission and propagation with wind direction will assist in:

- Improving the accuracy of noise prediction methods under a variety of wind conditions.
- Understanding the noise levels that receivers may be exposed to throughout the year rather than only during downwind conditions.
- Assessing the suitability of wind sector management as a noise mitigation option for wind farms. Wind sector management involves shutting down or reducing the power output of some turbines during particular wind conditions.

## EQUIPMENT SETUP

The noise measurements used for the analysis in this paper were taken at a distance from a modern upwind wind turbine, with a blade diameter of approximately 90 metres and hub height of 80 metres, installed at an operational Australian wind farm. The turbine and site have not been identified for commercial reasons but this particular turbine was selected for the assessment because it is located at the end of a line of turbines and therefore the distance from other wind turbines could be maximised.

Three Brüel and Kjær 2250 Class 1 sound level meters were installed at distances of approximately 120, 500 and 1000 metres from the base of the wind turbine. All of the sound level meters were located in the same direction from the turbine and approximately 180° around from the other turbines in the line. The aim of this setup was to maximise the distance of the sound level meters from the other turbines on the site and such that the wind direction at all of the turbines was approximately the same during the measurements.

The ground at the measurement site slopes steadily down from the turbine to the sound level meter located 120 metres away. The ground between the turbine and the meter at 500 metres forms a slight valley before levelling out between the 500 metre and the 1000 metre locations.

The sound level meter located approximately 120 metres from the turbine was installed in accordance with International Standard IEC 61400-11 Edition 2.1, which is used for sound power measurements of wind turbines. The microphone was located on an acoustically hard ground board and fitted with a 90 mm diameter windshield. At the other two locations the microphone was situated at 1.5 metres above the ground and also fitted with a 90 mm diameter windshield.

The equipment was left unattended on site to continuously measure one-minute noise levels. Fifteen days of data was obtained at the locations 120 and 500 metres from the turbine, with nine days of data obtained at the location at a distance of 1000 metres. During the measurements, wind speed, turbine orientation and active power data was obtained at the turbine nacelle. The turbine orientation data was corrected against the location of the sound level meters such that a direction of 0º corresponded to measurements upwind of the turbine and 180º corresponded to measurements downwind of the turbine.

## NOISE EMISSION WITH WIND DIRECTION

The noise level data collected at a distance of 120 metres from the turbine was used to characterise the noise emission with wind direction. This location was selected as it coincides with the location used during sound power measurements of operational turbines in accordance with IEC 61400-11. Any variation in the sound pressure levels at this location will translate to an identical variation in the calculated sound power levels for the turbine under the IEC Standard, as long as background noise levels are low enough to not affect the measurement results.

An analysis of the measured $L_{Aeq,1min}$ and $L_{A90,1min}$ data was undertaken and the $L_{A90,1min}$ data was selected for the assessment of noise emission with wind direction. The $L_{A90,1min}$ data was less subject to influence from extraneous noise sources, such as wind noise on the microphone from short-term wind gusts and from fauna noise at the site. The use of the $L_{90}$ metric is considered appropriate as:

- Compliance assessments of wind farms are typically undertaken based on the $L_{90}$ metric, allowing consistency between the results of this analysis and future noise assessments at receivers. Even where an assessment is based on the $L_{eq}$ metric, this is normally performed by adding 1.5 to 2.5 dB(A) to the measured $L_{90}$ noise level as described in Australian Standard AS 4959:2010.
- There was little variation between the $L_{Aeq,1min}$ data and $L_{A90,1min}$ data at the wind speeds across which the assessment was carried out. The $L_{Aeq,1min}$ data was found to be 1.3 dB(A) higher than the $L_{A90,1min}$ data on average, with a standard deviation of 0.5 dB(A) across the dataset. This difference is consistent with differences found during other assessments of measured wind turbine noise levels (Cooper, Evans & Najera, 2012).

Figure 1 and Figure 2 present the measured $L_{A90,1min}$ noise levels with wind direction at the measurement location 120 metres from the turbine for hub height wind speeds of 7 m/s and of 10 m/s to 12 m/s respectively. Note that a direction of 0º corresponds to upwind conditions and a direction of 180º corresponds to downwind conditions. The wind speeds of 7 m/s and 10 m/s to 12 m/s were selected due to the relative availability of data across a reasonable range of wind conditions. Hub height wind speeds of 10 m/s to 12 m/s were grouped together due to the relatively small variation in reported sound power levels across these wind speeds (less than 1 dB(A) when assessed under IEC 61400-11).

It can be seen from both Figure 1 and Figure 2 that noise emissions from the turbine peak during downwind conditions (180º), although the peak is not overly significant with respect to noise levels under other wind directions. Noise emissions reach a minimum during crosswind conditions (-90º and 90º) with the average levels between 2 to 4 dB(A) lower than under downwind conditions.

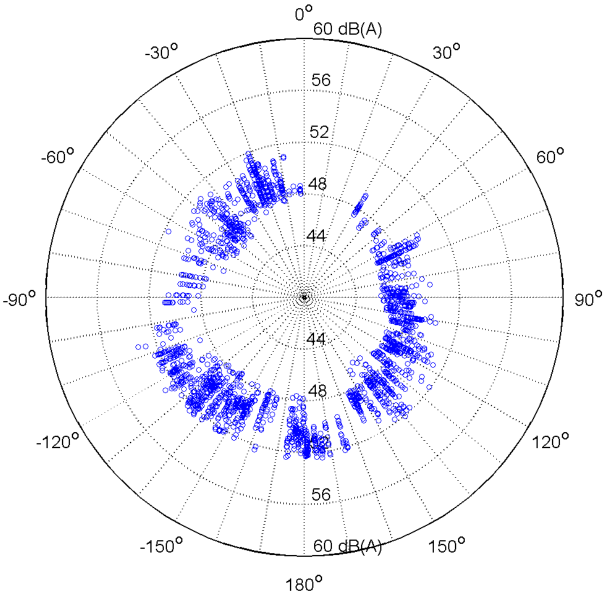

**Figure 1**. Measured noise level with wind direction at 120 m from turbine for hub height wind speed of 7 m/s. 0º corresponds to upwind conditions.

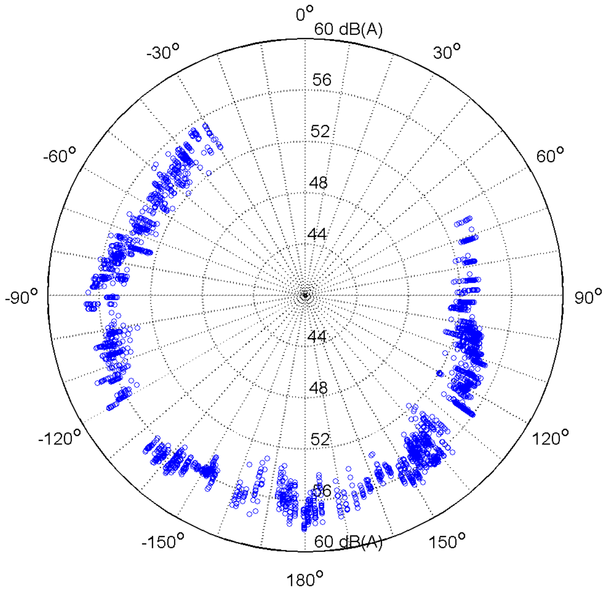

**Figure 2**. Measured noise level with wind direction at 120 m from turbine for hub height wind speeds of 10 to 12 m/s. 0º corresponds to upwind conditions.

The data also appears to show that noise emissions from the turbine are not symmetrical with wind direction around the upwind and downwind directions. Noise emissions were higher at -135º than at 135º for both wind speed ranges. It is not clear what the cause of this effect is, though it may be an error of approximately 10º in the wind direction sensor located on the turbine nacelle. This potential error is within the bin widths used for analysis in this paper and the noise levels in the downwind direction still represent the peak emission from the turbine.

The noise emissions during upwind conditions were found to be similar to those under downwind conditions, although there was a lack of data for upwind conditions at the higher wind speed range.

The spread of data at hub height wind speeds of 7 m/s was found to be greater than that at 10 m/s to 12 m/s. This is most likely due to the change in sound power level of the turbine being greater across the wind speed range of 6.5 m/s to 7.5 m/s than it is across the range from 9.5 m/s to 12.5 m/s when it is approaching rated power.

It can also be seen that there does not appear to be a significant change in the noise emission from the turbine for wind directions 45º either side of the downwind direction. This suggests that the worst case compliance assessment conditions proposed in the *Wind Farms Environmental Noise Guidelines* (wind in the directions within 45° of the worst case direction for a particular receiver) do consider the periods when noise emissions from the particular wind turbine considered as part of this paper will be greatest.

## NOISE PROPAGATION WITH WIND DIRECTION

To assess the influence of wind direction on the propagation of noise from the turbine over distance, the measured $L_{A90,1min}$ noise levels were compared for the locations at 120 metres, 500 metres and 1000 metres from the turbine.

At the two locations 500 metres or further from the turbine, the influence of extraneous noise became greater due to the reduced level of turbine noise. Therefore, as for the analysis of noise emission with wind direction, the $L_{90}$ metric was preferred to the $L_{eq}$ metric to reduce the influence of extraneous noise as well as to provide consistency with the standard noise compliance assessment methodology.

The data was filtered by wind direction, with eight 45º wind direction bins used which were centred at 0º, ±45º, ±90º, ±135º and 180º. These wind direction bins are finer than the 90º bins typically used for the assessment of wind farm noise but have been selected to highlight any finer differences in noise propagation under different wind conditions.

Data that was obviously affected by extraneous noise at any of the measurement locations were removed. For example, periods of low turbine noise (based on the active power output) were removed due to the likely influence of extraneous noise at the more distant measurement locations. Similarly, periods where the hub height wind speeds were above 12 m/s were excluded from the assessment as noise levels at all sites appeared to become influenced by wind noise induced on the microphone.

Figure 3 and Figure 4 show the decrease in turbine noise levels for upwind and downwind conditions between the locations at 120 metres and 500 metres, and 120 metres and 1000 metres respectively. The data has been correlated against hub height wind speed measured at the turbine.

The results clearly show that there is a marked difference in noise propagation between upwind and downwind conditions. Between 120 metres and 500 metres, the turbine noise levels decrease by between 3 to 5 dB(A) under upwind conditions than under downwind conditions. This difference increases to 6 to 7 dB(A) at a distance of 1000 metres.

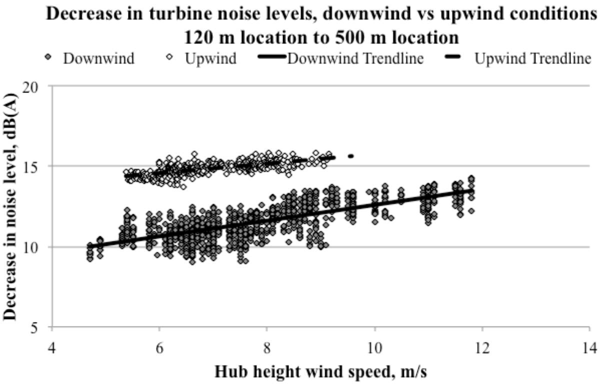

**Figure 3**. Decrease in noise levels for downwind and upwind conditions between 120 m and 500 m from the turbine.

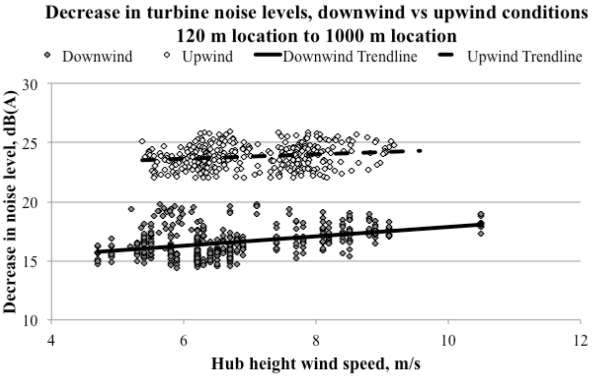

**Figure 4**. Decrease in noise levels for downwind and upwind conditions between 120 m and 1000 m from the turbine.

It can also be seen that the reduction in turbine noise levels appears to marginally increase with increasing wind speed. This suggests that the propagation of noise from wind farms may be higher during lower wind speeds at the turbine site, although it may also be an effect of the changing difference between the turbine sound level and background noise level at the distant measurement sites. For example, at lower wind speeds when the turbine sound level is lower, the background noise level may influence the measurement more (resulting in a lower apparent decrease in noise level). At higher wind speeds when the turbine sound level is higher, the background noise levels will have less influence if they have not increased accordingly.

Figure 5 shows the decrease in turbine noise levels between 120 metres and 500 metres for both crosswind directions, -90º and 90º. It can be seen that the decrease under both directions is almost identical (approximately 15 dB(A) across all wind speeds), and that both wind directions can be grouped together as an overall crosswind dataset. This was also found to be the same for the -135º and 135º dataset, and for the -45º and 45º dataset.

Figure 6 presents the decrease in turbine noise levels between 120 metres and 500 metres for both the ±45º and ±135º datasets. It can be seen that the decrease in noise levels for the ±45º dataset is only marginally higher than for the ±135º dataset, despite the fact that the ±135º dataset would be expected to be noticeably lower as a portion of the wind vector would be in the downwind direction.

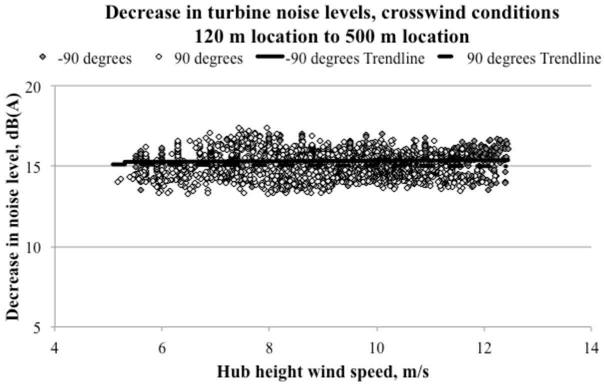

**Figure 5**. Decrease in noise levels for crosswind conditions between 120 m and 500 m from the turbine.

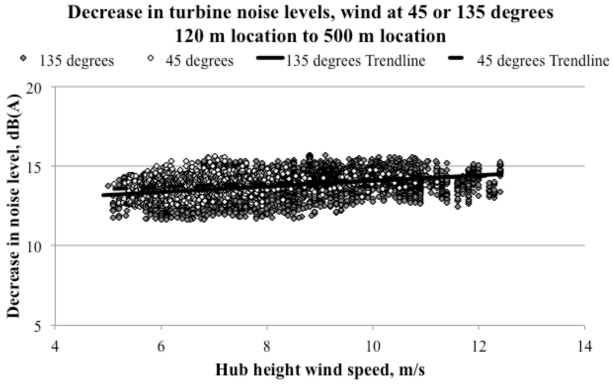

**Figure 6**. Decrease in noise levels for crosswind conditions between 120 m and 500 m from the turbine.

For each of the crosswind (±90º), ±45º and ±135º datasets, there only appears to be a marginal increase in propagation loss as the wind speed increases. This suggests that the larger decrease in noise levels with higher wind speed noted for the downwind conditions (refer Figure 3 and Figure 4) may be a result of a greater difference between turbine sound levels and background noise levels at the measurement locations for this wind direction.

Table 1 summarises the average decreases in noise levels found for each of the directional datasets between 120 metres and 500 metres, and between 120 metres and 1000 metres. The increase in propagation loss between 500 metres and 1000 metres appears to be relatively constant regardless of wind direction and is between 6 and 8 dB(A).

**Table 1**. Decrease in measured noise levels over distance for different wind directions

| *Measurement angle* | *Decrease in measured noise levels over distance, dB(A)* | |
|---|---|---|
| | *120 m to 500 m* | *120 m to 1000 m* |
| *0º (upwind)* | 15 – 16 | 23 – 24 |
| *±45º* | 14 | 22 – 23 |
| *±90º* | 15 | 20 – 21 |
| *±135º* | 13 – 14 | 19 – 20 |
| *180º (downwind)* | 10 – 13 | 16 – 18 |

Overall, it can be seen that, as expected, propagation is most significant for downwind conditions with 6 to 7 dB(A) lower propagation loss over a distance of 1000 metres than for upwind conditions at each considered wind speed. For other wind directions, the propagation loss appears to steadily increase at a distance of 1000 metres as the wind direction changes from downwind to upwind.

## DISCUSSION

### Summary of emission and propagation findings

When combined, the results presented for both noise emission and noise propagation with wind direction suggest that for receiver locations (typically located 1000 metres or more from the nearest turbines):

- Noise levels from a particular turbine will be highest under downwind conditions, typically 6 to 7 dB(A) higher than under upwind conditions.
- Noise levels from a particular turbine under crosswind conditions are likely to be relatively similar to those under upwind conditions. This is because the increased propagation loss under upwind conditions will be offset by the increased noise emissions relative to crosswind conditions.
- Noise emissions at ±135º from a particular turbine may be similar to those at downwind (180º) but the propagation loss over distance will be higher. This suggests that worst case conditions for noise at receiver locations from a turbine will be restricted to the downwind direction and directions immediately either side of it.

It should be noted that these results are based on the tested turbine and may differ for turbines of other makes and sizes, and for different topographies. However, the noise emission with direction from this turbine is largely consistent with our experience of other turbine makes of similar size and blade diameter, and the spectral content of this turbine is similar to others suggesting the propagation loss would be expected to be similar with distance. Therefore, it is expected that the findings of this analysis could be broadly applied to other turbine makes of a similar size.

### Application to overall wind farm levels at receiver sites

The results presented in this paper only consider the contribution of a single turbine, along with a minor contribution from a small number of turbines located further away and subjected to a wind from an almost identical direction. For receiver sites near a wind farm, there will be contributions from a number of wind turbines that are most likely subjected to different wind directions relative to the receiver location.

Lenchine & Holmes (2011) undertook measurements at a location approximately 1.3 kilometres from the nearest turbines at a wind farm site. Filtering the data to remove extraneous noise, it was determined through comparison of upwind and downwind regression curves that the “maximum statistical difference is in the order of 3 dB(A)” rather than the 5 to 8 dB(A) found from an individual turbine in this study.

As part of a previous paper (Cooper, Evans & Najera, 2012), we found that when wind farm noise levels were measured using the *Wind Farms Environmental Noise Guidelines* method (SA Guidelines method) they were between 0.2 and 1.5 dB(A) higher than the method outlined in New Zealand Standard NZS 6808:2010. Across thirteen sites, the average difference was 0.7 dB(A). The only difference between the two methods is that the SA Guidelines method only considers wind directions within 45º of the worst case direction (taken from the nearest turbine to the receiver), while the NZS 6808:2010 method considers all wind directions. Therefore, assuming that the wind direction profile for the average of the thirteen sites will be relatively evenly spread across all directions, this 0.7 dB(A) difference may be taken as the approximate difference in the noise level for all wind directions and the noise level only for those within 45º of the worst case direction.

Applying the results presented in this paper and assuming that the relative direction from all turbines at a wind farm is the same, an average difference of 4 dB(A) would be expected between the SA Guidelines and NZS 6808:2010 methods at a receiver site one kilometre away. Note that this assumes that the distribution of wind directions at the site is equal (e.g. the percentage of time that the wind is from the upwind direction is equal to that it is in the downwind direction). Given that the measured average difference is only 0.7 dB(A), this suggests that the fact that individual turbines will have different relative directions to a receiver will have a significant effect on the overall noise level. This will act to reduce the difference in noise levels at a receiver site across the range of wind directions.

### Application to wind sector management of wind farms

Wind sector management of a wind farm involves shutting down or reducing the power output of some turbines during particular wind conditions. If compliance with noise criteria is an issue under some wind directions, then wind sector management may be employed as a mitigation measure.

The analysis conducted in this paper suggests that wind sector management could be an effective noise mitigation measure for noise from individual turbines. For example, a turbine could be shut down during downwind conditions but operated at full power during other conditions, while resulting in a noise level 6 to 7 dB(A) lower (than the worst case downwind conditions) during crosswind and upwind conditions. This could considerably increase the number of turbines on a site, depending on the cost effectiveness of shutting or powering down turbines during particular wind conditions. It could also provide a noise reduction option in a situation where a non-compliance with the noise criteria may have been noted for an existing wind farm during particular conditions.

However, care needs to be taken during a sector management assessment such that the differences presented in this paper are only applied to the predicted/measured contributions from individual turbines and not to the overall noise level at a receiver site. As already discussed, the difference in the overall noise level at a receiver site between directions is likely to be considerably lower and this would reduce the noise mitigation benefit of wind sector management.

Overall, the results of this assessment show that wind sector management could be a viable option for increasing the number of turbines on a site, even if the noise mitigation achieved for particular wind directions is in the order of 1 to 2 dB(A) rather than the 6 to 7 dB(A) found from an individual turbine. In a theoretical study, Bullmore et al (2007) demonstrated that, a 3 dB(A) increase in the assumed noise propagation from a wind farm could result in a 42 per cent reduction in the power output of that site. This highlights the large impact that relatively small changes to noise levels can have for wind farms.

## CONCLUSIONS

This paper presents an analysis of measured noise levels from a wind turbine with reference to the wind direction relative to the measured locations. Noise levels were measured at three locations a distance of 120 metres, 500 metres and 1000 metres from a turbine in the same direction.

The levels measured at the location 120 metres away were used to quantify the noise emissions from the turbine as this approximately corresponded to the distance used for the measurement of turbine sound power levels. It was found that noise emissions were highest during downwind conditions and lowest during crosswind conditions. Noise emissions during upwind conditions were only marginally lower than those during downwind conditions. Overall, the average noise emission levels did not vary by more than 4 dB(A) across all wind directions.

All of the measurement locations were used to quantify the noise propagation loss with distance during different wind conditions. It was found that propagation loss was lowest during downwind conditions and steadily increased as the wind direction changed from downwind to upwind. The propagation loss during upwind conditions was 6 to 7 dB(A) higher than that during downwind conditions at a distance of 1000 metres from the turbine.

Overall, it was found that the noise levels from an individual turbine at a receiver location would be expected to vary significantly with wind direction. While this variation will reduce when considered over a whole site, as not all turbines will be located in the same direction from a receiver, it does highlight that wind sector management could be an effective noise mitigation option for a wind farm in some cases.

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