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# WHO Environmental Noise Guidelines for the European Region: conditional recommendation for wind turbine noise in the context of Australian regulations

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## Summary

The World Health Organisation (WHO)'s publication *Environmental Noise Guidelines for the European Region* [1] published in 2018 (the 2018 WHO Guidance) provides a conditional recommendation for addressing annoyance as a result of wind turbine noise in Europe. The conditional recommendation for wind turbine noise is provided amidst guidance for health-related effects from road, rail, aircraft and leisure noise. In keeping with strategic policy of the European Union, the publication adopts the $L_{den}$ noise metric. This paper considers the practical challenges of measuring and assessing wind farm noise in terms of the $L_{den}$ noise metric, and compares the conditional recommendation with the typical range of noise levels observed around Australian wind farm projects.

# 1. Introduction

The potential health effects of environmental noise have been topical subjects for wind farms, and have attracted concern from communities neighbouring proposed and operational wind farm developments in Australia and internationally.

The potential health effects of environmental noise range from community annoyance, sleep disturbance and speech interference, through to direct physiological impacts such as hearing damage. An important aspect of this range of considerations is that some effects will be highly dependent on the listener's perception and attitude to the noise in question, such as annoyance, while other effects are primarily related to the level of sound and the direct physiological risks these may represent, such as hearing damage.

In Australia, environmental noise levels from wind farms are regulated by dedicated policies which describe measurement and assessment methodologies that are specific to the operational noise characteristics of wind farms. In common with policies for other types of noise generating development, wind farm noise policies define criteria which are chosen to prevent direct physiological risks of sound, and minimise as far as practically possible the adverse health considerations such as annoyance and sleep disturbance.

The subject of health effects related to operational wind farms has been extensively reviewed by Australian Commonwealth, national and state health authorities. The findings of these reviews [2][3][4] support that, as with any audible sound, wind farm noise can represent a potential source of annoyance or sleep disturbance for some individuals. The review did however indicate that there was no reliable evidence to support a relationship between wind farm noise and direct adverse effects on human health. These findings lend support to the suitability of the wind farm noise policies in Australia, which are intended to provide reasonable protection of health and amenity at noise sensitive locations.

The publication of guidance on wind farm noise by the WHO provides an additional valuable reference for policy makers, stakeholder groups and the wind industry.

However, the guidance is based on the $L_{den}$ noise metric which is commonly used for transportation noise, but is not commonly used for wind farm noise assessment in Australia or internationally. This introduces complications when attempting to accurately compare Australian wind farm noise policy requirements with the 2018 WHO Guidance. Further, while the $L_{den}$ parameter is consistent with EU strategy policy requirements, there are technical challenges to its application to wind farms.

This paper presents a summary of the 2018 WHO Guidance for wind farms and a high level summary of Australian wind farm noise policies. An analysis of background sound level data from wind farm sites in terms of the $L_{den}$ is then presented to illustrate the difficulty of measuring this parameter for a wind farm. Example wind distributions and predicted wind farm noise levels are also presented to investigate the relationship between the conditional recommendation of the 2018 WHO Guidance and the noise criteria used to assess wind farm developments in Australia.

# 2. Summary of 2018 WHO Guidance & Australian Wind Farm Policy

## 2.1 2018 WHO Guidance

The 2018 WHO Guidance conditionally recommends the following for wind turbine noise.

> *For average noise exposure, the* [2018 WHO Guidance] *conditionally recommends reducing noise levels produced by wind turbines below 45 dB $L_{den}$, as wind turbine noise above this level is associated with adverse health effects.*
>
> *To reduce health effects, the* [2018 WHO Guidance] *conditionally recommends that policy-makers implement suitable measures to reduce noise exposure from wind turbines in the population exposed to levels above the guideline values for average noise exposure. No evidence is available, however, to facilitate the recommendation of one particular type of intervention over another.*

The conditional recommendation was made solely on the basis of annoyance related health considerations, with the guideline being set at the level of noise which corresponded to 10 % of the community being highly annoyed in the available research [5][6] for four wind farm sites. The recommendation is conditional on the basis that *"the evidence on the adverse effects of wind turbine noise was rated low quality".* The 2018 WHO Guidance notes that no suitable studies were available in relation to cardiovascular disease, hearing impairment and learning impairment.

The recommended $L_{den}$ metric is the day-evening-night-weighted sound pressure level as defined in ISO 1996-1:2016 and referenced in the European Noise Directive. The metric is determined as the average/equivalent noise level representing a 24 hour period, based on the aggregated noise of all day, evening and night periods in a year (times for the day, evening and night periods may vary between jurisdictions). Calculation of the $L_{den}$ includes 5 dB and 10 dB penalty weightings for the evening and night periods respectively. The $L_{den}$ is determined at facade locations for noise sensitive buildings but excludes the influence of facade reflections.

The use of the $L_{den}$ metric provides the benefit of alignment with broader strategical polices for transportation noise and metrics commonly referenced in large-scale community noise exposure research. The potential benefit of this type of metric for wind farms is that it may also differentiate between locations where the highest wind farm noise levels are similar, but where the amount of time that these levels are experienced differs significantly (i.e. due to receivers being in or out of the prevailing wind direction).

However, the 2018 WHO Guidance acknowledges limitations regarding the use of the $L_{den}$ metric for wind farm assessment. Key limitations with respect to the conditional recommendation for wind farm noise are:

- No account for background noise conditions – an important consideration for wind farm developments given that background noise levels at wind farm sites are generally comparable to, and often greater than, wind farm noise levels. This is relevant in terms potential wind farm annoyance and in terms of the feasibility of measuring $L_{den}$ wind farm noise levels at receiver locations in the presence of wind (noting that the operating range of a wind farm typically extends from 3-25 m/s or 11-90 km/h).
- No account for, or differentiation between, wind farm noise containing audible characteristics such as tonality or amplitude modulation, which the 2018 WHO Guidance acknowledges as factors that are likely to give rise to increased annoyance.

- No differentiation between neighbour receivers and involved receivers (i.e. receiver locations hosting or financially benefiting from a wind farm). This is particularly relevant as the conditional recommendations are based on health effects related to annoyance, and the evidence concerning annoyance is greatest for receivers who are not involved the wind farm project.

## 2.2 Australian Wind Farm Policy

Noise assessment requirements for wind farms in Australia vary by state. However, the underlying principles are similar and are based on:

- Assessing noise levels at receiver locations using the relationship between measured noise levels and hub height wind speeds.
- Wind speed dependent noise criteria defined as a minimum limit or the background level plus 5 dB, whichever is higher.
- Noise limits are often set in terms of equivalent noise levels, but $L_{A90}$ measurements are used to estimate $L_{Aeq}$ noise levels attributable to wind farms.
- The application of penalties for audible characteristics which are likely to increase annoyance (the type of assessable characteristics varies by state, but includes tonality, amplitude modulation, impulsiveness and low frequency).

The key noise assessment publications referenced in Australia, and their applicable minimum noise limit values, are detailed in Table 1.

**Table 1: Australian wind farm noise assessment – key publications and applicable minimum limits**

| Document | Minimum limit |
|---|---|
| South Australian publication *Wind farms: environmental noise guidelines* [7] | 35 or 40 dB depending on land zoning |
| New Zealand Standard *NZS 6808:2010 Acoustics – Wind farm noise* [8] | 35 or 40 dB depending on land zoning |
| NSW publication *Wind Energy: Noise Assessment Bulletin* [9] | 35 dB |
| Queensland publication *State code 23: Wind farm development planning* [10] | Day: 37 dB / Night: 35 dB |

Most regulatory approvals for new wind farm developments include mandatory requirements to prove compliance with noise criteria at receiver locations after the wind farm is operational. Compliance assessment methodologies are increasingly using noise measurement data for locations nearer to the turbines. However, compliance requirements are still predominantly based on post-construction operational noise measurements at receiver locations. This is a particularly important when considering the $L_{den}$ noise metric in the Australian regulatory framework i.e. the feasibility of the $L_{den}$ as a noise metric which can be reliably measured at a typical wind farm site.

## 3. Measured $L_{den}$ Noise Levels at Selected Wind Farm Sites

Noise measurement data from nineteen (19) measurement locations at five (5) wind farm sites in Australia have been analysed in terms of the $L_{den}$ metric (reference time periods for analysis: day 0700-1900 hrs, evening 1900-2200 hrs and night 2200-0700 hrs). The analysis was carried out for ambient noise level measurements at both proposed wind farm sites (i.e. in the absence of turbines) and operational wind farm sites. The primary purpose of this analysis was to provide an indication of the typical ranges of measured $L_{den}$ noise levels at a selection of locations around wind farm sites.

The wind farm sites were located in rural areas that are remote from major transportation routes. The terrain of the sites ranged from flat to gently undulating profiles. The predominant environmental noise sources comprised wind disturbed vegetation, local fauna, occasioning farming activity and wind turbines (at operational sites). The noise measurements were carried out at a combination of receiver (i.e. near to existing or proposed dwelling locations) and intermediate measurement locations (i.e. reference points between receivers and turbine locations). The receiver noise measurement locations were generally between the predicted 30 and 40 dB $L_{Aeq}$ contours for the wind farms (based on downwind predicted noise levels). Measurements at intermediate locations were located in the vicinity of the predicted 45 dB $L_{Aeq}$ contour of the wind farms. All of the receiver locations where operational noise measurements were carried out had previously been assessed as compliant with local policy requirements.

The noise level measurements comprised consecutive measurements of equivalent and statistical noise levels in 10 minute intervals for periods typically spanning 3-6 weeks. All noise measurement equipment comprised 01dB CUBE or DUO Smart Noise Monitors (Class 1) fitted with enhanced wind shielding systems based on the design recommendations detailed in the UK IOA good practice guide. To enable screening for extraneous noise, all noise measurements included third-octave band spectra local measurements of rainfall in concurrent 10 minute intervals.

For consistency with the $L_{den}$ metric, the analysis was based on measured equivalent noise levels for each period and location. However, as $L_{Aeq}$ measurements around wind farms are highly prone to the effects of extraneous noise and variable noise influences, an alternative $L_{den}$ parameter was calculated on the basis of the $L_{A90}$ measurements i.e. consistent with common assessment practice in Australia, the measured $L_{A90}$ as an approximation of the equivalent $L_{Aeq}$ noise level attributable to the operation of the wind farm. The same approach was adopted for the pre-construction noise measurement datasets to enable comparison with the corresponding analysis of the post-construction noise measurement datasets.

The comparison shown in Figure 1 illustrate the calculated $L_{den}$ ambient noise levels measured at the nineteen (19) receiver and intermediate locations around proposed wind farm sites only (i.e. without the influence of turbines). The intermediate locations are identified by the designation '(i)' in the label. The results are presented with the $L_{den}$ separately calculated using the $L_{Aeq}$ noise levels and the $L_{A90}$ noise levels. The results are also provided for datasets filtered as follows:

- Rainfall; and
- Prominent insect noise which is identified when the following conditions [11] are satisfied:
  - the highest A-weighted one-third octave band noise level is within 5 dB of the broadband A-weighted background noise level for that interval; and
  - the identified one-third octave band A-weighted noise level is greater than a level of 20 dB $L_{A90}$.

The results in Figure 1 illustrate that the ambient $L_{den}$ noise levels calculated on the basis of the equivalent noise level metric are typically greater than the 45 dB conditional recommendation level of the 2018 WHO Guidance, even after the application of filters to remove clearly identifiable sources of extraneous noise. This is likely to be a result of a combination of elevated ambient equivalent noise levels and potential wind inducted noise across the microphone during high local winds (noting that practical enhanced secondary windshields are primarily validated for the measurement of statistical noise levels which exclude momentary wind-gust related noise on the microphone).

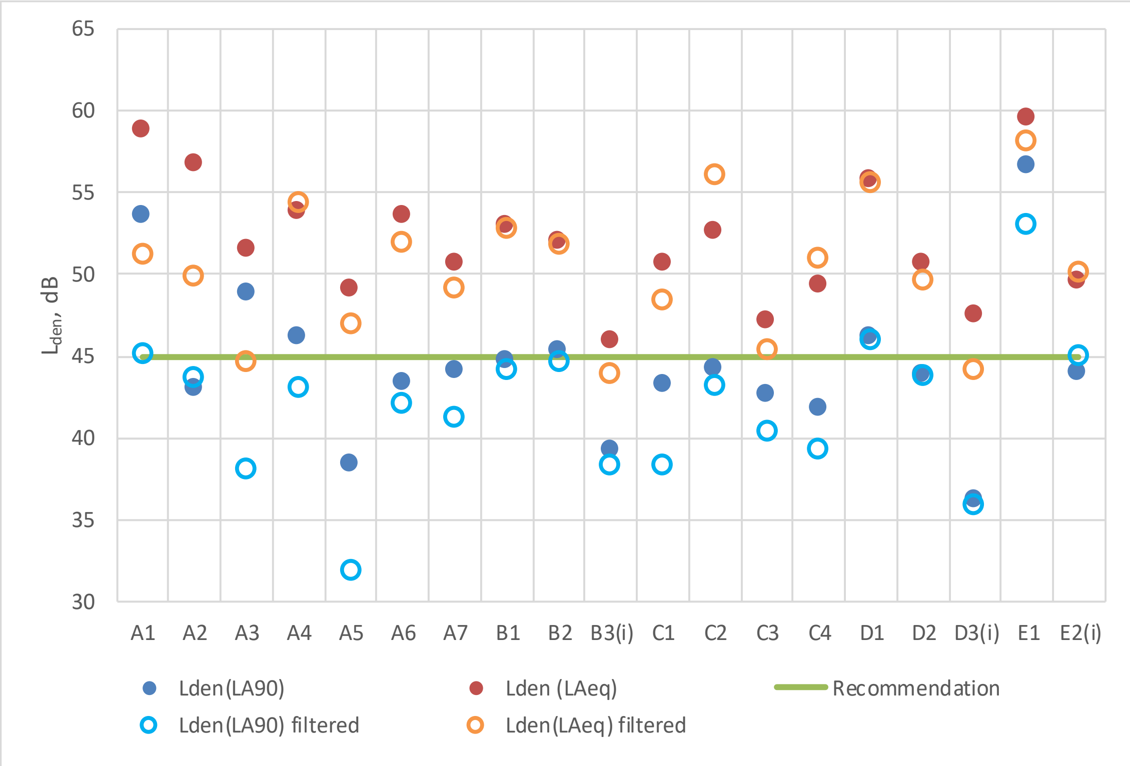
Shown in Figure 1, the ambient $L_{den}$ noise levels calculated on the basis of the measured $L_{A90}$ noise levels indicate a significant reduction, but still a high level of variation. The majority of locations demonstrate $L_{den}$ noise levels based on the $L_{A90}$ metric are between 40 and 45 dB, even after filtering the data.

These results therefore show:

- Direct evaluation of the $L_{den}$ wind farm noise levels from measured equivalent noise levels at receiver locations will generally not be possible, as a result of ambient noise influences and the limitations of practical enhanced wind shields
- Even using $L_{A90}$ post-construction measurements as an approximation of wind farm equivalent noise levels for the calculation of $L_{den}$ noise levels, the background noise environment is likely to significantly influence the measured levels and, in some cases, may dominate the measured level.

The measurement difficulties noted here are not exclusive to the $L_{den}$ metric. Standard wind farm measurement and assessment procedures based on regression analysis of statistical noise levels correlated with site wind speeds are also prone to similar ambient noise influences and complications. However, a range of supplementary measurement and analysis techniques can be used to address these difficulties with standard measurement and assessment procedures (e.g., analysis of selected data subsets for different periods or wind conditions in combination with measurement and extrapolation of intermediate location data. However, these types of supplementary techniques are either limited or not possible when the dataset for all time periods and wind conditions is aggregated to calculate an $L_{den}$.

**Figure 1: Proposed rural wind farm sites – ambient $L_{den}$ noise levels**

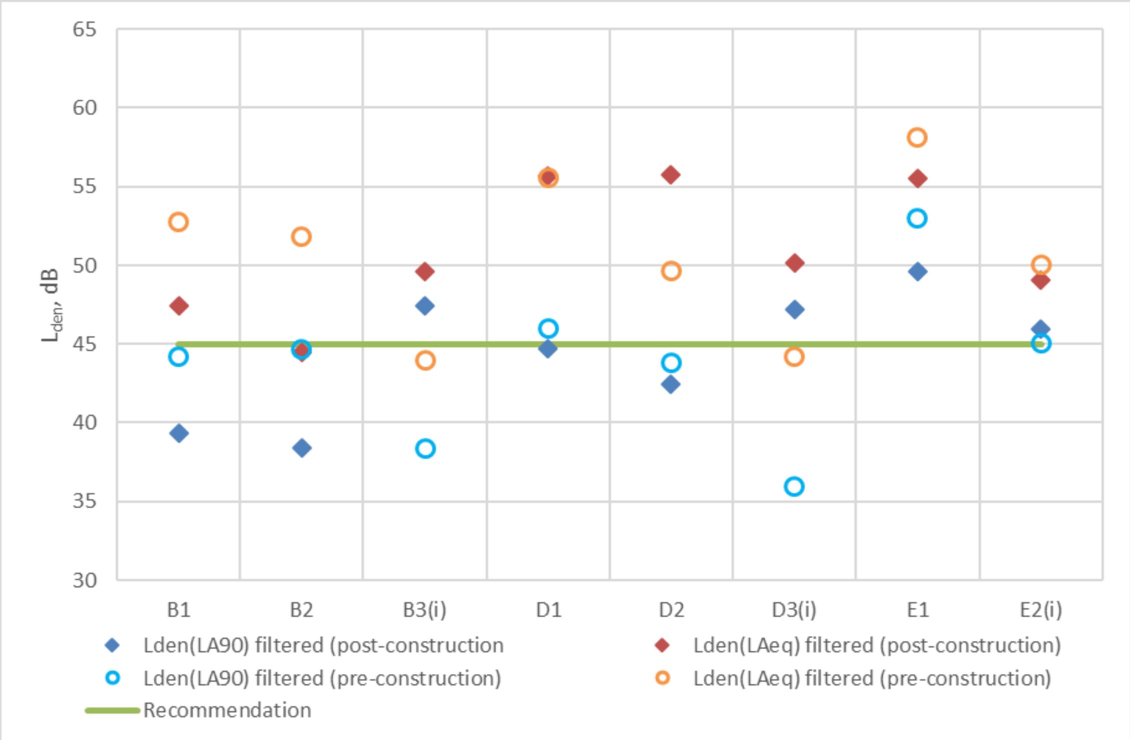



To further illustrate these complications, Figure 2 illustrates the results of pre and post construction noise level measurements at eight (8) locations around three (3) different wind farm sites. The measured levels are determined using the both the $L_{A90}$ and $L_{Aeq}$ noise levels. All noise levels are based on datasets which were filtered using the procedures outlined above.

The results in Figure 2 illustrate a high level of variation, particularly those relating to measurements at receiver locations. This small sample of receiver location measurements illustrates the $L_{den}$ noise levels derived from $L_{A90}$ measurements were lower after construction of the wind farm, suggesting background noise was a significant source of variation in the comparisons. However, despite the significant background noise influence, this limited number of receiver measurements indicated the post-construction $L_{den}$ noise levels derived from $L_{A90}$ measurements were at, or below, the 45 dB conditional recommended level. At the two intermediate locations (identified as B3(i) and D3(i)) positioned near the predicted 45 dB $L_{Aeq}$ contour of the wind farms, the post-construction measured noise levels show an increase relative to the pre-construction noise levels. However, despite being significantly nearer to the wind farm than the receiver locations, the post-construction derived $L_{den}$ noise levels are only marginally higher than the 45 dB $L_{den}$ conditional recommendation.

The comparison in Figure 2 further illustrates the complications of attempting to derive $L_{den}$ noise levels from measurements at typical receiver separating distances. However, the results provide a limited indication that, for locations where Australian noise policy requirements are met, wind farm noise levels may be comparable to, or lower than, the 45 dB $L_{den}$ conditional recommendation. This is examined further in the subsequent section using prediction-based datasets.

**Figure 2: Comparison of pre and post construction $L_{den}$ noise levels at receiver and intermediate locations**




# 4. Predictive Comparison of the $L_{den}$ Metric with Australian Policy Metrics

## 4.1 Overview

The $L_{den}$ noise level referenced in the 2018 WHO Guidance is based on noise levels averaged over the day, evening and night period of a year. To assess the relationship between Australian wind farm noise levels and the 2018 WHO Guidance, the $L_{den}$ has been predicted for typical receiver distances for an example wind farm layout, accounting for variations in noise levels occurring over the duration of a year.

The key sources of variation in receiver noise levels which are accounted for in this modelling are:

- the change in sound power level of the turbines for different hub height wind speeds
- the change in the noise propagation from the wind farm to the receiver due to wind direction.

The effect of these variations will vary for different sites, according to the orientation of the receivers relative to the wind farm, the turbine installed at the site and the wind characteristics of the site. The $L_{den}$ predictions have therefore been produced for multiple receiver locations, turbine types and example site yearly wind distributions.

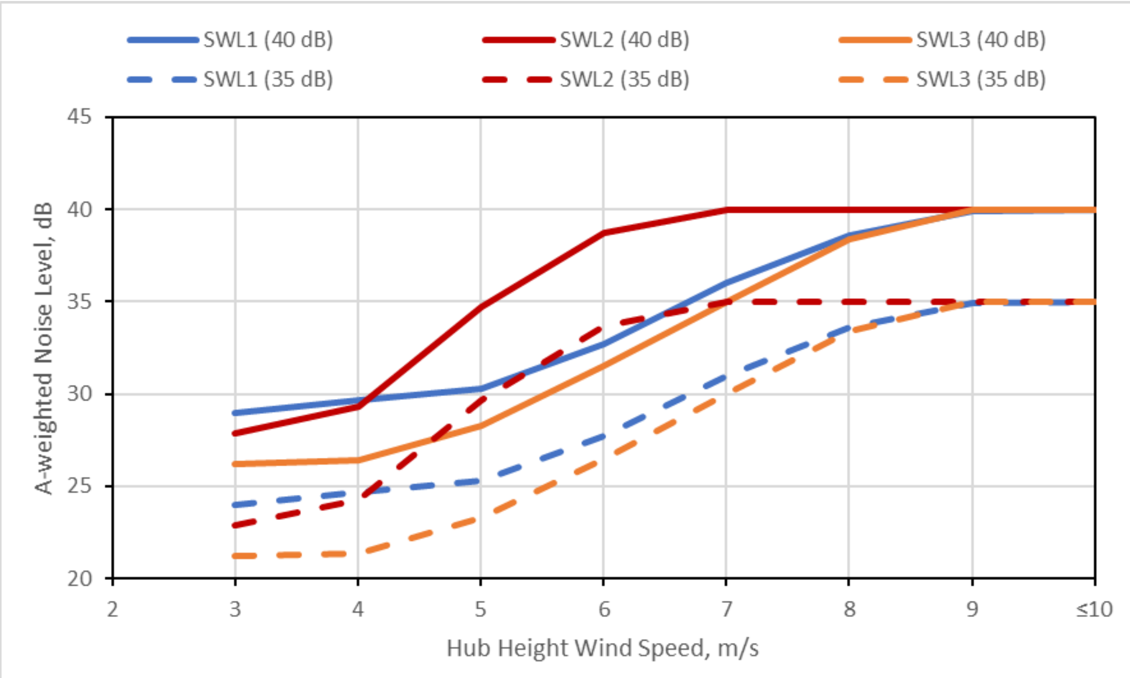
### 4.2 Example wind farm layout, noise emission characteristic and wind distributions

The example wind farm layout for the modelling consists of a generic arrangement of turbines extending over a rectangular area of approximately 30 to 35 km$^2$, aligned along a southwest-northeast direction.

Example sound power level data for three (3) types of multi-megawatt turbines with modelled tip height of 170 m, were sourced from a combination of manufacturer's specification data. The turbines for the analysis were chosen to represent a range of configurations, from turbines which are characterised by an increase to maximum sound power levels over a relatively short wind speed range, to turbines which exhibit a slower rate of increase in sound power level with increasing wind speed. Differences in the frequency spectrum of different turbines do not represent a significant source of variation for this type of analysis. As such, a single representative octave-band spectrum was used to represent all three (3) types of turbines.

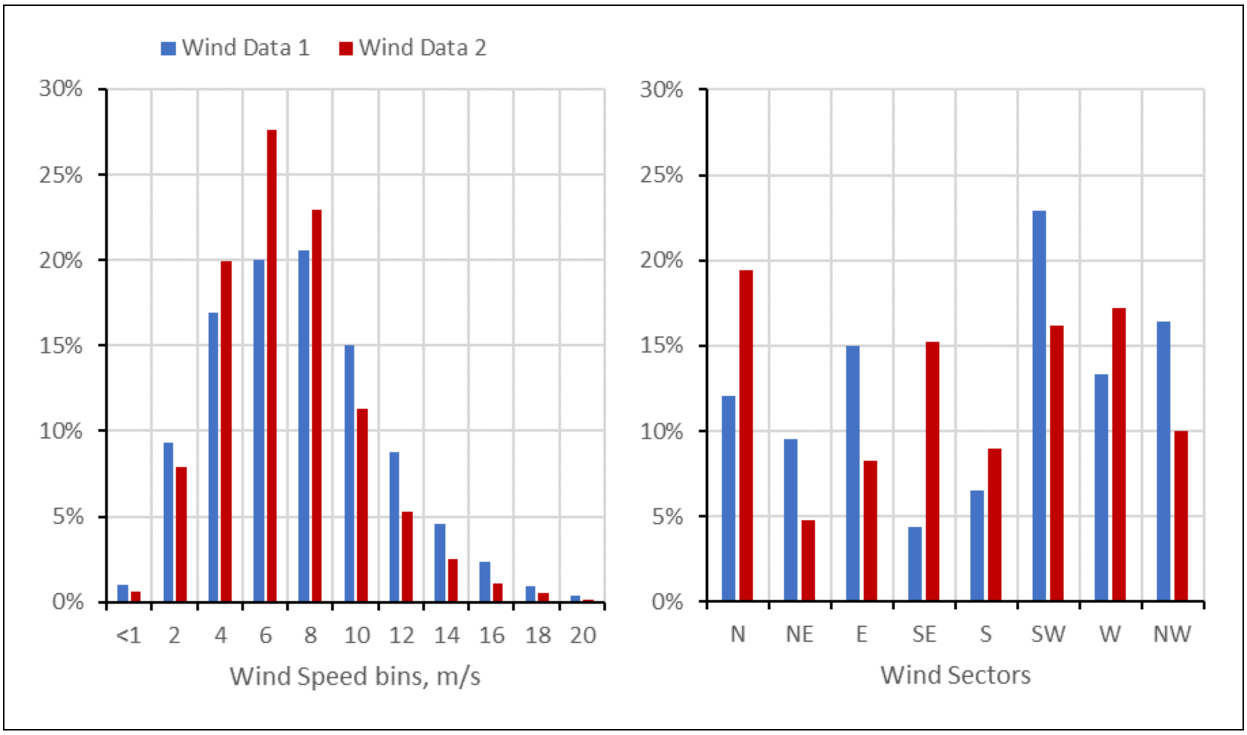
To illustrate the characteristics of the selected turbines, Figure 3 presents the profile of the predicted noise levels versus hub height wind speeds, normalised to upper predicted noise levels of 35 and 40 dB for ease of comparison (the range of minimum noise limits applied to wind farms in Australia).

**Figure 3: Assessed turbine characteristics – normalised to 35 dB & 40 dB upper predicted receiver levels**




Two example wind data sets consisting of hub wind speed and direction in ten (10) minute intervals over a period of a year were sourced from other Australian wind farm sites. The wind direction and speed distributions are summarised in Figure 4.

**Figure 4: Distribution of wind speed and direction for each wind data set**




The modelling was carried out for a total of eight (8) receiver locations in various directions within the predicted 35 to 40 dB $L_{Aeq}$ noise contours. The distance and orientation to the example layout are summarised in Table 2.

**Table 2: Receiver locations**

| Location | Distance from nearest turbine (number of tip heights) | Direction from nearest turbine |
|---|---|---|
| H1 | 5 | E |
| H2 | 8 | N |
| H3 | 6 | S |
| H4 | 7 | E |
| H5 | 9 | N |
| H6 | 14 | N |
| H7 | 9 | NW |
| H8 | 10 | E |

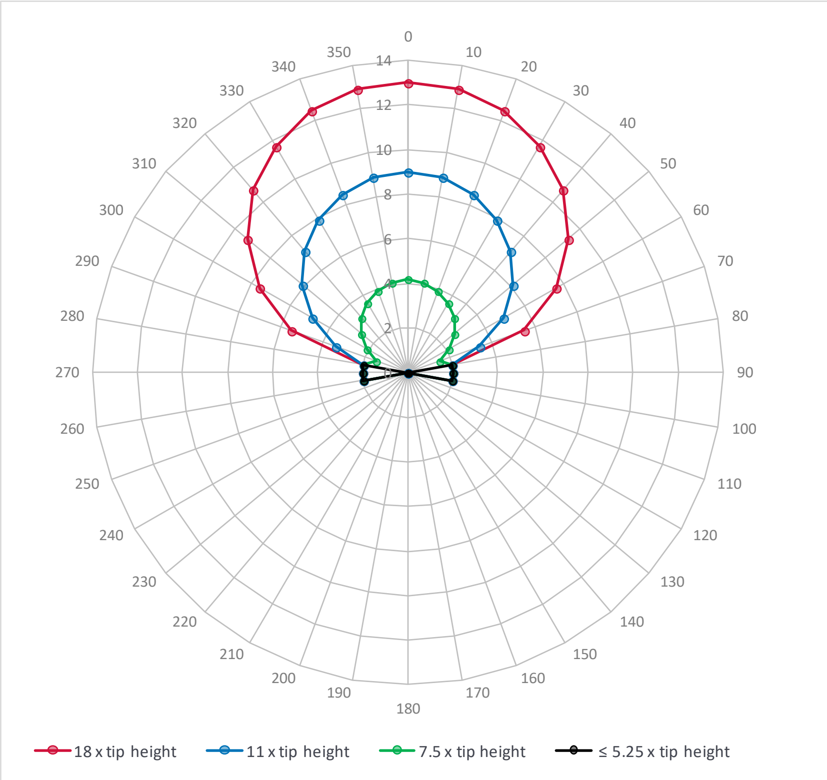
## 4.3 Prediction methodology

The noise predictions were calculated using the ISO 9613-2 [12] prediction method, based on the recommendations and adjustments detailed in the UK Institute of Acoustics guidance [13].

The ISO 9613-2 method provides predicted noise levels for conditions that are favourable to the propagation of sound, and a method of calculating a $C_{met}$ correction to determine long term average noise levels accounting for variations in atmospheric conditions. However, the assessment of suitable $C_{met}$ corrections for wind farm noise propagation, accounting for the wide range of wind speeds and directions that can give rise to favourable sound propagation for a wind farm, are not prescriptively defined in ISO 9613-2.

Adjustments to the predicted noise levels for wind direction have therefore been determined using the directional adjustments detailed in the UK Institute of Acoustics guidance. The applicable directional attenuation losses are illustrated in Figure 5.

**Figure 5: UK IOA Guidance – directional propagation losses vs. wind direction for flat terrain (0 degrees being upwind propagation)**



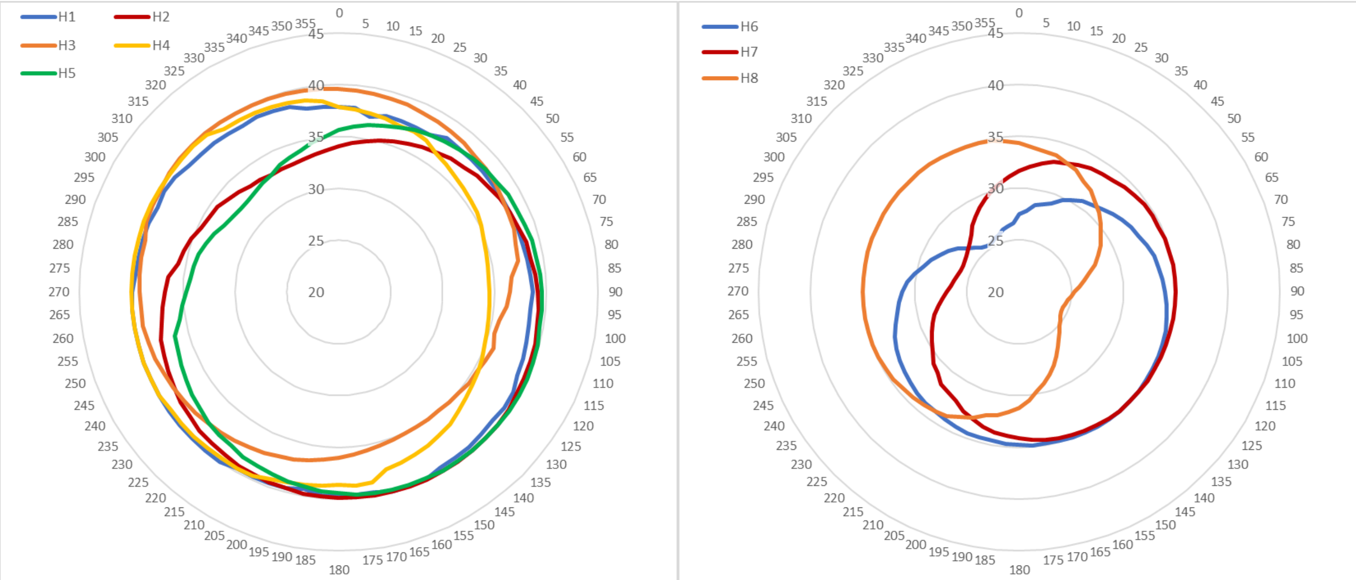

The predicted noise levels for each receiver location were determined for the highest sound power level and all wind directions in 5 degree increments. The results were then used to determine the predicted noise level for each receiver location for each 10 minute period of the year, based on the corresponding site wind speed and direction from the two wind data sets. The predicted noise levels for each 10 minute period were then aggregated to calculate the $L_{den}$ noise level for the year.

## 4.4 Results

The predicted directional noise levels corresponding to the highest sound power levels are presented in Figure 6 for the receiver locations adjusted to an ISO 9613-2 downwind reference level of 40 dB and 35 dB $L_{Aeq}$.

The directional noise predictions generally indicate values corresponding to the upper downwind predicted noise levels for around 30 % of wind directions or less. The reduction in noise level between favourable and least favourable noise propagation conditions varies from approximately 3 to 8 dB depending on the receiver location and their position relative to the wind farm.

**Figure 6: Directional plot showing predicted noise levels for receivers adjusted to an ISO 9613-2 downwind reference level of 40 dB (left) and 35 dB (right)**




Based on the directional predictions in Figure 6 for the highest sound power levels, the variations in sound power level with wind speed for three (3) turbine types, and the site wind speed and direction distributions, the predicted $L_{den}$ levels are presented in Table 3.

The key aspects of these results are summarised as follows:

- The predicted $L_{den}$ levels are below the conditional recommendation level of 45 dB at all locations
- At locations where the highest predicted wind farm noise levels correspond to 40 dB $L_{Aeq}$, the relationship between the $L_{den}$ and downwind predicted $L_{Aeq}$ ranged from -0.5 to +4.3 dB (average difference of +2.1 dB), with 44.3 dB $L_{den}$ being the highest predicted annual level
- At locations where the highest predicted wind farm noise levels correspond to 35 dB $L_{Aeq}$, the relationship between the $L_{den}$ and downwind predicted $L_{Aeq}$ ranged from -1.0 to +3.6 dB (average difference of +1.4 dB), with 38.6 dB $L_{den}$ being the highest predicted annual level.

The results indicate that the relationship between the $L_{den}$ and highest downwind $L_{Aeq}$ vary considerably according to the characteristics of the turbine and orientation of the receiver relative to the wind farm site. The latter predominantly relates to whether the receiver is in or out of the prevailing downwind direction range, but also relates to the reduction in noise level for unfavourable conditions being dependent on the angle of view of turbines from the receiver location. In all cases, the difference was significantly less than the maximum theoretical difference of +6.4 dB (i.e. assuming a constant noise level equal to the highest predicted noise level).

**Table 3: Predicted dB $L_{den}$ accounting for site wind speed and direction distribution**

| | Wind Data 1 SWL 1 | Wind Data 1 SWL 2 | Wind Data 1 SWL 3 | Wind Data 2 SWL 1 | Wind Data 2 SWL 2 | Wind Data 2 SWL 3 |
|---|---|---|---|---|---|---|
| *ISO 9613-2 predicted downwind noise level of 40 dB $L_{Aeq}$* | | | | | | |
| H1 | 43.1 | 44.3 | 42.9 | 42.0 | 43.9 | 41.6 |
| H2 | 41.5 | 42.8 | 41.3 | 40.1 | 42.3 | 39.6 |
| H3 | 42.6 | 43.8 | 42.4 | 41.8 | 43.4 | 41.5 |
| H4 | 42.7 | 43.8 | 42.5 | 41.6 | 43.4 | 41.3 |
| H5 | 41.3 | 42.6 | 41.0 | 40.0 | 42.1 | 39.5 |
| *ISO 9613-2 predicted downwind noise level of 35 dB $L_{Aeq}$* | | | | | | |
| H6 | 36.1 | 37.4 | 35.9 | 34.5 | 36.8 | 34.0 |
| H7 | 36.0 | 37.4 | 35.8 | 34.9 | 37.0 | 34.4 |
| H8 | 37.5 | 38.6 | 37.3 | 36.7 | 38.2 | 36.4 |

## 5. Conclusion

The publication of guidance on wind farm noise by the WHO provides an additional valuable reference for policy makers, stakeholder groups and the wind industry.

The use of the $L_{den}$ metric used in the 2018 WHO Guidance provides the benefit of alignment with broader strategical polices for transportation noise and metrics commonly referenced in large-scale community noise exposure research. However, the use of $L_{den}$ as an assessment tool for wind farms introduces several practical challenges.

The analysis presented in this paper demonstrates that measurement of $L_{den}$ noise levels at receiver locations is problematic due to the effect of ambient noise levels in rural environments being comparable to, or greater than, the conditional recommendation level of 45 dB $L_{den}$. Further, the use of $L_{den}$ as a measurement metric for wind farm assessment potentially precludes the use of common supplementary analysis techniques used to separate wind farm and ambient noise when conducting.

This finding is consistent with commentary with the 2018 WHO Guidance which notes that:

> [...] *it may be concluded that the acoustical description of wind turbine noise by means of $L_{den}$ or $L_{night}$ may be a poor characterization of wind turbine noise and may limit the ability to observe associations between wind turbine noise and health outcomes*.

Consistent with the intent conditional recommendations with the 2018 WHO Guidance, the 45 dB $L_{den}$ level noted for wind farms should be primarily used to inform the development and review of noise policies for wind farms, rather than a compliance metric for assessing individual projects.

To provide context to the policies used to assess wind farm noise in Australia, measured and predicted $L_{den}$ noise levels for compliant wind farm scenarios were assessed and demonstrated levels below the 45 dB $L_{den}$ conditional recommendation of the 2018 WHO Guidance.

Based on this finding, current Australian noise requirements are consistent with the WHO conditional recommendation.

## References


[1] World Health Organization (2018) *Environmental Noise Guidelines for the European Region*

[2] *The* University of Adelaide (2015) *Systematic review of the human health effects of wind farms*

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[11] Griffin, D., Delaire, C., & Pischedda, P. (2013). *Methods of identifying extraneous noise during unattended noise measurements* 20th International Congress of Sound & Vibration

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[13] UK Institute of Acoustics (2012) *A good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise*