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Prediction, Validation, Assessment & Compliance of Wind Farm Noise in Australia

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Abstract

The process of assessing noise from wind farms is being refined as more wind farm developments are installed in Australia. This paper addresses the current requirements and practical issues relating to acoustic monitoring, modelling, validation and compliance for wind farm developments. Relevant aspects of the new Australian Standard, draft National Wind Farm Development Guidelines and the revised SA EPA Wind Farm Noise Guidelines are discussed.

Measurement data requirements and statistically relevant datasets are discussed for background characterisation at the planning stage and for post-installation compliance assessment. Of particular importance is the robustness of the noise-wind regression analysis to determine noise criteria or check compliance. Noise propagation algorithms are evaluated in the context of their use and application to different sites, and the consideration of worst case propagation scenarios over various distances. The resultant model limitations and accuracy are compared based on validation after turbine installation at a number of wind farm sites.

The practical application of assessment requirements and the range of technical and logistical issues and their implications for wind farm developments are investigated. This includes the consideration and evaluation of the likelihood of special audible characteristics (such as tonality and amplitude modulation) and the effect of variations in terrain and atmospheric conditions (such as site stability and wind shear effects). In the vital area of public perception and responses or complaints, feedback is provided on the appropriate level of communication, education and expectations for the relevant local community. Examples of recent validation and compliance outcomes, and lessons learned through experience, for a range of recent wind farm installations throughout Australia are presented.

Introduction

Wind turbines and wind farms have unique noise generating characteristics. Unlike typical industrial noise sources, the sound power level of wind turbines varies with wind speed. The main noise source associated with a wind turbine is aerodynamic noise from the blades centred on the hub, which is located at a significant height above the local ground level (up to 100m AGL).

The environments surrounding wind farm sites are usually rural and often have low background noise; however, background noise increases with wind speed (due to wind induced noise from foliage etc) and provides a masking effect.

To predict and assess noise generated by wind farms therefore warrants special requirements for acoustic measurement, analysis, modelling, reporting and assessment. In Australia, there is a recently released Australian Standard (AS 4959-2010) and South Australia has published wind farm noise guidelines (SA EPA, 2009). This paper presents a mixture of experience related advice, standard and guideline requirements and practical application for new wind farm developments in Australia.

Measurement of Background Noise

The existing noise environment at potential receiver locations (in the vicinity of a proposed wind farm site) must be adequately determined for a representative range of conditions. This requires obtaining sufficient background noise measurements correlated with wind speed at the wind farm site.

Site Selection

Any residential premises within at least 3km of the nearest turbine of the proposed wind farm array need to be identified. Private landowners who enter into agreements with the wind farm developer to place wind turbines on their properties (ie. “windfarmers”) are classified as non-relevant receivers. Other premises (where someone resides or where a dwelling has development approval) that are not associated with the wind farm are classified as relevant receivers (RRs).

Background noise measurements should be undertaken at a sufficiently representative sample of the RRs. This sample should include the nearest RRs to the wind farm site and where the predicted noise from the wind farm is likely to exceed the base noise criterion for wind speeds of $10ms^{-1}$ or less. In a group of RRs, it may be sufficient to measure at one RR within the group that is representative of the worst case (highest potential noise exposure). The choice of measurement locations will require discussion and agreement with the wind farm developer and the regulatory authorities.

Particular attention should be made in regard to sheltered receivers (eg. that may be shielded from prevailing winds by terrain) where the wind-induced background noise may be low when wind speeds (and turbine operation) are high at the wind farm site.

Relevant receivers where measurements are not taken need to be characterised for their likely type of background environment and linked with a measured RR.

Site Access

Wind farm sites in Australia are typically situated in remote areas away from major centres, near coastal or hilly terrain. The travel time from the nearest city can be substantial and can involve driving on minor/unsealed rural roads.

It is important to obtain clear instructions on directions to the various relevant receiver locations. As the RR sites are often on rural properties, access and permission requirements need to be determined with the developer/landowner.

Before setting up the measurement equipment at RR sites, sufficient notice needs to be given to landowners on when, where and for how long the measurement equipment will be set up. Extra care needs to be taken when setting up as returning again to the remote site will be a time consuming exercise.

Background Noise Data

Sound levels meters (SLMs) or statistical noise loggers of at least Type 2 certification (in accordance with IEC 61672) are required for background noise measurements (AS 4959-2010; SA EPA Guidelines, 2009).

There may be a requirement in the near future to use only Type 1 SLMs. In addition to the measurement accuracy, it is important to have low noise floor equipment (< 20dBA) for measuring low background levels at "quiet" rural sites. L_{A90} levels in 10-minute intervals need to be measured at a height of 1.2 to 1.5m above the local ground level.

All equipment must be within calibration (with a current certificate) and the calibration should be checked (eg. with a piston-phone calibrator) before and after the measurements and noted.

Windshields must be used in accordance with manufacturer's instructions to reduce the influence of wind-induced noise on the microphone. Special windshields may be needed if wind speeds are likely to exceed $5ms^{-1}$ at the receiver location. From experience, this is not a common occurrence and measurements of wind speed at receiver sites can be used to discard measured data for when wind speed exceeds $5ms^{-1}$, or is determined to be at such a level, based on manufacturer's test data, to have influenced results.

Measurement equipment needs to be autonomous and have sufficient battery life to last over a minimum of 3 weeks. It is recommended that solar panel or other power backup is used and that the equipment is checked to have sufficient on-board memory for the amount of data to be collected. The on-board clocks on different monitoring equipment need to be on the correct local time and synchronised with each other. Additionally, the time stamp reference period needs to be noted, and adjusted to be consistent (i.e. some equipment timestamps data at the end of the period, whereas others at the start).

Equipment security needs to be considered such that equipment can not be tampered with or stolen. Bird spikes should also be affixed to microphone poles. There should not be any appendages or tape affixed to the equipment which could flap in the wind and cause extraneous noise generation that could affect the L_{A90}.

The noise logging equipment must be placed greater than 5m from the nearest reflecting surface/facade and within 20m of the main residence in the direction towards the wind farm. The equipment should not be placed close to overly noisy trees/shrubs, pumps, air conditioners or other extraneous noise sources and should be representative of the general environment in the vicinity of the residence. If a wind measuring anemometer is used it should not be placed close to the noise logging equipment such as to influence noise measurements.

It is important to take photographs of the equipment setup with the residence in the field of view and also in the direction of the wind farm site. Residents should note the times of any unusual or extended noise sources (eg. farm machinery near loggers) that occur during the monitoring period.

It is recommended that localised wind (near ground level) and rain data is collected at a subset of the relevant receiver locations. Bureau of Meteorology (BOM) data may also be used (particularly for rain data) if a BOM station is close enough to the site and representative of site conditions.

Variations in the terrain/topography and prevailing wind directions in the vicinity of a wind farm site may cause significant variations in wind and rain levels for different sites. In addition, seasonal variations (eg. atmospheric stability) or unusual prevailing wind variations may cause measurements to be sensitive to the time of year.

Wind Speed Data

Wind data needs to be measured at the wind farm site during the background noise monitoring period. Wind speed and direction is measured in 10-minute intervals at hub height (HH). Note that previous standards stipulate a reference height of 10m above ground level (AGL), however recent changes to guidelines and standards have moved away from this reference. This however does not match the current international measurement standard (IEC 61400-11 v2.1, 2006) requirement to measure the sound power level of wind turbines at 10m above ground level (AGL).

Recent research (van den Bergh, 2003; Fowler, 2005) does suggest that some sites may show variations in the vertical wind profile or shear between day and night (eg. due to greater atmospheric stability at night compared to day). In addition, the site wind profile (and terrain roughness) may be different to that at the initial turbine sound power measurement site. This may cause errors in the assumed turbine sound power level versus wind speed for different conditions at the site. Therefore the use of standardised 80m HH wind speed is warranted, and scaling using the IEC 61400-11 procedure gives more accurate results.

It is therefore important to define the inherent wind profile at the proposed wind farm site and use this to adjust the sound power level versus wind speed of the proposed turbines. In addition, it may necessitate separating the day and night data collected during the background noise monitoring period (Fowler, 2005). Stable conditions at night could cause lower background noise at the receiver for a particular wind speed at hub height.

In the absence of hard data regarding the influence of this effect in Australian conditions, measurement of wind speed at heights approaching hub height in conjunction with the “normal” 10m AGL measurements may provide the necessary site specific data on wind shear to enable informed decisions with regard to its influence, and any need to account for it.

Data Collection

The background noise data (L_{A90}) and wind farm site wind data need to be collected simultaneously and the 10-minute measurement intervals need to be synchronised. It is important to ensure which time interval relates to the record time stamp in the noise and wind data (which can vary).

A minimum of 2000 valid noise/wind data pairs need to be collected during the monitoring period to ensure a sufficiently representative dataset, in accordance with current practice driven by overseas and local experiences. The data must sufficiently cover or represent the wind speed range at the site and cover all wind directions as far as practicable.

Time intervals for which the wind speed exceeds $5ms^{-1}$ at the receiver microphone need to be excluded from the data-set. Data also needs to be removed for time intervals that are rain affected (eg. heavy rain/storms or intervals with >2mm rain). Care should also be taken for sites adjacent local creeks and waterways following periods of heavy rains.

To account for excluded/invalid data (and to ensure sufficient data in the applicable wind speed range), a period of 3 weeks should be allowed for the collection of data for planning purposes. If possible, a check of recorded data during the monitoring period can help to determine the total period required to ensure sufficient points are collected over the full wind speed range (after removal of invalid data).

Criteria Determination

Assessment Standard

An acceptable level of noise from wind farms is usually based on background noise levels. In Australia, there is a new Australian Standard (AS 4959-2010) and the South Australian Environment Protection Authority (EPA) has published wind farm noise guidelines (SA EPA, 2009).

The AS establishes a guide to the methodology to be used when undertaking wind farm noise measurements, predictions and assessments. The SA EPA guidelines specify the noise criteria to be used for compliance in addition to specific methodology requirements, which align well with AS 4959-2010.

Other applicable standards include the New Zealand Standard (NZS 6808, 2010), which also provides criteria. Assessment guides are also given in reports or guidelines by ETSU (UK), the Australian Wind Energy Association (AUSWEA) and the New Zealand Wind Energy Association (NZWEA). In addition, a new draft set of national wind farm development guidelines have been developed by the EPHC, the Environment Protection and Heritage Council (Draft NWFDG, 2010). These draft guidelines build upon AS 4959-2010 but appear to provide an unbalanced focus on special audible characteristics from wind farms, which are uncommon in practice.

The SA EPA Guidelines have been widely adopted throughout Australia by regulatory authorities, although some local councils or shires (eg. in Victoria) use different approaches provided by the NZS. Care should be taken when determining the appropriate standard applied by the authority due to differences across states.

From the SA EPA guidelines, the wind-speed dependent criterion is the maximum of the base criterion of 35dBA or background plus 5dB for each integer wind speed in the turbine operating range (between cut-in and rated power). The criteria assume the normal operational noise from a wind farm with the exception of unusual tonality effects. A criterion of 40dBA can be applied to other locality zones such as intensive primary production areas. These criteria align with most wind farm criteria in Europe.

These criteria are not applicable to non-relevant receivers, and other approaches developed in conjunction with these landowners, such as sleep disturbance criterion (WHO, 1999) of 45dBA (external $L_{Aeq,\ 8\ hr}$), can be used.

Different states within Australia assess allowable WTG noise to different standards. Some use NZS 6808-2010, while others use the SA EPA noise guidelines (some use the original 2003 version and some the 2009 version). Also, some planning and development approval boards have additional requirements to the standards.

For example, some councils do not require planning approval if a land owner is to build a new premises at any location on their land. This in turn means that when planning the wind farm, and more specifically the noise impact, the noise levels are to meet the required limits at the boundary of the property, and not at the specific residential premises. As in the future the land owner may decide to build another

residence closer to the wind farm, and therefore experience higher noise levels from the wind farm than previously predicted.

Data

The final data-set to be used for analysis (and criteria determination) must have all invalid data excluded. This includes removal of wind affected data (where wind speed exceeds $5ms^{-1}$ at the receiver microphone) and rain affected data (eg. heavy rain/storms or intervals with > 2mm rain).

A total of 2000 valid noise/wind data pairs need to be correlated and plotted on a graph. As a check, the plotted points must look realistic, ie. generally increase with increasing wind speed at all points, but expect a variation in noise levels for any given wind speed.

If there are known variations in the vertical wind profile at the site (or if it is suspected that background levels are dependent on time of day) it may be necessary to separately plot the day and night data. It may also be necessary to separately plot data for some wind directions if significant seasonal variations are known to occur (or if it is suspected that background levels are strongly dependent on wind direction).

Calculation of Regression Curve

A best-fit regression analysis needs to be applied to the valid data-set collected for each relevant receiver. A regression curve, defined by a second or third order polynomial, usually provides the best correlation coefficient. If the correlation coefficients are low, other lines of best fit should be tried.

The data-set used for regression curve fitting should include only wind speed data (at the wind farm site) inside the normal turbine operating range (from cut-in wind speed, usually around 3 to $4ms^{-1}$, and up to rated power wind speed, usually around 12 to $14ms^{-1}$, at hub height). Data at the extreme ends of the wind speed range can influence the slope of the regression curve.

The fitted regression curve (overlaid on the plotted data points), the polynomial equation describing the curve and the correlation coefficient must be displayed on the final graph.

The wind-speed dependent criteria are determined by adding 5dB to the regression curve and then taking the maximum of this or the fixed 35dBA base criterion. An example of the resultant curves is shown in Figure 1.

Criteria then need to be applied to the other relevant receivers (where noise measurements were not taken), based on the characterisation of their likely type of background environment, by linking with a measured receiver.

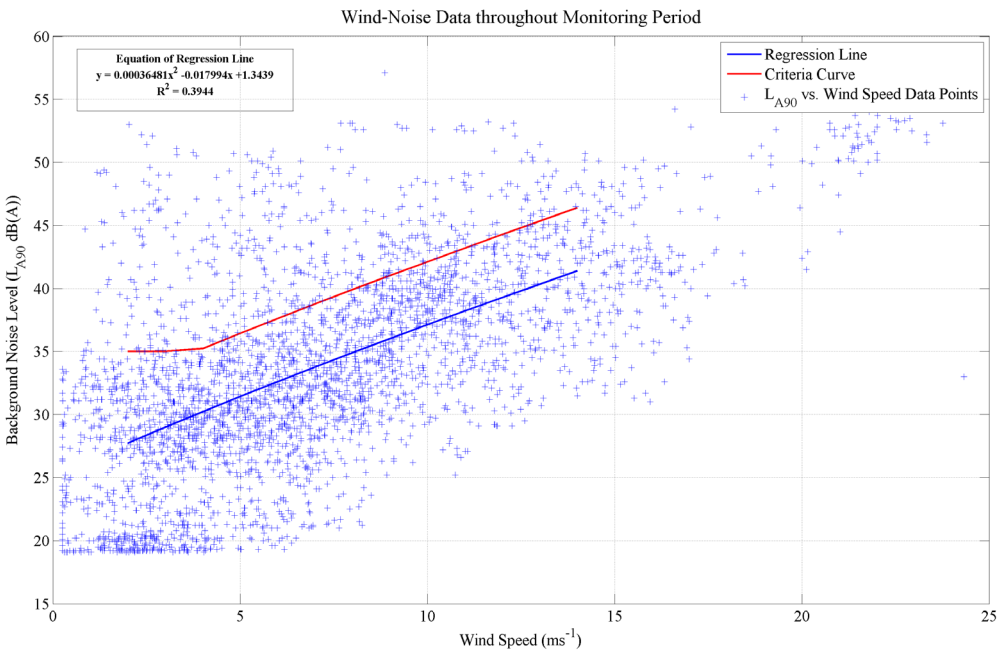

Figure 1. Wind-Noise Data with Regression/Criteria Curves.

Site Wind Shear Issues

IEC 61400-11 stipulates a measurement method of the sound power level of a WTG at a wind speed measured at hub height (usually derived from generated electrical power output), and then adjusted to 10m AGL using a wind speed reference height scaling process using an equation which is a function of the roughness length (site specific), rotor centre height, and the anemometer height. Therefore this 10m AGL sound power data is used assuming that the site wind speed profile behaves in the manner assumed in the scaling equation. We note however that this assumed wind speed profile may not accurately fit the site conditions where the measurement was taken, and also where turbines are to be installed for a planned project.

Previous Australian noise guidelines and standards have outlined that the background noise determination is performed using wind speed data from a 10m AGL anemometer. From this background noise data, criteria for each site are set. A noise model is then built to determine the noise levels at each site, and is designed to meet the determined criteria.

The sound power levels used in the noise model are based on hub height wind speed data, scaled to 10m AGL, however the noise criteria the wind farm is designed to meet is based on a measured 10m AGL wind speed. Therefore if the wind speed profile at the wind farm site does not match the assumed profile in IEC 61400-11, then the sound power used in the design modelling process will be erroneous.

For example, for a wind farm in Australia we have extrapolated measured 10m AGL wind speed data up to hub height using equation 7 given in IEC 61400-11 (with a roughness length of 0.01m). We then compared this predicted hub height data (defined as HH*) to measured wind speeds at a hub height anemometer at the same time.

We found that in some cases, both the predicted hub height wind speed from the 10m wind speed agreed with each other. However in other cases the derived hub height wind speed was between 4m/s under, and up to 10m/s over the actual hub height wind speed. We found that on average, the derived hub height wind speed was approximately 2m/s above the actual measured speed.

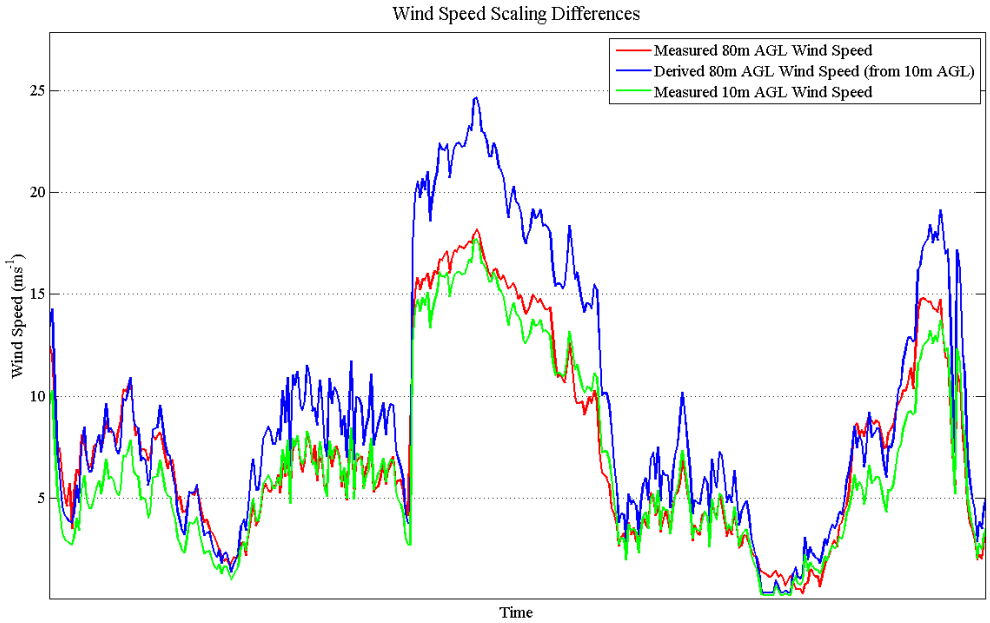

Figure 2. Wind Speed Scaling Differences

As can been seen in Figure 2, there are times when the measured HH data agrees with the data scaled from 10m to HH (seen at the beginning of the graph), however there are also times when these two wind speeds do not agree by a significant amount (middle of graph).

Therefore this shows that the noise model (which uses sound power data, based on hub height wind speeds, scaled down to 10m AGL using an assumed universal shear) is incongruent with the criteria it is assessed/designed to (which is based on 10m AGL wind speed measurements).

The implications of this are (for this specific case):

If we were to perform the background noise assessment using hub height wind speeds scaled down to 10m AGL (using IEC 61400-11 Eq. 7), and compare this with an assessment using the measured 10m AGL wind speeds, the resultant background noise regression would take on a different shape, as shown in Figure 3.

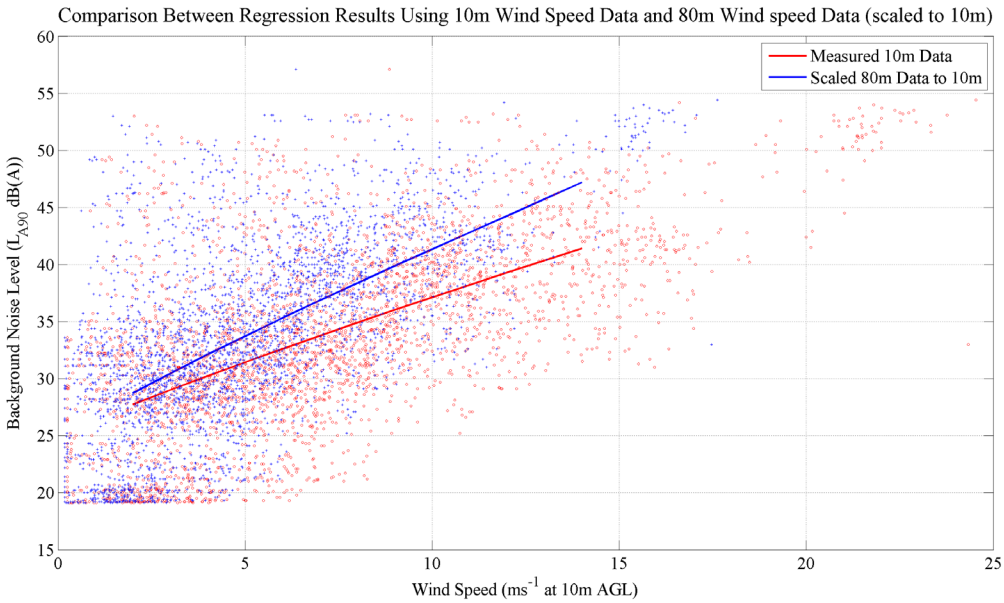

Figure 3: Comparison Between Regression Results With Measured and Scaled Data

Therefore, compliance criteria are set via the 10m AGL measured graph (shown in red), which the wind farm is designed to, however the actual sound power output at each of these individual wind speeds created by the wind farm will follow the scaled data (shown in blue). In this instance, it can be seen that the assumed wind shear (as calculated in IEC 61400-11) does not match the actual wind shear on site and therefore the predicted noise result is matched with the incorrect background noise level at that same wind speed (as it is set via different datums). The net result (in this instance) is that the wind farm will be designed to meet a stricter standard, and possibly suffer layout changes as the actual background noise at a certain wind speed is actually higher than determined in the initial background noise monitoring (when determined using 10m AGL measured data).

To avoid this, it is recommended that the background noise determination uses the same wind speed datum as the sound power level calculations (i.e. hub height), and if required to scale down to 10m AGL wind speed, both use the same method. It is in this way that the site specific factors which determine wind shear are in effect cancelled out, and therefore gives a much more accurate picture of each site.

This change has started to be implemented in the latest standards and guidelines, where background noise data is to be matched with hub height wind speeds, however the sound power data from WTG manufacturers are still being performed to the IEC 61400-11 standard, and therefore giving derived 10m AGL referenced sound power data. When scaling these 10m AGL referenced wind speed sound power levels back towards hub height, the adjusted wind speeds are then non-integer.

Regulatory agencies in Australia (EPA, planning departments) however are rigid in their use of hub-height data, and therefore this inconsistency or lag between international standards and Australian standards/guidelines is proving difficult to efficiently progress with wind farm noise assessments.

Modelling and Predictions

Data Requirements

Data required to undertake noise modelling include the wind turbine locations (including local ground height data) and the residence locations out to at least 1.5km distance (including local ground height data). A consistent coordinate system should be utilised (eg. UTM WGS84). Ground topography data across the region (out to receiver locations) is required to reasonable accuracy (at least 5m height interval contours).

Wind turbine acoustic performance data should be determined in accordance with the international measurement standard (IEC 61400-11, 2006). Data should be provided as a sound power level for each wind speed (at a height of 10m AGL) between cut-in and rated power. The sound power frequency spectrum should be provided in third octave bands to assess tonality; however, ideally narrow band data should be used to properly assess tonality.

The source height in the model should be set at the hub height above the local ground level for each turbine. It may be necessary to use the inherent wind profile (and terrain roughness) at the proposed wind farm site to adjust the wind speed dependency of the sound power level of the turbines.

Physical parameters such as air absorption and ground hardness need to be determined for the considered site. Assumptions need to be considered, such as whether barrier effects due to topography and structures are included and whether wind propagation effects are included; if not, then safety margins need to be added to account for these.

Prediction Software

A number of proprietary software packages are available for modelling the prediction of noise including SoundPLAN, ENM, CadnaA, Nord2000 and many others. Packages such as WindPRO and WiTuProp have been developed for specific application to wind turbine noise prediction.

The SoundPLAN and ENM packages provide a choice of theoretical algorithms to use for calculating the propagation of noise over distance.

The application of modelling software to specific situations needs to be carefully considered and, where possible, based on validations with actual measurement data to provide confidence and minimise associated inaccuracies.

Propagation Algorithm

The algorithm for calculating the propagation of noise over distance needs to be optimised for the situation considered. Calculation algorithms can be theoretical (based on physical theory), numerical, empirical or heuristic and they vary in their assumptions and applicability to certain situations. Some algorithms may have limitations if they are simplistic and do not incorporate the effects due to some processes or assume incorrect fixed values for some physical parameters.

Applicable algorithms include International Standard ISO9613-2, British Standard BS5228, CONCAWE, Harmonoise, GPM (General Prediction Method, Nordic), Nord2000 (Delta, Denmark), WiTuProp (Delta, Denmark) amongst others. There are a number of differences between the algorithms. ISO9613-2 and GPM are relatively

simplistic methods whereas CONCAWE, Nord2000 and WiTuProp contain more complex methods.

Assumptions relating to processes and parameters (eg. ground effect/hardness, air absorption, screening/shielding effect) vary. CONCAWE is essentially the only algorithm that incorporates meteorological effects, including the wind propagation effect. The air absorption parameter is usually given by the ISO9613-2 formulation. The ground hardness (or absorption) parameter needs to be reasonable for the typical terrain (eg. partially soft) at the wind farm and receiver sites.

A comparison of models has been performed by others (Tickell, Ellis & Bastasch 2004; Berndt 2004). There can be significant differences in the prediction results over distance for different model algorithms. For example, the CONCAWE model tends to overpredict noise levels relative to WiTuProp. Quoted accuracies of models are typically in the range ±2dB to ±5dB.

A preliminary comparison of measured wind farm noise levels with predicted levels has now been performed at a number of installed wind farms throughout Australia. The results show that the CONCAWE model may overpredict by about 1 to 3dB relative to measured wind farm levels at $8ms^{-1}$. The CONCAWE model has been shown to overpredict relative to the other models; by about 1dB relative to Nord2000, by about 4dB relative to GPM and by up to 6dB relative to ISO9613 (Marchuk 2006).

After validation for a range of situations, we have found the best correlation with measured wind farm noise levels to be the CONCAWE algorithm with a ground attenuation factor of 0.5 to 0.7 (slightly soft ground, as in reality) or the ISO9613-2 method with a conservative ground factor of 0 (hard ground). This closely aligns with the findings presented in previous studies (e.g. Kaliski & Duncan 2008).

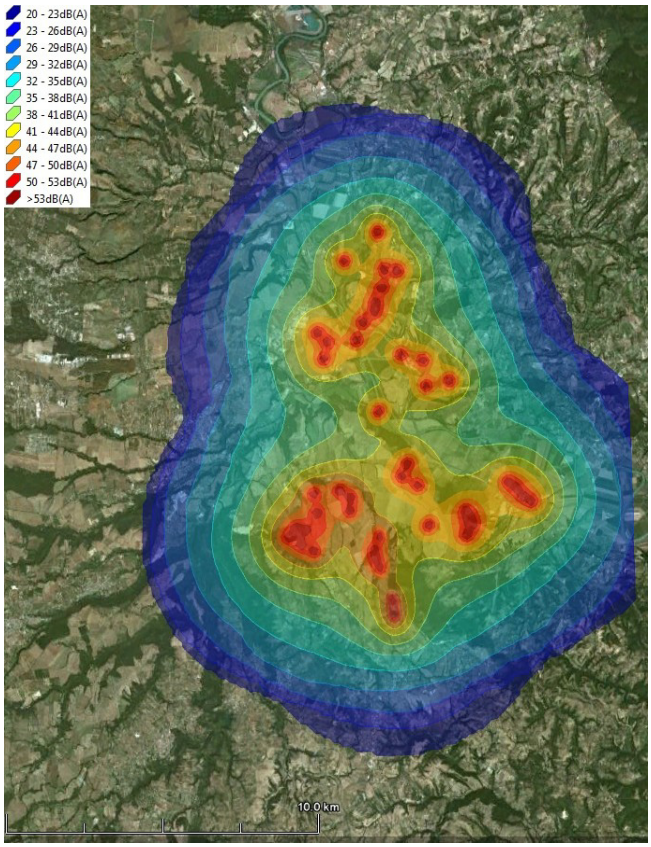

Figure 4. Predicted Noise Contour Plot.

Prediction Results

Using the chosen model, single point calculations with all turbines operating (at maximum power rating for each wind speed) should be performed for each receiver (relevant and non-relevant). The model should be run for neutral (no wind) and wind propagation scenarios. The wind propagation effect should be calculated for the operating range of wind speeds for the worst case wind direction for each receiver.

Noise contour plots should be produced (with reasonable grid resolution) showing the likely spread of noise over the whole area up to at least 1.5km from the wind farm (for neutral and worst case wind scenarios). However, noise contour plots should only be used for presentation purposes to show the general propagation of noise from the wind farm site (see Figure 4).

Prediction results for each receiver should be tabulated, for neutral and worst case wind scenarios, for each integer wind speed between cut-in and rated. If necessary, data could be tabulated for a range of wind directions. Tables should display the applicable criterion level adjacent to the predicted levels (and where any exceedances occur).

Predicted noise levels should be rounded up or down to the nearest integer or, at best, to the nearest 0.5dB increment (modelling inaccuracies do not warrant any more accurate presentation of predicted levels). A list of the most dominant turbines (ranked in order of contribution to overall noise level) could be provided for critical receivers (which exceed, or are close to exceeding, the criterion level).

Audible Characteristics and Assessment

Adjustments are required for tonality or other potential audible characteristics if they exist. The turbine manufacturer's report for sound power level must state whether any tones were measured or audible, using both a subjective and an objective method (IEC 61400-11, 2006). IEC 61400-11 outlines a procedure to objectively determine the severity of tones experienced in the near field of a wind turbine generator, however the transfer function between near field tonality levels and far field tonality levels is not properly recognised in Australia. A common acceptable level at a residential receiver is to have a tonality audibility $\Delta L_{a,k}$ of less than 0dB to be considered not audible, and has been accepted by the SA EPA as reasonable. Other standards (ETSU-R-97) have a sliding scale for penalties to apply to the noise levels if $\Delta L_{a,k} \geq 2$dB in the WTG sound power measurements.

Features or characteristics in the noise from noise sources, such as special audible characteristics, can cause annoyance to people. Potential types of special audible characteristics (SACs) include low frequency noise (LFN), infrasound, modulation, impulsiveness and tonality. From all of the available literature and studies from around the world, SACs from WTGs or wind farms are an uncommon and unlikely occurrence, and there are limited confirmed reports in the literature (ETSU/DTI 1996, Leventhall 2003/2006, Bellhouse 2004, BWEA 2005, Styles et al 2005, Pederson & Waye 2005, HayesMckenzie/DTI 2006, Moorhouse et al 2007, Sonus 2010, Draft NWFDG 2010). In addition, there have not been significant SAC incidents recorded to date with measured acoustic data at a receiver location in Australia.

Modern upwind turbines do not typically exhibit noise characteristics such as impulsiveness, modulation or low frequency components. Infrasound was a feature of some older downwind turbines; any low frequency noise from turbines has been

found to be measurable but well under (by 20 to 30 dB) perception thresholds (Leventhall 2003/2006, Bellhouse 2004, BWEA 2005, Howe 2006, Sonus 2010).

In the close vicinity of a turbine there is a slight swish-like modulation resulting from the rotor blade passing through the air and past the support tower in addition to a slight hum emanating from the turbine generator. These typically minor effects diminish rapidly over distance and, for an array of turbines, are usually randomly mixed to form low-level background white noise.

However, under some rare conditions such as extreme wind profile effect and the phasing of numerous turbines, cyclic variations could cause audible modulations that could be clearly discernible above the background for some distance.

The most likely SAC and potential source of annoyance may be from amplitude modulation (AM) - this is the modulation or cyclic variation (over blade pass cycles of once per second or so) in the amplitude or level of the broadband aerodynamic noise (200 to 1000 Hz) from the turbine blades (most likely trailing edge turbulence/vortice shedding). Note though that this should not be classified as low frequency noise or infrasound or impulsiveness (sharp peaks or impulses < 100 millisec duration). AM is a naturally occurring part of turbine noise (usually at low levels, ie. swish) but can be increased at times to cause "thumping" involving 5+dB variation every second or so but occurs very rarely (Leventhall 2003/2006, Bellhouse 2004, BWEA 2005, Pederson & Waye 2005, Hayes McKenzie 2006, Moorhouse et al 2007, Oerlemans & Schepers 2009). Note that to our knowledge there has not been any recorded incident of AM to date with actual measured data at a receiver location near a wind farm in Australia; however, there have been some unverified anecdotal accounts.

Importantly, AM may not be well defined and is a complex issue. It appears from the literature that it could be influenced by: 1) wind shear (esp. across turbine blades), 2) inflow turbulence (onto turbine blades), 3) atmospheric stability, 4) local topography, 5) series of in-phase turbines. This means that it is not necessarily a turbine type issue but is likely to be site specific (and could be more pronounced at a distant receiver than close to the turbines), but it is very difficult to capture given it is so rare and requires the simultaneous alignment of a range of specific conditions/effects. Note that if there is an occurrence then resonances in dwellings (with certain room dimensions) could amplify the effect inside.

The impact of any other wind farms in the vicinity needs to be taken into account (and likely combined noise levels should be presented) and existing or future stages of the wind farm in question also need to be addressed.

The predicted noise levels (with any safety margins applied to provide conservatism) need to be assessed against the criteria at each applicable wind speed (between cut-in and rated power speeds).

For relevant receivers, exceedances of the wind farm criteria at any wind speed need to be highlighted. It is recommended that non-relevant receivers are assessed relative to sleep disturbance criteria (eg. WHO, 1999). There may be special council or EPA requirements for additional criteria to be met.

If criteria are not met (or are close to being exceeded), then the most dominant turbines (ranked in order of contribution to overall noise level) should be determined for the critical receivers. The noise model should be rerun with turbines taken out or operation modified until the criteria are met at all relevant receivers.

The assessment should state whether turbine operational changes will need to be applied for compliance eg. for the major contributing turbines, use of lower power rating (de-rating) or noise minimisation mode or wind sector management (turn off at certain wind speeds and directions).

The likely noise impact of the electrical substation needs to be assessed against the applicable industrial noise regulations (eg. SA EPA, 2007). The noise impact due to the construction of the wind farm needs to be addressed, with attention paid to the likely period of time that certain equipment will be used and assessed relative to the applicable EPA guidelines.

Reporting

The assessment report should include the time history plots of noise and wind over the whole monitoring period. Any locally obtained (at receiver) wind and rain data needs to be summarised, with the number/extent of affected intervals.

For each relevant receiver, the fitted regression curve (overlaid on the plotted data points), the polynomial equation describing the curve and the correlation coefficient must be displayed on graphs, along with a line showing the resultant criterion level. Separate plots of the day and night data and wind direction data may need to be provided if applicable.

The report should include a discussion of the noise model accuracies, assumptions and likely conservatism. The report should contain the results described in the Prediction Results section above. The predicted impacts due to construction noise and electrical substation noise need to be included as well as the wind farm operation noise. Any other existing noise producing activities in the area need to be described and taken into account.

Regulatory authorities will generally want to sight any agreements between the developer and each windfarmer (landowner with turbines on their property). The agreements need to include the expected noise impact relative to accepted criteria such as sleep disturbance (WHO, 1999) and whether the impact is likely to cause significant interference or health effects.

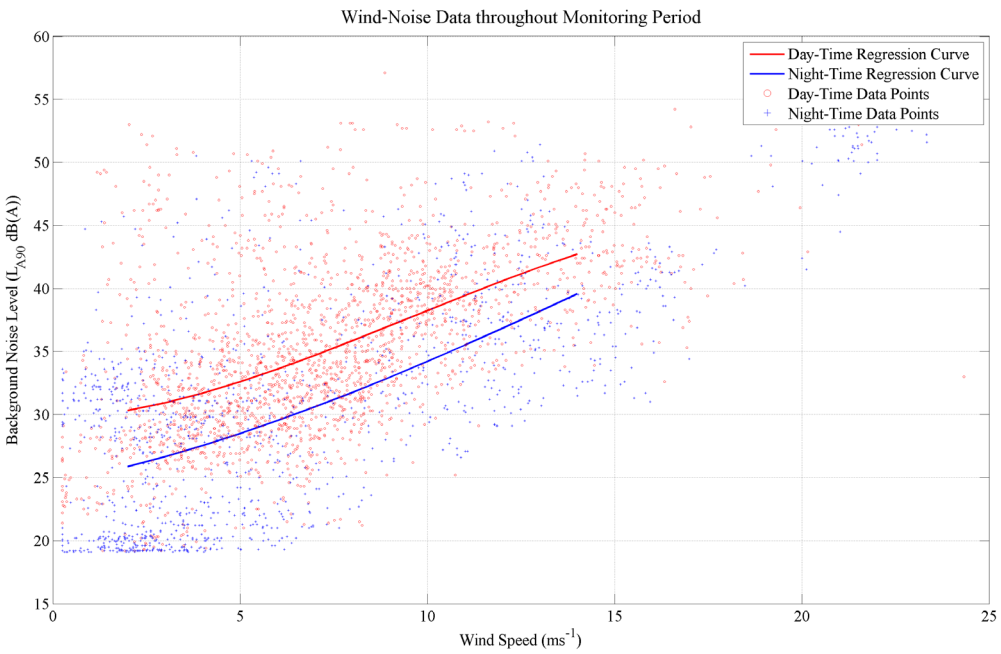

Figure 5. Day- and Night-Time Separated Data Plots.

Operation and Compliance

Measurements of noise levels are required post-installation of the wind farm. It must be ensured that this is undertaken for full operation of all wind turbines at nominal power settings.

Compliance measurements are required at a representative subset of relevant receivers and should generally include those receivers at which initial background noise measurements were taken. If valid noise complaints have been received from residents since operation then these additional receiver locations may also require monitoring.

In many cases the measured noise levels at receivers (with the wind farm operational) are dominated by background noise – it is often not possible to get a "clean" measurement of the wind farm impact. This may necessitate also measuring at a "near field" location close to (< 300m) the nearest turbine, or turning the turbines on and off to determine the influence of the ambient noise environment.

Background levels may vary due to seasonal changes, climatic conditions and environmental changes (including vegetation near dwelling). If this is the case, then it may need to be checked, which will require a significant down-time for the operational wind farm. Additionally, shut down measurements could be undertaken at each residence where the wind is blowing directly from the wind farm to the residence. Noise levels are to be measured before the shut down period (for at least 1 hour), a select number of turbines to be turned off which are impacting on the residence, and noise levels measured whilst these turbines are not operational for approximately 1 hour. After this shut down period, noise measurements should be taken for approximately 1 hour to determine the re-established noise levels at the receivers due to the operational wind farm. This would hopefully show the worst case noise influence of the wind farm at this receiver by taking the difference in noise

levels between the shut down measurements and the measurements taken before and after the shut down period. In this case, hopefully the meteorological conditions will be similar to make a proper comparison.

The compliance measurements should collect sufficient data associated with the worst case wind direction (eg. ± 45º either side of direct line between nearest turbine and receiver). It is important to ensure or check that the compliance measurements are reasonably repeatable regardless of the time of the year.

As with the initial background measurements, it may be necessary to separately plot the day and night data (if background levels are dependent on time of day). It may also be necessary to separately plot data for some wind directions (if significant seasonal variations are known to occur).

A subjective assessment of noise from the wind farm must be undertaken during the compliance monitoring period to determine whether wind farm noise is discernible or clearly audible and whether there are special characteristics present. In addition, objective evidence may need to be collected including measuring the frequency spectrum (ideally narrow band but at least third-octaves) with a SLM at the "near field" location. Any extraneous noise or influence from other sources such as road/rail traffic (or other wind farms!) should also be noted.

Longer monitoring periods of 4 to 6 weeks or more could be required to account for variations and invalid data. For a statistically robust data-set, this could require double the amount of measurement data for separate day/night analysis (ie. 4000 data points) and 4 times the amount of data (ie. 8000 points) for a quadrant wind direction analysis to secure appropriate conditions. If any special audible characteristics are detected (subjectively or objectively) then a 5dB penalty needs to be added to the measured levels.

The measurements at the "near field" location (and other sites if clean wind farm impact measurements are obtained) can be used to compare with the predicted noise levels.

From compliance measurements at a number of wind farms, we have found that the shape of post construction noise levels at receivers sometimes does not match the sound power output of the installed WTG at higher wind speeds. We found that at some higher wind speeds, where the sound power output of the turbines usually plateaus, the background noise increases (higher than that originally measured). We note that the time difference between background noise measurement, and compliance noise measurement is in the order of years (in some cases 5 to 6 years), and environmental conditions at the receiver may vary significantly during this period (trees grown, removed), which will influence the post construction noise measurements.

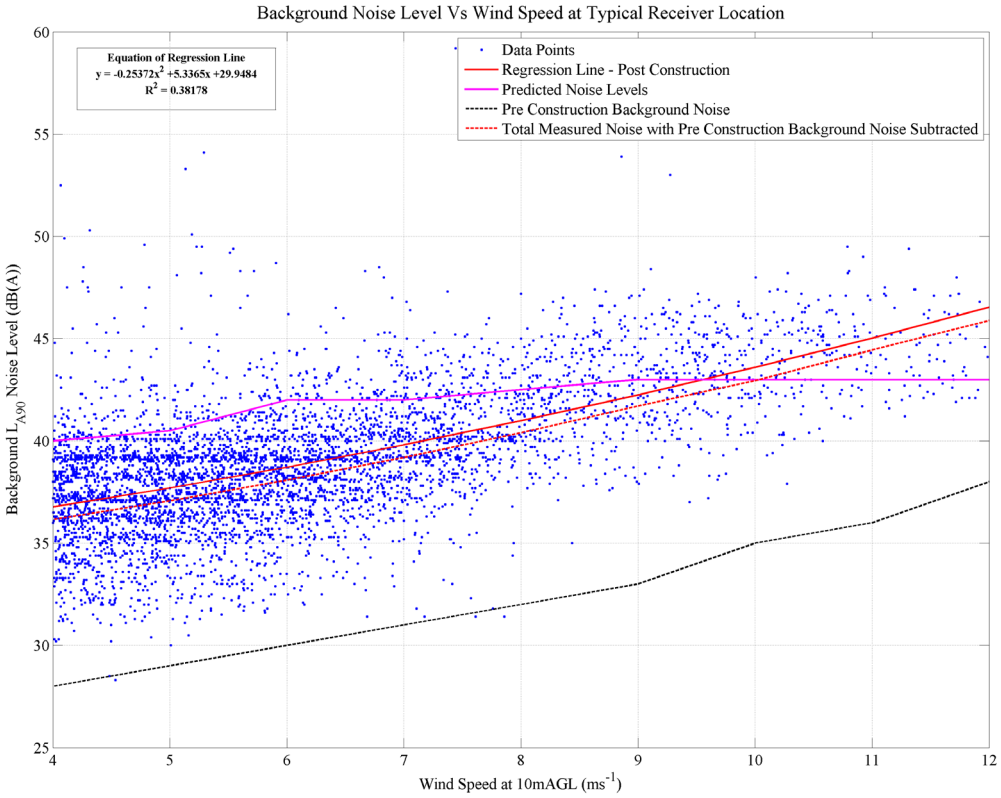

Figure 6: Typical Post Construction Compliance Plot

As can be seen in Figure 6 above, the predicted noise levels (pink line) are much higher than the noise versus wind speed data point regression line. Also of note is that the noise levels at this site are significantly higher than the pre construction background noise levels (black line). Therefore it is most likely that the newly installed wind farm is the major influence for this jump in noise levels. The predicted noise levels (using Concawe worst case conditions) are over-predicting for the majority of the wind speeds until about $10ms^{-1}$. It is interesting to note that the post construction noise levels do not match the shape of the predicted noise levels (based on WTG SWL data), and where the sound power levels (and therefore predicted noise levels) plateau (from $9ms^{-1}$ onwards), the background noise does not.

The shape of the post construction noise data at higher wind speeds seems to follow the shape of the pre construction noise data. Possibly this is due to the addition of the wind farm noise to the already existing ambient background noise at these higher wind speeds. However, most compliance measurements at newly constructed wind farms in Australia have showed that noise criteria were met over the operating range of wind speeds.

If the measured noise levels do not achieve the criteria, then the data may need further careful analysis. A longer and more comprehensive measurement programme may need to be performed. If the wind farm still does not meet the criteria, then turbine operational changes will need to be applied eg. for major contributing turbines, use lower power rating (de-rating) or noise minimisation mode or wind sector management (turn off at certain wind speeds and directions).

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