# WIND TURBINE GENERATOR NOISE PREDICTION - COMPARISON OF COMPUTER MODELS

Tickell, C.E. (1), Ellis, J. T. (2), Bastasch, M. (3)

(1) Connell Hatch, Sydney, Australia
(2) EMA Ltd, Newcastle, Australia
(3) CH2M HILL, Portland Oregon, USA

## Abstract

The development of wind turbine generators as alternative sources of energy supply is a growing fact both in Australia and worldwide. One of the many aspects of the environmental impact assessment process for new wind farms is the prediction of their noise impacts (immissions). As well as the assessment of objective sound levels for environmental noise, the other main activity in assessing their noise impact is the prediction of receiver sound levels caused by emissions of noise from the wind turbine generators (WTG's). There are a number of computer noise models available for the prediction of environmental noise, as well as some specifically designed for noise emissions from WTG's. This paper presents the results of modeling for a typical wind turbine generator using three different prediction models. There is a significant difference between the predicted results using a noise model designed for static industrial sources, compared to algorithms or models designed specifically for WTG's. The main difference appears to be the method in which elevated sources are computed. A significant contributor to WTG noise is aerodynamic noise from each blade tip. These blades can vary in height by as much as 80m per revolution and have an axis 60 to 80m above ground. Wind farm noise emissions also increase with wind speed (typically from 4 to 12m/s), as does associated background noise. This makes the monitoring of background sound levels over the range of operating wind conditions also important. Selection of accurate prediction models for WTG's will enable a better assessment of the noise impacts from wind farms to be made.

## Introduction

As communities seek alternative forms of electricity supply to those traditionally from coal, oil and gas, there has been an increase in the interest and establishment of wind farms around the world, including more recently in Australia. In this year of 2004, there are regular reports in the press of proposals for wind farms comprising from 20 to over 100 wind turbine generators (WTG's) in locations with good wind resources. These are often coastal or rural locations because of both the locations of the wind resources and for minimal environmental impact.

New proposals for industrial or community developments require an assessment of the environmental impact to be made to assist the public and decision-makers determine the suitability for the location of the development. This applies to wind farms and the impacts assessed range from visual and radio-transmission effects to bird strikes and noise. This paper considers how the noise impacts from wind farms are assessed; in particular the methods used for prediction of WTG sound levels at residential receiver locations. Different computer models are considered and the differences between them compared. Where there is a significant difference between prediction methods, the effects can be either a higher sound level and hence a higher noise impact than predicted, or less utilization of the resource where the sound levels are over-predicted. Further work is proposed to develop an "authorized" or "standard model" approach to ensure all developments within Australia are as accurate as possible.

## Noise Assessment of Wind Farms

The noise assessment of wind farms follows a similar approach to those of other industrial developments. In very simple terms, the steps for general proposals are:

1. noise objectives are determined;
2. predictions made of the sound levels of the proposed development;
3. the two are then compared and any exceedance of the objectives is used to assess the potential impact.
4. mitigation may then be considered if needed to reduce the exceedance or potential impact.

The objectives may be either based on the existing background sound levels (prior to the development), such as background plus 5 dB, or a statutory/guideline sound level based on agreed acceptable sound levels for different times of the day and type of receiver area (rural, suburban, city, etc). Predictions can be made using simple algorithms or detailed and complex computer models, depending on the type of development.

The approach for wind farms is slightly different through its determination of the existing background sound levels. In February 2003, the South Australian Government released "Environmental Noise Guidelines - Wind Farms"[1]. This provided the outlines of information required by the Environment Protection Authority (EPA) and the methods to be used to provide the noise impact assessment for wind farms. This approach was also taken up by the New South Wales EPA. The NZ Standard is used in Victoria, [2].

In March 2004, Standards Australia released a Draft for Public Comment for measurement prediction and assessment of wind turbine generator noise[3]. This appears to have been based loosely around the SA document, with some influence from the New Zealand standard and references to international standards.

The Guideline notes that as wind speed increases, so too does the background sound level. Wind turbines do not operate below a cut-in speed, usually around 4m/s wind speed referenced to 10m above ground level. (Most WTG information and calculations are based on the wind speed at 10m above ground level.) While for normal industrial developments, background sound levels are measured with low or calm wind conditions, it is considered inappropriate to compare the noise from a WTG with the background sound level in wind conditions in which they do not operate. So the approach is to measure sound levels over a period of several weeks and prepare a regression analysis of the LA90 statistical sound levels with the wind speed occurring at 10m above ground at the turbine location. An actual regression analysis is given below.

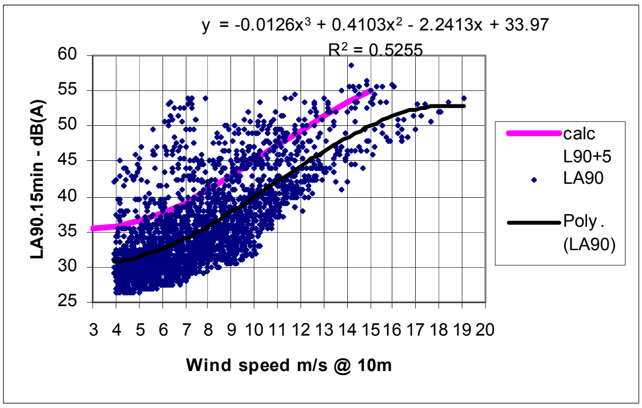


Figure 1: Regression Analysis of Receiver $L_{A90.15min}$ vs Wind Speed at 10m elevation at WTG site

The guideline then recommends that the objective sound level should be 5 dB(A) above the regression curve, or 35 dB(A) if the regression curve + 5 dB falls below 35 dB(A). Then comes the task of predicting the sound levels from the wind farm and comparing them with the objective. That is the main topic of the paper.

## Wind Turbine Generators

A modern wind turbine generator is typically a three bladed rotor which drives a generator through a gearbox. The rotor blades can be 30 to 40m long and sit on a hub which is located between 60 and 100m above ground level. The height depends on the wind resource. The tower may be of tubular steel (which appears to becoming the most common) or open structural steel, similar to a high-voltage power line transmission tower.

Figure 2 below shows a photograph of a WTG at Blayney in NSW and Figure 3 shows a schematic of the internals of the generator-hub section.

Figure 2: WTG's at Blayney, NSW (500kW)

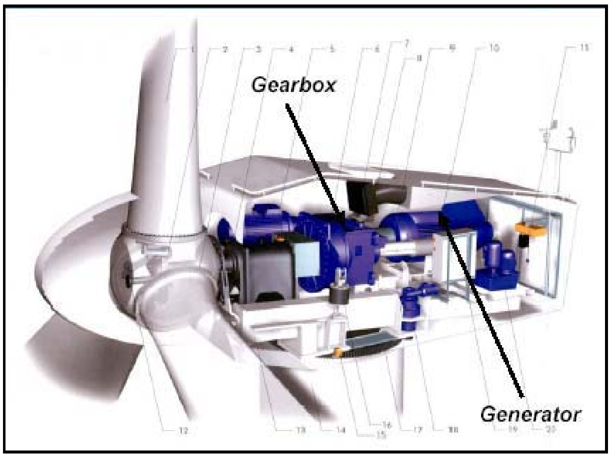


Figure 3: Cut-away schematic view of a WTG hub [4]

Modern WTG's have upstream rotor locations, whereas earlier models had downstream rotors. The downstream models suffered effects from wind shedding around the tower with reduced stability and increased noise. The noise emission characteristics of WTG's are determined principally by rotor noise, although hub noise should not be discounted for locations in close proximity to the tower. The aerodynamic noise of the rotor and vortex shedding at the tip appears to be the main determinant of the sound power levels and spectra emitted.

Measurement of noise emission from WTG's is guided by the international standard IEC 61400-11 [5].

This provides methods and conditions under which the sound power levels and spectra of WTG's are to be determined. It includes measurement at ground level at various distances from the tower, both upwind and downwind, over a range of wind speeds, and uses a ground reflection board for the mounting of the microphone to increase the signal to noise ratio. All suppliers of WTG's provide sound power level and spectral data measured according to this standard.

As may be expected, the total power and sound power level of WTG's increase with increasing wind speed, up to a point after which they plateau. In comparing units, the power level is stated at a wind speed of 8m/s referenced to 10m height. Current commercial WTG electrical power outputs range from 100kW to over 2 MW. Sound power levels (at 8m/s) range from 95 to 105 dB(A). A typical WTG may be named Company XY-2.0 MW 104.5, to nominate it as a 2.0 MW unit with a sound power level of 104.5 dB(A) at 8m/s.

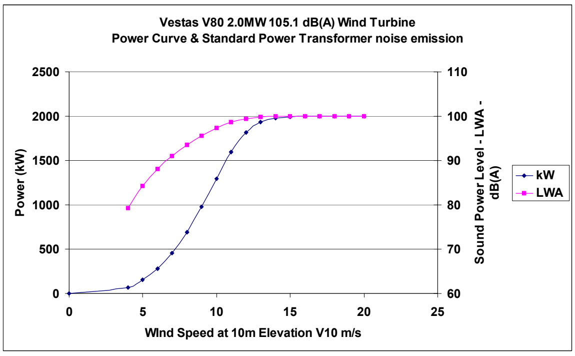


Figure 4: Electrical Power Curve of a 2.0MW WTG [6]

The range of wind speed operation of a WTG is from around 4m/s to over 20m/s, as shown in Figure 4. Most have safety control systems which shut-down the turbine at wind speeds greater than 25 m/s. Most achieve rated power at 15m/s wind speed, and the objective for suppliers is to bring that rated power to even lower speeds, to improve the power yield at lower wind speeds. The sound power level curves for variations on the same model follow a similar shape

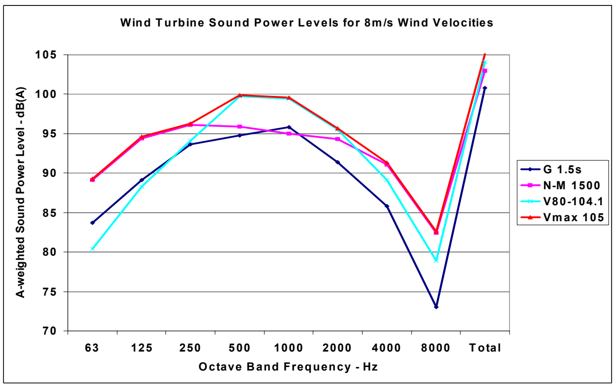


Figure 5: Comparative Sound Power Level spectra of four different WTG's [6, 7, 8]

The shape of the spectrum, as determined according to the IEC method, is based on measurements over a range of wind speeds. Suppliers will provide spectral data for wind speeds typically from 6 to 11 m/s. Figure 5 shows the A-weighted octave band spectra for a range of WTG's between 1.5 and 2.0 MW rated power, all at 8m/s wind speed.

It is the sound power level spectral data, such as that given above, which is used in the prediction of sound pressure levels at the residential locations

## Sound Level Prediction Models

There are many computer noise models available for prediction of sound levels from various types of sources. They range in complexity, ease of use, accuracy and cost. They have developed from individually programmed systems based on theoretical algorithms when computers were first introduced into engineering around 25 years ago, to the commercially available proprietary systems that are available today. Some are preferred by regulators for some types of sources, having been developed specially for them by government funded technical committees, such as the Nordic Railway noise prediction models, others are preferred because of their simplicity and ease of use. However, this is not a paper about comparing the benefits of a range of different models for general use. Cost is usually the constraint on comparing different models – with costs of over $10,000 for some, a commercial acoustical consulting business usually will only have licences for the use of one or two models. So collaboration is required in comparisons. For the subject of this paper, two commercial models were used for comparison of single turbines. They were ENM and the ISO 9613-2 variant of CadnaA.

ENM (for Environmental Noise Model) is an Australian developed program first released in 1986. It is used by and acceptable to the regulators in Australia [9]. CadnaA (for Computer Aided Noise Abatement) is a more recent software model developed in Europe [10]. Both are for use with fixed industrial plant and also allow the use of different algorithms for road or rail traffic noise, aircraft noise and environmental noise mapping.

Both of these models were designed more for fixed plant of relatively small size. They allow treatment of sources as points, areas or surfaces. However that type of source is different to a WTG, where there are three rotating small linear sources at a significant and time-varying elevation.

The draft Australian Standard DR 04173 [3] provides a simple algorithm for conservative calculation of sound levels, which has also been used. This is:

$$L_R = L_w - 10 \text{ Log } (2\pi R^2) - \Delta L_a \quad (1)$$

Where:

$L_R$ is the sound pressure level at distance R

$L_w$ is the sound power level (PWL) in dB(A)

$\Delta L_a$ is the attenuation caused by atmospheric absorption over the distance R

The atmospheric absorption used in the calculations with Equation 1 for this paper were based on ISO 9613-1:1993 [16]. An interactive version of this equation is provided on the NPL's web page Wind Turbine Noise Model, with either spherical or hemispherical spreading [11]. Their model uses an overall A-weighted PWL for the calculation and suggests an atmospheric attenuation rate of 0.005 dB/m. This may explain the difference with octave or 1/3 octave band models, particularly at greater distances. The NPL web page calculation method has also been used in the calculations for this paper. ENM uses the Concawe algorithm for calculating air absorption, while CadnaA uses ISO 9613-1:1993.

In considering a recent project to assess noise from a proposed wind farm, the potential shortcomings of traditional industrial based propagation models was of concern to the authors. A web-based literature search of international approaches to wind turbine noise identified many activities in Europe.

The problem of prediction of noise from WTG's has been around for some time, especially in Europe, where population densities and the search for alternative energy supplies has meant a large expansion in wind farms over the past 10 years. In order to provide improved reliability of noise prediction of wind turbines, in 1995 the European Commission funded a joint project to investigate turbine measurement methods, the knowledge of noise propagation under different meteorological conditions, measurement of immission at dwellings and the assessment of possible tonal noise from machinery components. [12]

The study was a collaboration between nine European partners in six countries, which commenced in January 1997. The noise propagation model aspects of the study were undertaken by Delta Acoustics & Vibration, of Denmark. One of the outcomes of this project was the development and validation of a noise propagation model for wind turbines, known as *WiTuProp*. After the model was developed, the project included noise propagation measurements in different weather conditions around wind turbines situated in different types of terrain, to validate the model. A number of technical papers have been published about the project and the propagation model, most of these being in 1998. Delta have since developed their commercial noise propagation software packages Nord2000 and exSound2000, using similar principles.

*WiTuProp* is a heuristic model, based on classical geometrical ray theory for a non-refractive atmosphere, modified for a refractive atmosphere. [13-15] (Heuristic models are a method of solving mathematical problems for which no algorithm exists, by narrowing down the field of search for a solution by inductive reasoning from past experience of similar problems). *WiTuProp* was used as the other model for comparison in this paper.

Transformer noise also increases with increasing power (from the increasing wind speed), and is a factor which needs to be considered. Industrial noise models can be used for these types of ground level sources.

# Comparison Scenarios & Results

The approach taken for comparisons in this paper was to calculate the receiver sound levels from one WTG of 105 dB PWL at distances from 500m to 5000m. The height of the hub was set at 70m above ground and the rotor length was 30m. This is typical of a range of larger WTG's of 1 to 2 MW rated power. The wind speed was set at 8m/s at 10m above ground level, with atmospheric conditions set around minimal atmospheric attenuation. These were an air temperature 5°C and relative humidity of 95%. Lapse rate used was for a standard atmosphere, of –0.66 °C per 100m elevation. Whilst it is common to consider atmospheric inversions with positive lapse rates for industrial developments, these tend to only occur with calm or low wind speeds. For a WTG to operate at 8m/s wind speed, there is little chance of there being an inversion. However each model allows consideration of the effects of different lapse rates.

Different scenarios were considered for each model. For example, for ENM different wind directions and distances were used. For CadnaA, three different ground absorptions were considered. For WiTuProp, different distances and lapse rates were considered. For the NPL method, both spherical and hemispherical equations were used. The comparison for downwind propagation is shown in Table 1 and Figure 6 below. The NPL algorithm uses air absorption of 0.005 dB/m, Equation 1 uses ISO-9613-1:1993 for the given condition calculated at each octave band center frequency.

Table 1: Comparison of Predictions for same conditions

| Model | Sound Level dB(A) at Distance metres | | | | |
|---|---|---|---|---|---|
| | 500 | 1000 | 1500 | 2000 | 5000 |
| ENM | 52 | 46 | 42 | 39 | 26 |
| WiTuProp | 32 | 22 | 16 | 11 | -3 |
| CadnaA G= 0 | 42 | 35 | 31 | 27 | 18 |
| CadnaA G=0.5 | 38 | 31 | 27 | 23 | 13 |
| CadnaA G=1.0 | 35 | 28 | 23 | 20 | 9 |
| NPL Sph no air | 40 | 34 | 31 | 28 | 20 |
| NPL Sph air | 38 | 29 | 23 | 18 | -4 |
| NPL Hem no air | 43 | 37 | 34 | 31 | 23 |
| NPL Hem air | 41 | 32 | 26 | 21 | -2 |
| DR04173 | 42 | 35 | 30 | 27 | 16 |

*In CadnaA,, G is ground abs. coefficient: 0 = hard, 1.0 = absorptive*

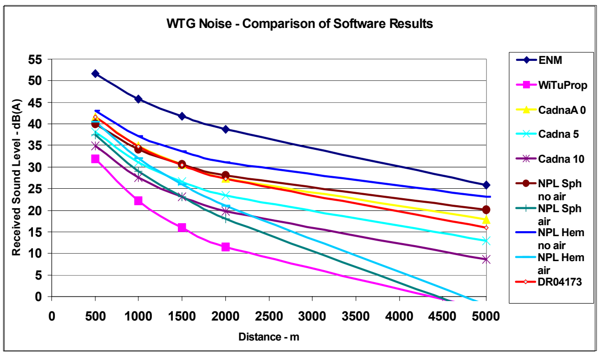


Figure 6: Compared results of various models in Table 1

The difference is largest between the ENM results and those from WiTuProp. This difference ranges from

20 dB at 500m to 30 dB at 5000m. The difference between the NPL results for hemispherical spreading with air absorption and those of Equation 1 is much more than would be expected, seeing as the equation is the same. The NPL hemispherical results are 1 to 18 dB lower than for those with Equation 1, showing the effect of a minor simplification

ENM has a significant variation for wind direction. This is shown in Figure 7 for a distance of 1000m. The difference between the lowest and highest value at a wind speed of 8m/s is 21 dB. The only other model on which the effect of wind direction has been calculated is *WiTuProp*, and this shows no variation as that wind direction effects is included within the model calculation. At 1000m, the minimum ENM result is 24 dB(A) for propagation against the wind. With *WiTuProp* the calculated sound level is 22 dB(A).

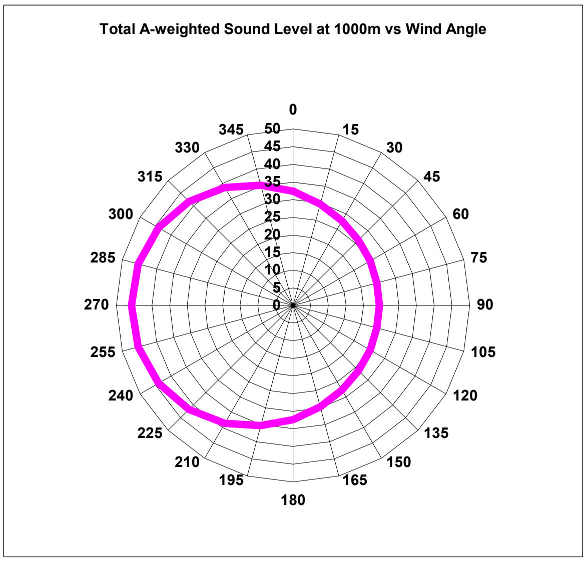


Figure 7: ENM Results at 1000m for wind directions

More detailed distance and frequency comparisons were made with ENM and *WiTuProp* because of their availability. Figure 8 compares the upwind, downwind and crosswind results of ENM with *WiTuProp*.

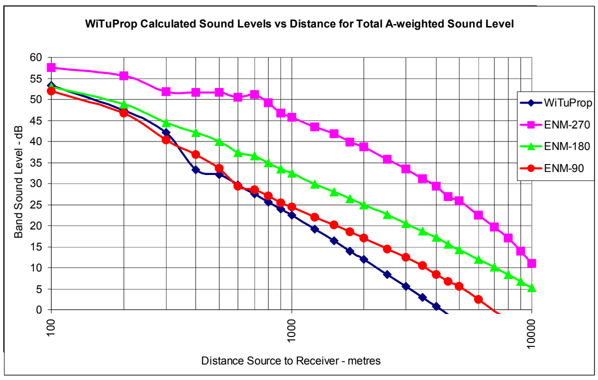


Figure 8: Comparison of ENM sound levels with distance for wind direction and WiTuProp results

The *WiTuProp* results are similar to those of ENM upwind propagation for distances up to approximately 1,500m, which other studies have found to be the minimum distance for the closest proximity of residences to wind farms for acceptable sound levels. Beyond distances of 1,500m, the difference between ENM and *WiTuProp* exceeds 5 dB.

Figures 9 and 10 show the variation between one-third octave band frequency results for ENM downwind and WiTuProp. They are presented to show that, by simple visual inspection of the graphed results, there appears to be a different approach for the calculation of atmospheric absorption between the two methods.

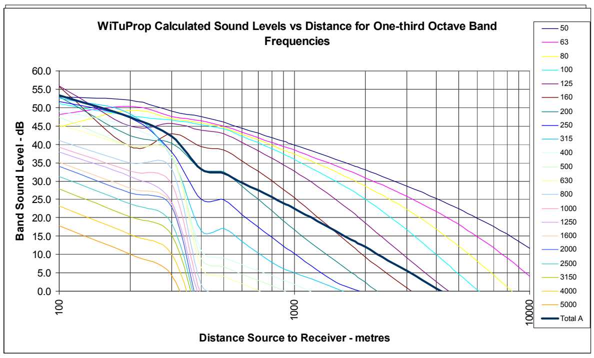


Figure 9: *WiTuProp* Frequency vs Distance

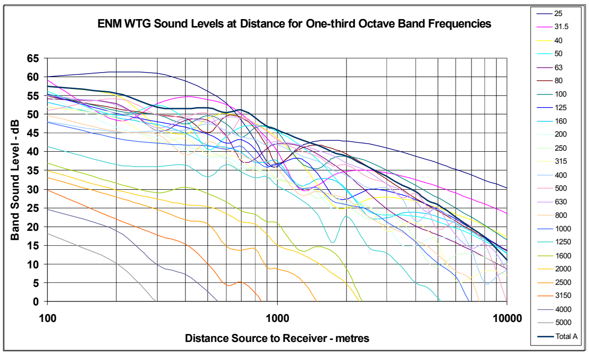


Figure 10: ENM Frequency vs Distance

With the ENM spectra, only frequencies below 80 Hz have un-weighted sound levels which are above the total A-weighted sound level. With the WiTuProp spectra, frequencies up to 160 Hz have unweighted sound levels which are above the total A-weighted sound level. When these are A-weighted, the highest WiTuProp spectra are all less than 160 Hz, whereas the ENM spectra are in the range 400 to 1000 Hz.

The calculations have attempted to compare the results for a similar data-set using different software. ENM and CadnaA have had the source treated as a point at the hub height. It may be possible to calculate the results considering the source as a vertical plane area equal to that of the rotor sweep, but this has not yet been done for CadnaA. When done in ENM, there was only a difference of 0.8 dB for the 100m distance and no difference at higher distances. The NPL method and Equation 1 also treat the source as a point.

## Implications and Conclusions

The calculations have shown the variation between different software and algorithm approaches to WTG sound level calculations with increasing distance. Only four models have been used but there are many others which could have been considered.

The variation between results makes it difficult for both wind farm developers and their consultants, and regulators, to assess the realistic impact of wind farm projects. For one recent project of 38 WTG's undertaken by the authors, noise contours were prepared using both ENM and *WiTuProp*. The difference between the two was significant, as might be expected for a large wind farm development extending over several kilometers of ridgelines. The distance from the WTG's to the 35 dB(A) contour for the ENM calculations was 4km for locations end-on to a ridgeline and 6km for locations side-on to a ridge-line; with *WiTuProp*, the distances to the 35 dB(A) contour were 400m for end-on and 1000m for side-on. If 35 dB(A) had been taken as the objective level to be achieved, the exclusion area would have been extended by 4 to 5km on all sides of the development. Use of ENM would have excluded this proposed farm from the locality and meant that future wind farms would have to be significantly further from residential properties, even isolated rural properties, than would occur with other models.

All parties want to utilise the resource to the greatest extent possible, while protecting the amenity of people living within the area exposed to noise emissions. However the variation in models potentially available for use means that authorities will question the validity of models suitable for use in Australia. The EU obviously faced this problem in the 1990's and commissioned the studies into noise immission from wind turbines. WiTuProp was the model they developed and validated for their conditions. Having studied the references, the authors are satisfied that it has a strong scientific basis for valid use in Australia. However validation studies on existing Australian wind farm developments is warranted.

With the expected increase in proposals for wind farms, irrespective of Commonwealth Government renewable energy targets, there is considered to be a need for validation studies to be funded, preferably jointly by industry and regulators. This work need not take long, but needs to be done to provide the public with confidence that their amenity is being protected.

## References

[1] Environment Protection Authority - South Australia "Environmental Noise Guidelines - Wind Farms", ISBN 1 876562 43 9, February 2003
[2] Sustainable Energy Authority Victoria, "Policy & planning guidelines for development of wind energy facilities in Victoria" May 2003
[3] Standards Australia Committee EV-016 " DR 04173 Draft for Public Comment Australian Standard": Acoustics – Measurement, prediction and assessment of noise and wind turbine generators" 31/03/2003
[4] White, G., Stack, G. Bechly, M., "Wind Farm Projects" Garrard Hassan Pacific Pty Ltd, paper presented at Rega 2002 Forum, Coffs Harbour May, 2002
[5] International Electrotechnical Commission "International Standard IEC 61400-11 Wind turbine generator systems – Part 11: Acoustic noise measurement techniques" Second Edition 12/2002.
[6] Jorgensen, H.K., "Power Curve and Sound – Some Vestas experience" Vestas 2003
[7] NEG-Micon A/S "Sound power level data for NM 1500C/NM 72c wind turbine generator"
[8] Manufacturer G "Sound power level data for 1.5s wind turbine generator"
[9] RTA Technology "ENM Windows" brochure.
[10] DataKustik "CadnaA" brochure.
[11] National Physical Laboratory (UK) "Wind Turbine noise model" February 2004.
[12] National Engineering Laboratory for the Energy Technology Support Unit "Noise immission from wind turbines" ETSU W/13/0053/REP, Department of Trade and Industry, 10/2/1999
[13] Kragh, J., et al, National Engineering Laboratory, "Noise immission from wind turbines", ETSU W/13/00503/REP, 10 February, 1999
[14] Kragh, J. & Plovsing, B. (Delta Acoustics & Vibration) "Wind Turbine Noise Propagation Model EU Commission DGXII" Report AV 1119/98, Delta Acoustics, 6 March 1998.
[15] L'Esperance, A. et al, "Heuristic model for outdoor sound propagation based on an extension of the geometrical ray theory in the case of linear sound speed profile" Applied Acoustics, 37, No.2, p. 111 – 139, 1992.
[16] ISO 9613-1:1993 Acoustics–Attenuation of sound during propagation outdoors – Part 1: Calculation of the absorption of sound by the atmosphere" ISO TC43/SC1

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