Contribution of wind farm into noise at a distant receiver in a rural environment

Valeri V. Lenchine and Byron Holmes

Science & Assessment Division, SA EPA, GPO Box 2607 Adelaide SA 5001 Australia

ABSTRACT

Noise exposure from wind farms is one of major factors forming negative public opinion regarding this source of renewable energy. Due to strict compliance requirements, the noise contribution from wind farms at relevant receiver locations may be comparable to or less than the background noise. Measurement and calculation of wind farm noise becomes a challenging task at a distant receiver. In cases where it is proposed to upgrade an existing wind farm to accommodate a greater number of turbines, it is important that the contribution of the existing wind farm can be extracted from the overall noise measurements. Many regulatory procedures are based on reporting of total noise measured over 10 minute intervals. Possible short term fluctuations in noise from wind turbines during this interval due to variations in turbine operating regimes and atmospheric conditions is a potential cause of concern for residents. This paper details an assessment of the noise contribution from a wind farm with a focus on a shorter time interval. The results of the monitoring indicate that, when measured over shorter periods, normally variation in the noise contribution of the wind farm when compared with 10 minute values is either insignificant or moderate. If the data is well refined from extraneous noises, the scattering of data points is less than is normally reported as a result of an unattended monitoring. Comparison of the directional noise contribution with data gathered by traditional methods shows that noise contribution from the wind farm may not be adequately calculated if the data post- process is made in accordance with conventional procedures.

INTRODUCTION

Noise exposure from wind farms is one of the major factors forming negative public opinion regarding this source of renewable energy. The measurement and calculation of wind farm noise can become a challenging task at distant receivers. Generally, the natural background noise is relatively low in areas where wind farms are commonly installed. Nonetheless, due to strict compliance requirements, the noise contribution from wind farms at relevant receiver locations may be comparable to or less than the background noise. In cases where it is proposed to upgrade an existing wind farm to accommodate a greater number of turbines, it is important that the contribution of the existing wind farm can be extracted from the overall noise environment. This information is useful for prediction of the possible environmental impact of the additional turbines, and for updating the background noise levels for potential use in establishing new criteria based on the background noise level +5dB(A) methodology. Such measurements may also be employed in the correction for background procedure for future post-construction measurements (Australian Standard, 2010, New Zealand Standard, 2010, SA EPA 2009).

Many regulatory procedures are based on reporting total noise measured over 10 minute intervals. Possible short term fluctuations in noise from wind turbines during this interval due to variations in turbine operating regimes and atmospheric conditions is a potential cause of concern for the residents.

This paper details an assessment of the noise contribution from a wind farm focussed on a shorter time interval. The results of the monitoring indicate that, when measured over shorter periods, normally variation in the noise contribution of the wind farm when compared with 10 minute values is either insignificant or moderate. If the data is well refined from extraneous noises, the scattering of data points is less than is normally reported as a result of unattended monitoring. Analysis of possible estimates of wind farm noise for consequent short term intervals brings an estimate of possible level variations. It is shown that variations in the natural background noise are higher than in the wind farm noise and there is no value in analysing data gathered over shorter intervals. Comparison of the directional noise contribution with data gathered by traditional methods indicates that noise contribution from the wind farm may not be adequately calculated if data post- processing is undertaken in accordance with conventional methods.

ESTIMATE OF POSSIBLE VARIATIONS IN NOISE CONTRIBUTION FROM WIND FARMS

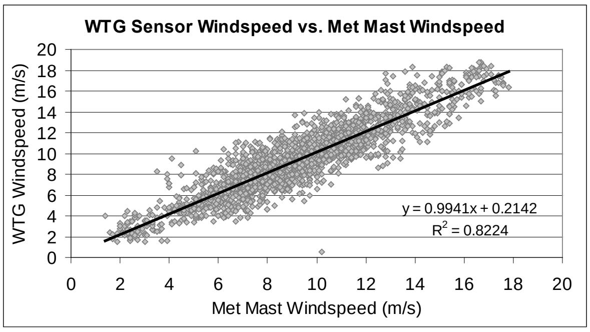
This section focusses on claimed variations in wind farm noise contribution in reference to analysis using shorter than conventional time intervals (1-min). The majority of widely used noise prediction routines (International Organization for Standardization, 1996, CONCAWE, 1981) is based on a relatively simple procedure where the contribution from each individual noise source is calculated from the following relation:

$$L_p = L_W + D - \sum_{i=1}^{n} K_i \,, \tag{1}$$

where L_W is the sound power of the source, D is the directivity index and the sum of K_i terms represents losses due to geometric spreading, atmospheric attenuation *etc*. Assuming that changes in ground and barrier effects, temperature, humidity and atmospheric pressure are insignificant over a few consecutive 1-min intervals, exploration of potential sound pressure level (SPL) variations due to other factors which have a greater influence on the short term trend in wind farm noise is possible. Changes in the sound power of the source, wind speed and wind direction are factors which are likely to influence the measured noise level at a distant receiver.

Change in source sound power output

In general, only a particular group of wind turbine generators (WTGs) provide the major contribution to wind farm noise at a distant receiver. Generally, analysis of meteorological data from wind turbines and meteorological towers shows a good correlation between wind speed and direction as measured at neighbourhood turbines and an on-site meteorological mast (for a typical example see Figure 1). Normally, the indication of a wind sensor installed at a meteorological mast or relevant WTG is a good integral descriptor of the average wind speed for the local part of the wider wind farm site. This assumption, supported by the example shown in Figure 1, suggests that changes in wind speed and direction for neighbourhood WTGs with opposing trends within the group of the WTGs is practically improbable.



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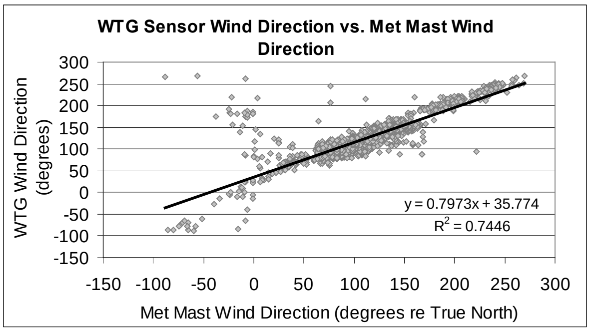

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Figure 1 Wind speed (a) and wind direction (b) measured at the wind turbine and meteorological mast (10 minute averages)

This means that, in general, a localised group of WTGs all follow the same operational pattern, and wind speed data for turbines in the group is similar. If one considers the influence of the noise source on the variation in the measured directional contribution assuming other factors constant, changes in the noise contribution from the turbines follow the sound power characteristic as follows from expression (1). In the conservative case, when the group of turbines operates at approximately the same wind speed, the change in SPL due to variations in the sound power is also consistent with the sound power characteristics of the turbine (Lenchine, 2008). The maximum possible change in SPL due to variations in the sound power for a 1 minute interval can be determined from the sound power characteristic of the WTG:

$$\Delta L_{\max} = \sup_{\Delta v_{\max} \in V} \Delta L_W , \qquad (2)$$

where Δv_{max} is the maximum possible variation in average wind speed that can be accommodated by the turbine during 1 minute, V is the span of operating wind speeds from cut-in wind speed to the speed of rated power, and ΔL_W is the change in sound power.

An industrial wind turbine is an inertial machine which normally does not react to abrupt variations of the wind. For example, WTG, the sound power characteristic of which is presented in Figure 2 (measured in accordance with IEC 61400-11), during 1 minute can adjust the operating mode to accommodate no more than a 2m/s change in the average wind speed. Respectively, the maximum possible change in the sound power of the source will be not greater than 2dB(A).

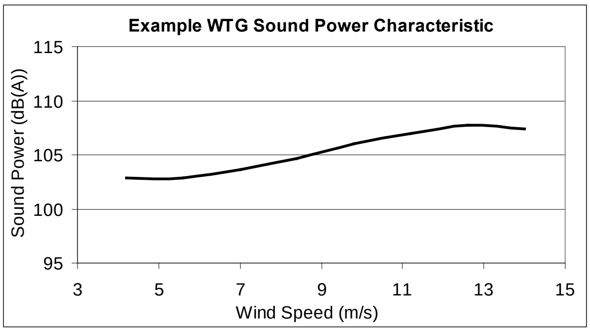


Figure 2 Sound power characteristic of WTG reported versus wind speed at the hub height

Influence of wind speed variation

One widely used sound propagation prediction routine is based on *ISO9613-2:1996*. This method does not account for variations in the wind speed as one of the factors, and is intended for generic downwind conditions. Another sound propagation method, CONCAWE, takes into account variations in the wind speed and wind direction (upwind or downwind) implicitly via assigning a weather category best matching the specific atmospheric conditions. After analysis of the available weather categories, only weather categories 5, 6 (downwind with wind speed above 3m/s at 10m above grougn level (AGL)) and 1 (upwind, above 3m/s at 10m AGL) are considered relevant for the operational noise from wind farms. Inspection of the CONCAWE attenuation curves for models independent of frequency (CONCAWE, 1981, pg. 72) demonstrates that the CONCAWE routine does not discriminate between categories 5 and 6 for broadband noise sources (independent of frequency) and does not allow changing of the attenuation coefficient if, for example, wind speed increases from 4m/s to 5m/s. Therefore, none of the sound prediction methods can be utilised to predict variations in the measured noise contribution due to changes of the wind speed for consequent 1 minute periods. It can therefore be assumed that these variations are minor or can not be easily attributed to wind speed measured at one particular height and place.

It is difficult to segregate variations in the SPL at distant receivers as they are influenced by different factors. One can make an attempt of doing such an analysis in a statistical sense, where the effect of the factor in question is assumed to dominate other factors.

Generally, regulatory procedures and technical standards do not require noise prediction be made, nor post-construction noise be assessed at wind speeds exceeding the speed of rated power (Noise Working Group 1996, Standards Australia 2010, SA EPA, 2009, Standards New Zealand, 2010). It is therefore implied that since the turbine operates at maximum capacity, increasing wind speeds do not lead to an increase in noise emission. Therefore, there are few investigations that detail assessment of WTG noise at high wind speeds. In many cases, it is likely to be difficult to collect a sufficient amount of data to make meaningful analysis at such wind speeds. If there is only a small number of points above the speed of rated power, this can significantly affect the trend of the regression curve and distort the calculated values. Figure 4 shows a graph for operating speeds above rated power. The wind farm noise is detected as a directional contribution from the group of turbines at a receiver approximately 1.3km from the nearest turbine. There were no trees, extraneous noise sources or significant vegetation in the direction of the major contributors (see Figure 3), and 1-min time histories from the directional noise monitor were thoroughly analysed taking into account technical limitations of the instrument (Bullen, 2003).

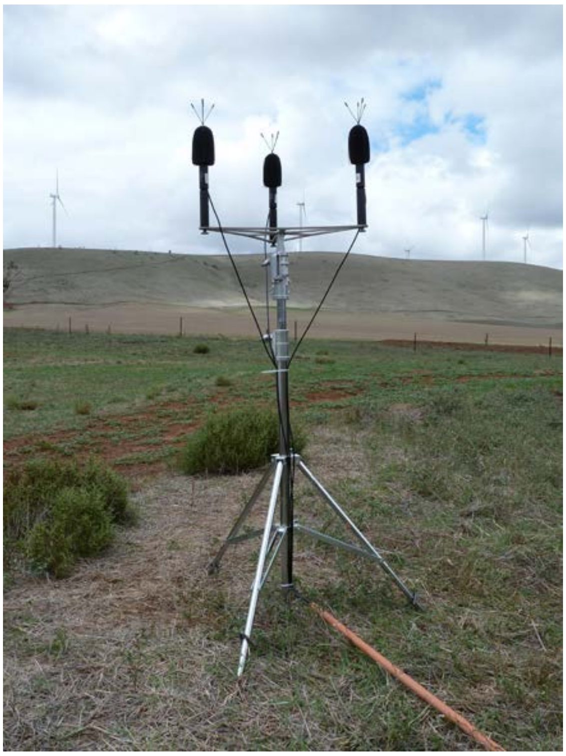
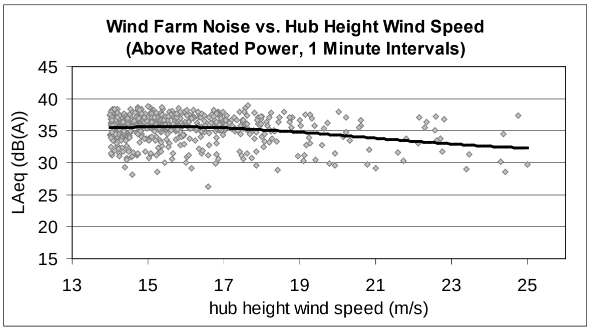


Figure 3 Noise monitoring location at the wind farm

Rectification of the dataset was based on information from the operator of the wind farm, in addition to local measurement (at the noise measurement location) of the wind speed to exclude noise measurements where wind speed exceeded 5m/s. In addition, analysis of trends, audio records, the difference between equivalent directional levels, low pass filtered signal (to indicate presence of insect noise), and analysis of the relationship between different acoustic descriptors to ensure that the directional contribution was detected accurately were engaged to produce the valid dataset representing wind farm noise. The dataset collected during the monitoring period was practically free from rain affected data. Despite this, the strict rectification routine undertaken resulted in a final dataset which contained less than 40% of the total amount of data gathered.

Assuming that variations in the sound power of the WTGs at wind speeds exceeding the rated power wind speed are insignificant gives a better opportunity to judge the influence of wind speed on sound propagation. Figure 4a shows the directional noise contribution for operating speeds above rated power. The regression curve has a slightly decreasing trend which may be due to an insufficient amount of data at very high wind speeds (above 20m/s) and fact that the data is collected for a wide range of atmospheric conditions and wind directions. Figure 4b demonstrates the time history of 1-min wind farm noise which shows that variations in the average wind speed (deviation in the wind speed direction is insignificant) does not result in a significant change in the measured wind farm noise. The wind speed magnitudes varied from 14m/s to in excess of 22m/s, and the corresponding change in measured SPL was of the order of only 1.2dB(A), and these changes are practically not correlated. It is unlikely that the poor correlation is due to the sound propagation delay from the source to the receiver. The distance between the nearest WTG (which normally provided the major contribution) and the receiver is approximately 1.3km, and therefore the time delay remains insignificant in comparison with 1 or 10-min integration periods. Therefore, fluctuations in the measured noise contribution are more likely controlled by factors other than wind speed, and the sensitivity to wind speed variations on the sound propagation from WTGs to the receiver is minor.



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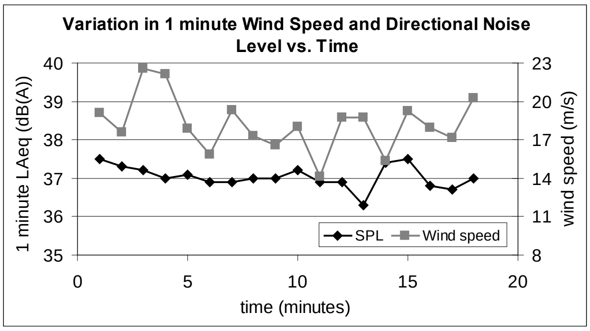


b)

Figure 4 Wind farm noise contribution (1-min) at the distant receiver at wind speeds above the speed of the rated power (a) and typical time history of the noise contribution with insignificant variations in the wind speed direction (b)

Change in wind direction

ISO 1996-2 considers downwind sound propagation conditions where deviation of the wind speed vector from the imaginary line connecting the noise source and receiver is within a 45° angle (either side). Another standard relevant for acoustical assessment of WTGs- IEC 61400-11: "Wind turbine generator systems- Part 11: Acoustic noise measurement techniques" (International Electrotechnical Commission, 2006) describes the sound power measurement procedure where downwind measurement conditions should be met with ±15º accuracy. This standard assumes that any deviation within this angle should not cause significant discrepancy in the measured levels.

Statistical analysis of 1-min directional contribution data (see the previous section) for downwind conditions within 15º sectors (Table 1) shows that the calculated levels (by regression curve) are similar to each other within 2.5dB(A) for data analysed at a wind speed deviation within ±60º. Data in the symmetrical sectors also is in good compliance with each other (within 1.4dB(A)). The difference increases for greater angles which may be attributed to the fact that the noise propagation conditions become more cross-wind than downwind.

This analysis allows for the assumption to be put forward that minor variations in the wind direction for consequent 1 minute noise contributions do not cause a change in measured noise level exceeding 2.5dB(A). If this assumption is considered along with the possible change in wind farm noise due to variations in the wind speed and sound power, we get a conservative estimate that the difference in wind farm noise measured in adjacent 1 minute intervals will not exceed 4.5dB(A) for downwind conditions. This is in good agreement with the data rectification criteria employed to form the dataset of 1-min directional contributions, where every event which involved the consequent increase in wind farm noise contribution above 5dB(A) was thoroughly investigated.

Consequently, the analysis of possible variations in the wind farm noise does not support the opinion that WTG noise can exhibit significant variations in SPL when investigated for shorter time intervals. Changes in the wind farm noise contribution may be connected with amplitude modulation of noise from the WTG which is normally more distinct at closer distances. This effect is less distinct at greater separation distances, where the masking effect of background noise influences perception of the amplitude modulation (Lenchine, 2009). Abrupt changes in the measured overall levels may be caused by extraneous noise sources which are not associated with the operation of a well maintained WTG. As a result, there is no practicability in changing noise measurement intervals since conventional routines (normally 5 or 10-min intervals) are able to adequately reflect noise exposure from wind farms. Normally, wind farm noise at distant receivers is low, and is comparable to the strictest criteria contained in noise policies for application to industrial and other community noise sources. As was demonstrated previously, significant change in the measured wind farm noise under relatively stable atmospheric conditions is not expected for WTGs.

COMPLIANCE CHECKING AND NOISE PREDICTION PROCEDURES

In some practical situations, the difference between predicted and measured wind farm noise can be significant (Lenchine, 2008). A number of factors can contribute to this discrepancy, such as conservatism of model inputs, inadequate representation of turbines as a noise source etc. However, it is difficult to explain significant differences between measured and predicted levels by these factors alone. One of major reasons leading to the high discrepancy between the predicted SPLs and measurements is the data rectification process. The standard methods of compliance checking are based on collection of a large volume of data representing overall SPL at the monitoring location. Rectification of the collected data is a time consuming process which does not always adequately take place. There are also other factors which influence the accuracy of conventional wind farm noise monitoring. Some of these factors are considered in the following sections.

Conventional and alternative procedures for wind farm noise monitoring

Widely used regulatory procedures for wind farm noise monitoring are based on the collection of 10-min overall SPLs at relevant receivers, correlated with wind speed measured at the wind turbine hub height (SA EPA, 2009, Standards Australia 2010, Standards New Zealand 2010). Normally 90th percentile noise levels L_{A90} (A-weighted level which is not exceeded for 90% of the time) are used as a statistical filter to decrease the influence of extraneous noises on the dataset (Harris, 1998).

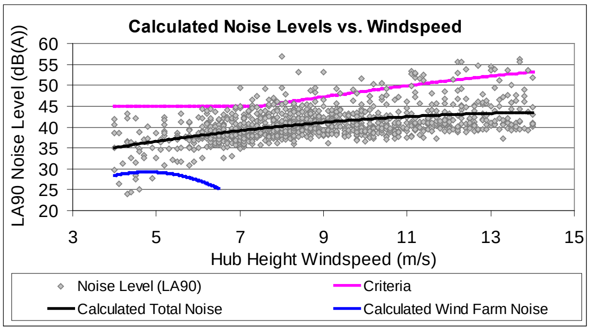
Figure 5a represents the wind farm noise level calculated in accordance with the procedure in *the Windfarms: Environmental Noise Guidelines* (SA EPA, 2009). The dataset is plotted and compared with the noise criteria derived from the pre-construction background noise measurements undertaken at a representative location. It is not possible to derive the wind farm noise in accordance with the correction for background procedure for the full range of the wind speeds since the pre- construction background noise exceeds the total noise for the higher wind speeds. Therefore there is doubt about accuracy of the calculation of the wind farm noise even where it is possible to derive a valid number. Figure 5b represents the wind farm noise defined as the directional contribution with L_{Aeq} descriptor. Data for the 1-min directional contribution demonstrates significantly less scattering than the overall noise descriptor.Taking into account that the standard procedure uses the L_{A90} descriptor, difference in the scattering is even higher when compared with the overall L_{Aeq}.

Background noise and representative location

In many situations, it is not practicable to undertake preconstruction background noise measurements or post- construction monitoring for a new wind farm at all noise sensitive receiver locations in the surrounding area. The concept of representative locations is widely used in such cases, where background noise measured at one particular location is considered generic for group of receivers in the neighbourhood area (Noise Working Group, 1996, SA EPA, 2009). This may be a critical factor affecting calculation of wind farm noise in accordance with conventional methods, as the correction for background procedure can be used if necessary.

The background noise levels during post-construction noise monitoring can be investigated by employing the 'start/stop' method to generate a dataset consisting of enough points to statistically derive the background levels, and hence the contribution from the wind farm. This is a large scale scientific exercise which involves stopping the entire wind farm or a group of turbines to collect the background noise data and resuming operation of turbines to obtain total noise at a particular wind speed. The authors are unaware of any investigations employing the 'start/stop' method which resulted in sufficient data to derive a viable update of background and wind farm noise levels.

Under such circumstances, use of another method, which does not require start/stop of the turbines, is generally a far more financially viable option. Figure 6 shows pre-construction background measurements at a representative location which has similar terrain and vegetation to the measurement location. Two additional curves represent updated background levels. One curve is derived on the basis of the logarithmic energy difference between overall equivalent 10-min levels and the directional contribution representing the wind farm noise. The second curve is derived in a similar way, where the logarithmic difference is taken for L_{A90} descriptors.



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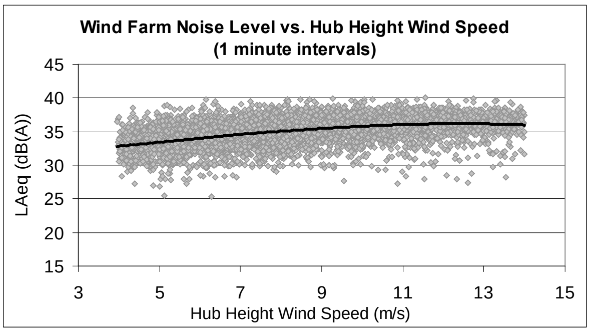

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Figure 5 Wind farm noise calculated by the standard procedure (a) and as 1-min directional contribution (b)

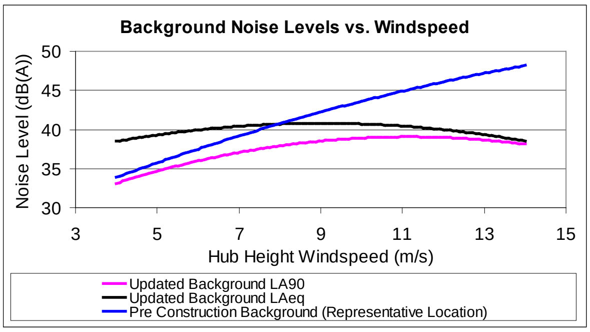

Figure 6 Background at the representative location and updated background levels and the monitoring place.

The 10 minute L_{Aeq} derived background noise appears to demonstrate an opposite trend to the pre-construction monitoring, with the derived background L_{Aeq} noise levels appearing to slightly decrease with increasing wind speed. The difference between the pre-construction and post-construction calculated levels for the same descriptor (L_{A90}) is marginal at low wind speeds, and reaches approximately 10dB(A) at the rated power wind speed. This raises concerns about the validity of the correction for background method if applied for wind farm noise calculations, as well as the concept of a representative location in reference to compliance checking.

Result of the comparison is not unexpected since it is difficult to establish a robust connection between any conventional acoustic descriptor and wind farm noise in environment where noise is not controlled by the source of interest. Superceded New Zealand standard NZS 6808:1998 suggests that typical difference between L_{A95} descriptor and equivalent level is about 1.5~2.5dB. This conclusion was based on analysis of particular data used for drafting the standard and has not been confirmed by later investigations. The statistical descriptors play positive role in diminishing influence of relatively short- term extraneous noises on overall SPL. However it is diffucult to recommend any statistical descriptor which provides greater accuracy in detection of the wind farm contribution using conventional methods. Such recommendations may lack universality and may be usefull for specific situations only. Development of alternative instrumental and methodological solutions may provide better benefints for the wind farm noise monitoring.

Noise prediction methods

As it is noted above, ISO 9613-2 and CONCAWE are recommended methods for calculating the possible noise impact from wind farm developments. The ISO routine was developed for generic downwind (from source to receiver) noise propagation conditions, whereas CONCAWE may be used for downwind, upwind or neutral (no wind) atmospheric conditions.

Comparison of the predicted levels (Figure 7) indicates a very good match between the measured 1-min directional contribution and CONCAWE predictions (demonstrating congruence within around 1dB(A) for most wind speeds). The difference is greater for levels derived using the ISO procedure. It is difficult to compare the predicted levels with the the wind farm noise levels derived in accordance with the conventional procedure because the valid numbers are absent for the majority of the wind speeds (Figure 5a).

The monitoring dataset used for this paper contains significantly fewer data pairs for upwind conditions, compared with downwind. Nonetheless, it is interesting to compare the prediction results with measurements for non-downwind conditions. The difference between the frequency independent meteorological correction for upwind propagation (meteorological category 1) and downwind propagation (categories 5 and 6) for a receiver at a distance of 1.3km from the source is 11.6dB (CONCAWE, 1981). Also directivity characteristic of WTG show negative directivity correction for upwind conditions in comparison with the downwind measurement position. Therefore the expected difference for downwind and upwind wind farm noise levels should be even higher than derived from the meteorological corrections. Comparison of upwind and downwind regression curves (Figure 7 and Figure 8, 1-min data) indicate that maximum statistical difference is on the order of 3dB(A).

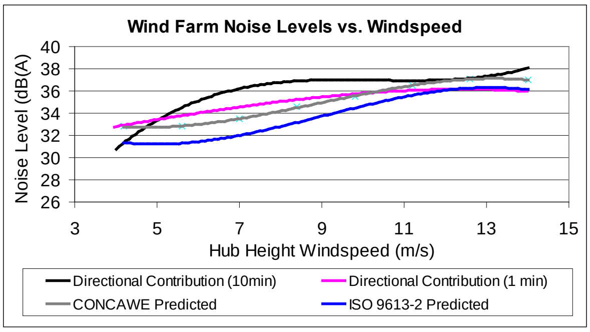

Figure 7 Comparison of predicted noise levels with the measured wind farm noise for downwind conditions

As is noted above, the number of data points for upwind conditions is small; however, such a large difference between expected and measured values brings doubts regarding the accuracy of the CONCAWE for calculation of noise propagation from wind farms for upwind conditions. This may be unimportant for most practical tasks as the vast majority of relevant measurements are concentrated on downwind conditions representative of the worst case scenario.

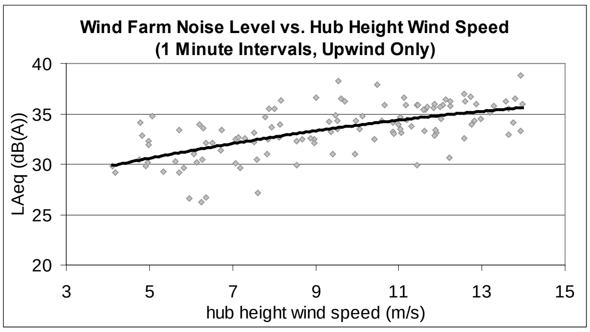

Figure 8 Wind farm noise for upwind meteorological conditions (±45º sector)

Comparison of predicted and measured SPLs relies on the selection of an appropriate reference. In this case, the choice of monitoring location, directional contribution acquisition and thorough data rectification procedure are intended to assure that the gathered SPLs represent "true" wind farm noise. The deviation of calculated wind farm noise levels based on 10-min or 1-min intervals (Figure 7) is within approximately 2.5dB(A). Such a small difference scarcely can be used as justification for another monitoring routine based on 1-min data analysis. The difference could be further reduced by utilising a more thorough data rectification process for 10-min data than is generally undertaken for conventional noise monitoring reports, as such a process can be prohibitively time consuming. Furthermore, the analysis of possible variations in the wind farm noise does not provide evidence that there are significant changes in the wind farm noise contribution that could add value to a shorter integration period.

SUMMARY

Extraction of the contribution from a particular noise source in a quiet rural environment is a technically challenging task when noise at the receiver is not controlled by this particular source. Analysis of overall SPLs does not allow accurate identification of the source contribution, and use of statistical descriptors such as L_{A90} does not notably improve accuracy of the method.

In this paper, a refined data set of 1-min directional contributions is utilised to produce a statistically accurate estimate of the wind farm noise contribution at different wind speeds in an environment where wind farm noise contribution often is comparable or below that of the background noise. The data analysis shows that the conventional wind farm monitoring routine may deliver a significant overestimate of the wind farm noise contribution, and the standard correction for background procedure may not produce a valid estimate of the wind farm noise. The pre-construction background noise measurements may significantly differ from their estimates during subsequent monitoring periods, and the concept of a representative location may be not valid even with apparent similarity of terrain and surrounding environment.

Analysis of possible variations in the consequent short-term estimates of the wind farm noise complies well with the acquired data, and does not support the opinion regarding possible abrupt fluctuations in wind farm noise. Furthermore, the difference in statistical estimates of wind farm noise based on 1-min and 10-min wind farm noise contributions is not significant and may be improved by a more rigorous data rectification procedure. Therefore, the value in assessing wind farm noise with shorter integration periods is minimal.

Many wind farm noise monitoring reports highlight significant discrepancies between predicted noise levels and the results of measurements. It is necessary to resolve the question of "true" contribution from the wind farm to make such comparisons. The conventional noise monitoring procedure based on the collection of overall 90th-percentile SPL sometimes can not give a valid estimate of the wind farm noise, therefore use of alternative methods such as directional noise monitoring is justified in a quiet rural areas where the wind farm is not the dominant noise source. The case study referenced in this paper indicates a very good agreement of the measured wind farm noise and magnitudes predicted by CONCAWE noise prediction routine with slightly higher discrepancy for ISO9613-2 predicted levels. This emphasises the need for alternative approaches to wind farm noise monitoring in cases where the wind farm noise contribution is not significant, and conventional noise logging gives erroneous results.

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Table 1 Wind farm noise for different wind direction (from downwind direction) versus wind speed at the hub height, dB(A)

Angle / **Wind speed, m/s**	**0 - 15°**	**0 - -15°**	**15°- 30°**	**-15 - -30°**	**30 - 45°**	**-30 - -45°**	**45 - 60°**	**-45 - -60°**	**60- 75°**	**-60 - -75°**	**75 - 90°**	**-75 - -90°**
4	33.1	32.0	33.9	33.0	32.8	31.4	31.8	32.2	32.6	29.2	30.8	32.3
5	33.6	33.2	33.9	33.6	32.9	32.9	32.2	33.0	31.9	31.0	30.5	33.8
6	34.2	34.2	34.1	34.1	33.2	33.9	32.7	33.7	31.5	32.5	30.5	34.8
7	34.8	34.8	34.5	34.5	33.7	34.7	33.2	34.3	31.2	33.8	30.7	35.2
8	35.4	35.3	35.0	34.8	34.4	35.2	33.8	34.8	31.1	34.7	31.1	35.1
9	35.9	35.6	35.5	35.1	35.0	35.5	34.3	35.2	31.1	35.3	31.4	34.6
10	36.3	35.7	36.0	35.2	35.6	35.7	34.8	35.5	31.2	35.7	31.7	33.7
11	36.5	35.7	36.4	35.3	36.1	35.9	35.1	35.6	31.4	35.8	31.8	32.5
12	36.6	35.7	36.6	35.4	36.4	36.0	35.3	35.5	31.7	35.7	31.5	31.1
13	36.5	35.7	36.6	35.4	36.4	36.1	35.3	35.2	32.0	35.3	31.0	29.6
14	36.2	35.6	36.4	35.3	36.0	36.4	35.1	34.6	32.2	34.7	29.9	27.9