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Wind turbine noise measurements - How are results influenced by different methods of deriving wind speed?

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ABSTRACT

With the increasing number of operational wind farms/turbines, the requirement for noise measurements required to demonstrate compliance with planning conditions is increasing as well. The British ETSU-R-97 noise limits are often set relative to measured or standardised 10 m height wind speeds and therefore the assessment of noise from wind turbines requires simultaneous noise and wind speed/direction measurements. For financial reasons, smaller and single turbine sites are often not equipped with a meteorological mast. If no independent hub height wind measurements are available, wind speed is either taken from nacelle anemometers or derived from power measurements combined with the power curve for the respective wind turbine type. Noise measurements referenced to nacelle anemometer data will be compared with the same measurements but correlated with derived power curve wind speed, and measured wind data from separate met mast or other remote sensing devices. The influence of incorrect filtering of wind data for shadow effects (mast and/or nearby wind turbines) on the noise assessment may be presented, depending on how much time is available. The advantages and disadvantages of the various methods will be discussed.

Keywords: Wind Farms, Wind Speed Measurement, Noise Limits
I-INCE Classification of Subjects Number(s): 14.5.4

1. INTRODUCTION

In countries where noise limits at residential properties with respect to wind turbine noise are set relative to wind speed, it is essential to obtain the correct wind speed during wind turbine noise measurements in order to verify whether the noise limits set out in planning conditions are being met or exceeded.

In the UK, ETSU-R-97 *The Assessment and Rating of Noise from Wind Farms* is generally used to assess wind farm/turbine noise at the nearest noise sensitive properties at the planning stage. In this document the method for deriving noise limits is to undertake a survey of the background noise at locations representative of each affected property and set the limits relative to the prevailing background noise with a margin of + 5 dB, if predicted wind turbine noise levels are greater than 35 dB $L_{A90,10\ min}$. The prevailing background noise is calculated from a regression curve calculated from the measured noise correlated with wind speed measurements at the wind farm site. Lower fixed limits apply for day- and night-time for very low noise environments. Since the wind turbine noise and the noise limits are wind speed dependent, the knowledge of the correct wind speeds is important for any wind farm noise assessment.

Where reference is made to wind speed, it is also essential to define the height to which the wind speed refers, in order to compare measurements taken before (background noise survey to derive noise limits) and after the wind farm is built (compliance noise survey of the total noise including the operational wind farm to show compliance with the adopted noise limits), and to compare noise measurements with predicted turbine noise if required, for example if the noise measurements show great discrepancies to the expected (predicted) wind farm noise.

Wind speed in wind turbine sound power level documents is mostly given with reference to 10 m height. This is often arbitrarily referred to as 'measured at 10 m height' or similar whereas, in fact, the quantity it refers to is hub height wind speed 'standardised' to 10 m height wind speed using a logarithmic wind profile and a roughness length of 0.05 m. ETSU-R-97 generally refers to 10 m height

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wind speed, however, since the publication of Van den Berg's *The sound of high winds: the effect of atmospheric stability on wind turbine sound and microphone noise* (Van den Berg 2006) it has been generally acknowledged that extrapolating wind speed measured at 10 m height to hub height wind speed underpredicts the actual wind speed as it does not consider site-specific wind shear and atmospheric stability. This has now been taken into account in the recently published UK Institute of Acoustics' *Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise* (GPG 2013) which describes the preferred method for wind speed derivation to be one that references noise limits to 'standardised' 10 m height wind speed derived from wind speed measurements at hub height in line with the way source noise levels are described.

Not all operational wind farm sites have tall meteorological masts installed to monitor wind speed and direction during the wind farm's operational life. Therefore alternatives have to be found when assessing wind farm related noise at residential properties against wind speed dependent noise limits. Various methods of measuring or deriving wind speed are described below. Depending on the location of a tall met mast in relation to the residential property, it may even not be possible to use this data at all due to shadow effects from the operational wind turbines.

2. METHODS OF WIND SPEED AND DIRECTION MEASUREMENTS

2.1 Meteorological Mast

A well sited meteorological mast with an anemometer and wind vane at hub height should give representative measurements of wind speed and direction experienced by wind turbines on the site. However, care needs to be taken of wake effects from the wind turbines, and turbulence and shadow effects caused by other obstacles upwind of the anemometer. The measured data needs to be filtered appropriately.

If the mast is lower than the turbine hub height, the hub height wind speed can be calculated from measurements at two different heights by calculating the wind shear exponent between those two heights and deriving the hub height wind speed using an exponential wind profile.

The hub height wind speed can subsequently be 'standardised' to 10 m height wind speed by using the standard roughness length of 0.05 m. The calculation methods can be found in IEC 61400 *Wind Turbines - Part 11: Acoustic noise measurement techniques Ed.3* (2013) amongst others (IEC61400-11Ed3).

Smaller schemes may not have a permanent met mast on site or, in some cases, planning permission for a tall mast may have expired before the wind farm was built and therefore no tall met mast data is available. Unless noise limits are explicitly referenced to measured 10 m height wind speed, a 10 m met mast should not be used. Standardised and measured same height wind speed are not directly comparable. Occasionally, measured 10 m height wind speed may be converted to standardised 10 m wind speed with average wind shear values from a long period (minimum of 1 year) but this method has its own pitfalls and will not be discussed further in this paper.

2.2 Hub Height Wind Speed from Power Curve or Nacelle Anemometer

Most large wind turbines have cup or ultrasonic anemometer mounted on the nacelles, mainly for the turbine controller to establish cut-in and cut-out wind speed and for pitch regulation of the blades where applicable. This data is usually available in 10 minute averages from the turbine manufacturer or the site operator. This method may be inaccurate unless it can be determined with certainty, whether the anemometer output is corrected for the presence of the passing blades in front of it. Certainly during shut-down periods for background noise measurements a blade stationary in front of an anemometer gives false readings.

More accurate is the method described in (IEC61400-11Ed3) for derivation of wind speed from a measured or calculated power curve during wind turbine operation. This requires obtaining the electrical output of the turbine during operation. However, this method is not suitable for wind speeds outside the 'allowed' range, i.e. at the lower and higher end, when the slope of the power curve gets too shallow. For higher wind speeds than that when the turbine approaches full rated power, this method provides no meaningful wind speed values. For data points above the 'allowed' range, however, the wind speed can be taken from the nacelle anemometer which is to be calibrated in-situ against the power curve derived wind speeds.

This method requires a measured or calculated power curve (in particular smaller wind turbines may not have a power curve available) and operation in the corresponding settings to the supplied power curve. If the turbine is running in a different 'mode' during the survey, for example due to a technical fault, this method may no longer be applicable. If the turbines are operated in noise reduced modes for reasons of mitigating the noise impact, a power curve for such a mode is required.

2.3 LiDAR and SoDAR

LiDAR (Light Detection And Ranging) and SoDAR (Sonic Detection And Ranging) have established themselves as stand-alone wind speed and direction measurement devices. They have the advantage that they can measure wind speed and direction at a wide range of heights unlike anemometry mounted on met masts whose height cannot be changed without taking down the met mast or rearranging beams, so that hub height wind speed can usually be measured directly. They are mobile and can be placed on the wind farm site in a location where influence from the wind turbines and other obstacles can be minimised. The location needs to be chosen carefully in order to avoid reflections from the wind turbines which may invalidate the measurements or lower the quality of the data.

3. Preliminary results

3.1 Comparing two cup anemometers mounted on a met mast at the same height

It may seem obvious but it should be pointed out that data from any anemometer mounted on a beam at any other height than the very top, needs to be filtered to remove wind directions corresponding to it being in the shadow of the mast. The following graph shows two anemometers mounted at the same height with clear shadowing effects. Wind speed measured in the shadow affected wind direction is shown to be too low compared to the wind speed from the unaffected anemometer. If the wind flow on the anemometer is not affected, the ratio of the two anemometers should be 1 for all other wind directions. The effect of the tower on the anemometer in its shadow can clearly be seen in Figure 1. The anemometers were mounted facing north and south.

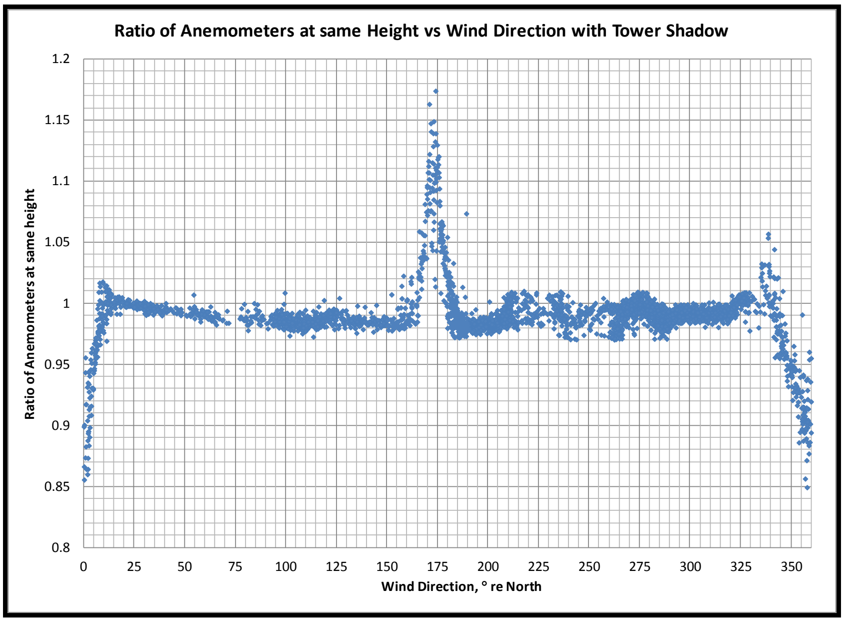

Figure 1: Shadow Effect of Tower on Anemometer

The met mast location plays an important role for the correctness of the wind data. Poor siting (in the wake of wind turbines, near tall obstacles etc.) and wear and tear of the bearing can cause further effects on the measured wind speed.

3.2 Comparing SoDAR wind measurement with cup anemometers on a met mast and anemometers mounted on wind turbine nacelle on wind farm site 1

A SoDAR device from Secondwind, the Triton wind profiler, was set up alongside a met mast on wind farm site no. 1 which has been in operation since before the wind farm was built. Neither of the instruments had been calibrated since the installation, which is why the Triton was used to check the performance of the cup anemometers. The Triton was sited in accordance with the specification of the manufacturer for comparison of Triton with met tower measurements (Walls 2010). The data showed a great spread in sectors where the met mast was downwind from a wind turbine and such data were excluded from the correlation. After this filtering, the data showed a good correlation with slight underreading from the anemometers. However, this was more accurate than the wind speed reading from the nacelle anemometers as will be discussed below.

The Triton wind speed was correlated with the nacelle anemometer of the wind turbine closest to the residential property where the noise study was undertaken. The rationale behind using data from this turbine was that the noise emission of the closest turbine would have the greatest influence on the measured noise level at the property. The Triton position was approximately equidistant from the met mast and the wind turbine. Both may have experienced some wake effects from another turbine further upwind. Firstly the data was only filtered for periods of turbine shut-downs as the nacelle anemometer was not considered accurate for those periods due to blade effects mentioned earlier. This resulted in a regression curve rather than a linear correlation with the difference between Triton and the nacelle anemometer being about 1 m/s for wind speeds below 14 m/s (nacelle anemometer reading lower) which decreased for higher wind speeds until it matched up at 17 m/s. This upper part was outside the normal measurement range so that for the purpose of the wind farm noise assessment, the discrepancy was 1 m/s. Subsequently sectors where the wind turbine or the Triton were in the wake of another wind turbine were also excluded from the correlation which resulted in a linear regression. At lower wind speeds the same 1 m/s difference was found, however at 10 m/s the nacelle anemometer was reading 1.5 m/s lower and at 12 m/s the difference had increased to 2 m/s.

Figure 2 shows measured wind farm noise with standardised 10 m height wind speed derived from the SoDAR measurements. Figure 3 shows the same noise data with standardised wind speed derived from the nacelle anemometer of the closest wind turbine and Figure 4 shows the data with wind speed derived from the average of all wind turbine nacelle wind speeds over the operational range.

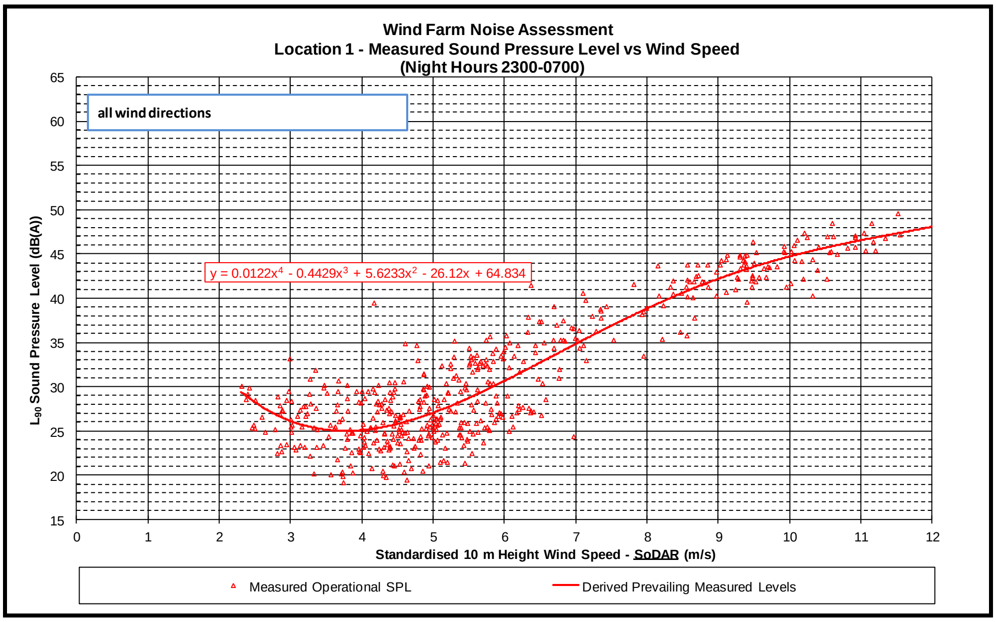

Figure 2: Wind Farm Noise Assessment with SoDAR wind speed

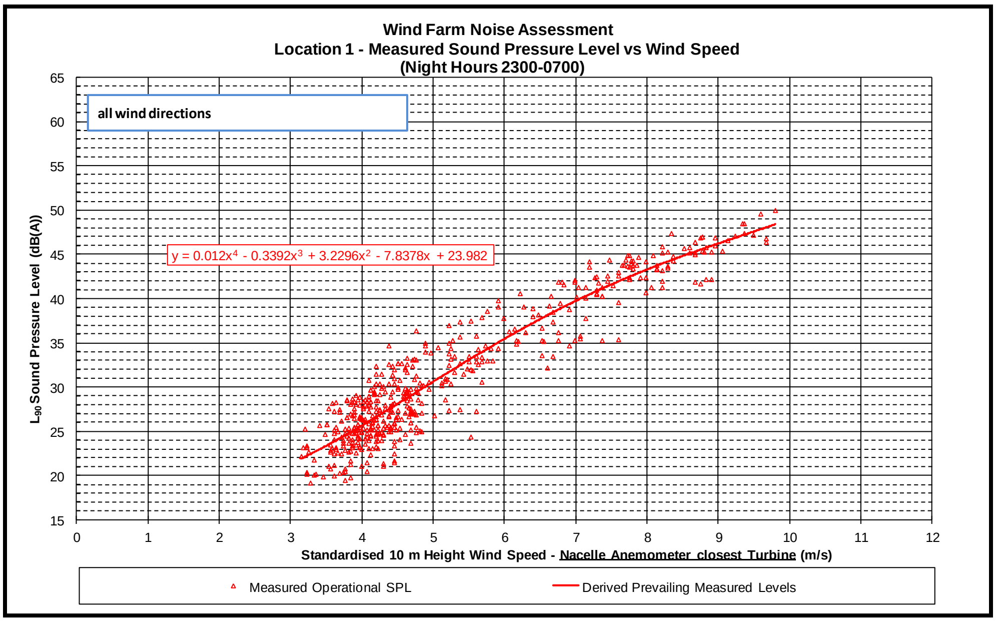

Figure 3: Wind Farm Noise Assessment with Wind Speed from Nacelle Anemometer of the closest Wind Turbine

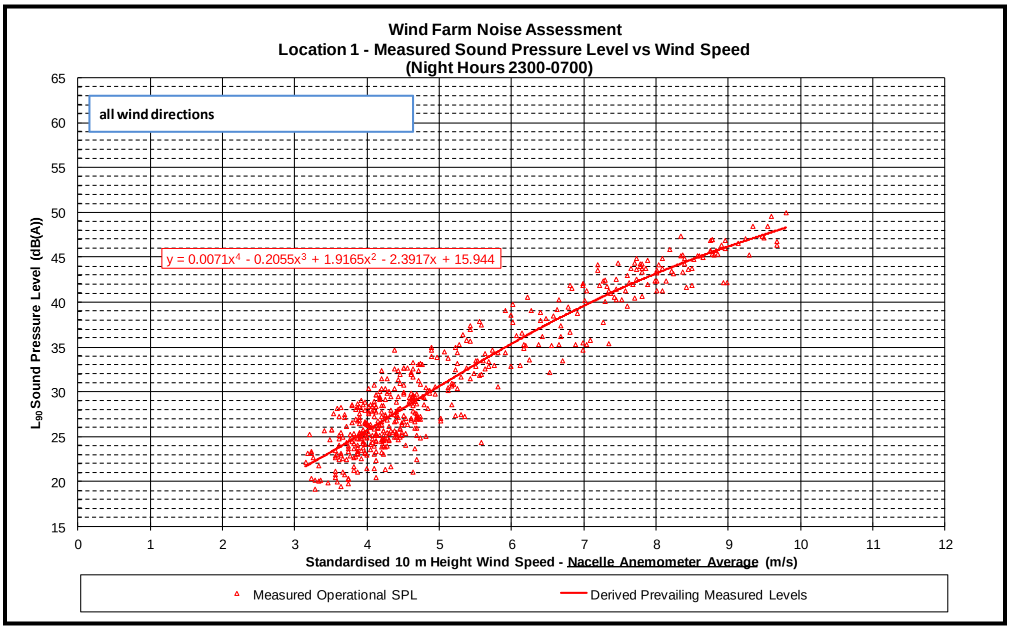

Figure 4: Wind Farm Noise Assessment with Average Wind Speed from all Nacelle Anemometers

It can be seen that the data cloud does not differ significantly between Figure 3 and 4 but that there is a clear change of shape between the SoDAR and the nacelle anemometer wind speeds. The data range is smaller, it looks more compressed. The difference between averaging and the single nacelle anemometer is 0.2 dB at the most. The wind farm site consisted of three wind turbines on 50 m hubs. Results for large wind farm sites will probably differ as it is expected that the wind speed across a larger site may vary more.

Figure 5 shows the curve of the three assessment charts in one chart for easier comparison.

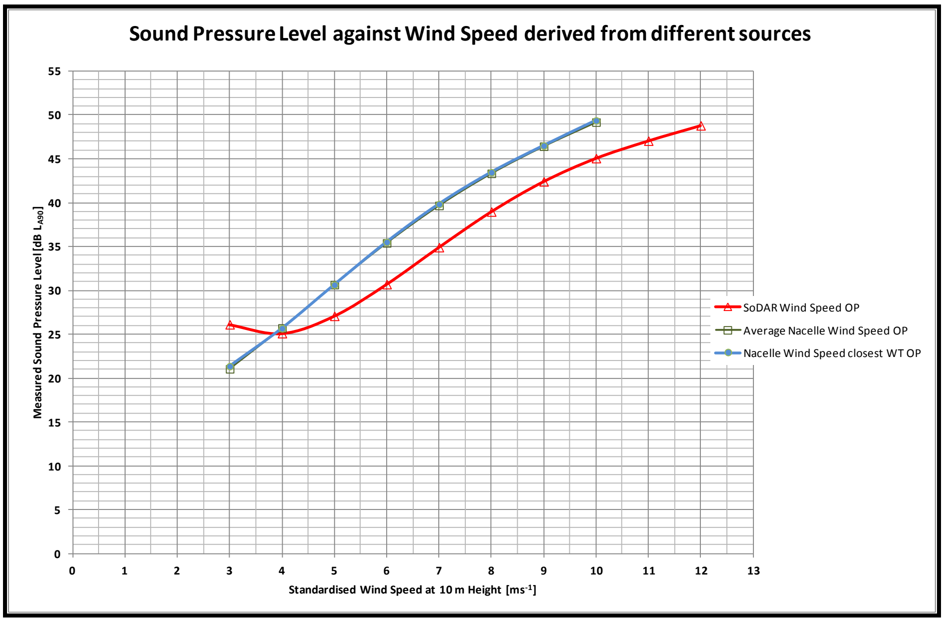

Figure 5: Wind Farm Noise Assessment with Wind Speed derived with three different Methods

The maximum difference of derived noise levels per integer wind speed between the regression curve for nacelle anemometer and SoDAR derived wind speed is 4 dB at wind speeds of 6 and 7 m/s, usually the critical wind speed range for compliance and complaints measurements.

3.3 Comparing wind measurements with a cup anemometer on met mast, anemometers mounted on wind turbine nacelles and power curve derived wind speed on wind farm site 2

On wind farm site 2 a met mast with one anemometer mounted near hub height (just 1 m below) was installed for which data was available to compare with the power curve derived wind speed of ten wind turbines and the average of ten nacelle mounted anemometers. This hub height or near hub height wind speed was standardised to 10 m height as described above.

The latest edition of the international standard for the determination of sound power level of wind turbines (BS EN 61400-11) very clearly requests the 'power curve method' as means of wind speed measurement: 'The wind speed is to be measured from the produced power through a power curve' (chapter 8.2 Wind speed measurements).

However, this method is applicable for a certain range of the power curve only which is different for each individual wind turbine type. For wind speed measurements outside this range during wind turbine operation the nacelle anemometer is used and for periods where the wind turbine is stopped, an anemometer on a met mast at a height of at least 10 m is required. The standard requires that the nacelle anemometer wind speed can be used as a representation of the wind inflow before reaching the turbine, however does not suggest how to test this. The position of the met mast is defined to be in two areas to both sides of the turbine on the semi-circle behind the turbine. It needs to be selected in a way that the inflow is as undisturbed as possible by the turbine's wake and other obstacles.

A turbine manufacturer either calculates or measures the relation of inflow wind and the electrical power output of the turbine which is issued as a power curve. Associated with this power curve but usually not public available is the pitch of the blade and the relation-ship of rotational speed to wind inflow which, amongst others, are parameters of the operational mode associated with a certain power curve. The measurements for the determination of such a power curve are described in the standards IEC 61400-12 Part 1 and 2. The resulting power curve is converted to the power output at standard atmospheric conditions (temperature 15°C and air pressure 101.3 kPa). Power curves can be based on measured values or calculated values and would be guaranteed by the manufacturer when purchasing a wind turbine. The power curves are, in particular, important for determining whether a project is financially viable as they are used to calculate the energy yield of a particular wind farm site, and are required for financing such a project.

It was mentioned earlier that the wind speed determination via the power curve method is only applicable for a certain range, the so-called 'allowed range'. The allowed range is defined as the part of the power curve, where the slope of the curve including uncertainty is positive and where the same power output cannot result in several values for the wind speed, i.e. the flat part of the curve when the turbine reached its maximum power production. The formula for calculating the allowed range is given in equation (3) in IEC 61400-11:2012.

$$(P_{k+1} - P_{tol}) - (P_k + P_{tol}) > 0$$

where k is the wind speed bin number of the power curve
P_k is the power curve value at wind bin k
P_{tol} is the tolerance on the power reading, typically between 1% and 5% of the maximum value

The wind speed $V_{P,n}$ is then calculated for the measured power by linear interpolation between the two neighbouring data points of the power curve.

For data outside the 'allowed range', a different method of wind speed determination has be to be used. The correlation coefficient κ_{nac} (for the nacelle anemometer) is calculated by averaging the values of the ratio of power curve derived wind speed over measured nacelle anemometer wind speed:

$$\kappa_{nac} = \frac{V_{P,n}}{V_{nac,m}}$$

$$V_{nac,n} = \kappa_{nac} \cdot V_{nac,m}$$

where $V_{P,n}$ is the wind speed derived from the power curve
$V_{nac,m}$ is the wind speed measured with the nacelle anemometer
$V_{nac,n}$ is the normalised wind speed from the nacelle anemometer, corrected to hub height

In order to avoid duplicating data, values of $V_{nac,n}$ which fall into the allowed range of the power curve wind speed, have to be excluded.

For periods where the turbine is stopped to measure the background noise on site, wind data is measured on a meteorological mast (met mast) at a height of at least 10 m above ground level (agl). The same procedure as for the nacelle anemometer wind speed is used to calculate the correlation coefficient κ_Z for the background noise wind speeds. It is thus normalised to hub height:

$$\kappa_Z = \frac{V_{P,n}}{V_{Z,m}}$$

$$V_{B,n} = \kappa_Z \cdot V_{Z,m}$$

where $V_{Z,m}$ is the wind speed measured with at a height of Z m (minimum 10 m agl)
$V_{B,n}$ is the normalised wind speed of the background noise periods at hub height

The table below gives an overview of which calculation of the wind speed is used for the different conditions to result in the normalised hub height wind speed $V_{H,n}$.

Table 1: Calculation of normalised hub height wind speed

Wind Speed $V_{H,n}$ is equal to	**Condition**
power curve WS: $V_{P,n}$	inside allowed range during WT operation
normalised nacelle anemometer WS: $V_{nac,n}$	outside the allowed range during WT operation
normalised met mast WS: $V_{B,n}$	all periods during which WT is stopped

The measured data has been filtered for time and wind direction so that the displayed data only include measured noise between 23:00 and 04:00 to reduce the impact of extraneous noise sources and obtain the best possible correlation between wind farm noise and wind speed. Furthermore data during periods of rain have been excluded as well. Only data where all ten wind turbines were operational have been included for the operational range and where all ten turbines were stopped for the background noise data. There were not many shut down periods so that information about prevailing background noise at this site during the measurement period is limited.

Figure 5 shows regression curves for the measured noise correlated with each of the three wind speed measurements for the downwind angle which encompasses the outer wind turbines of the wind farm. Figure 6 shows the same data sets but including ±45° as often used in wind farm compliance assessments.

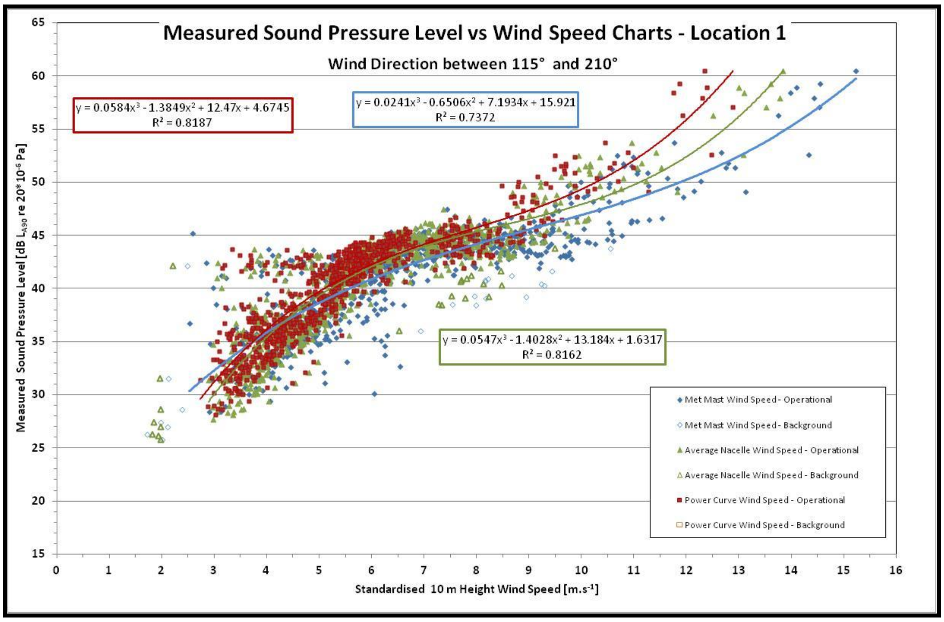

Figure 6: Wind Farm 2 Noise Assessment with 10 m Height Wind Speed standardised from Met Mast Anemometer, Average of 10 Nacelle Anemometers and Average of Power Curve derived Wind Speeds.

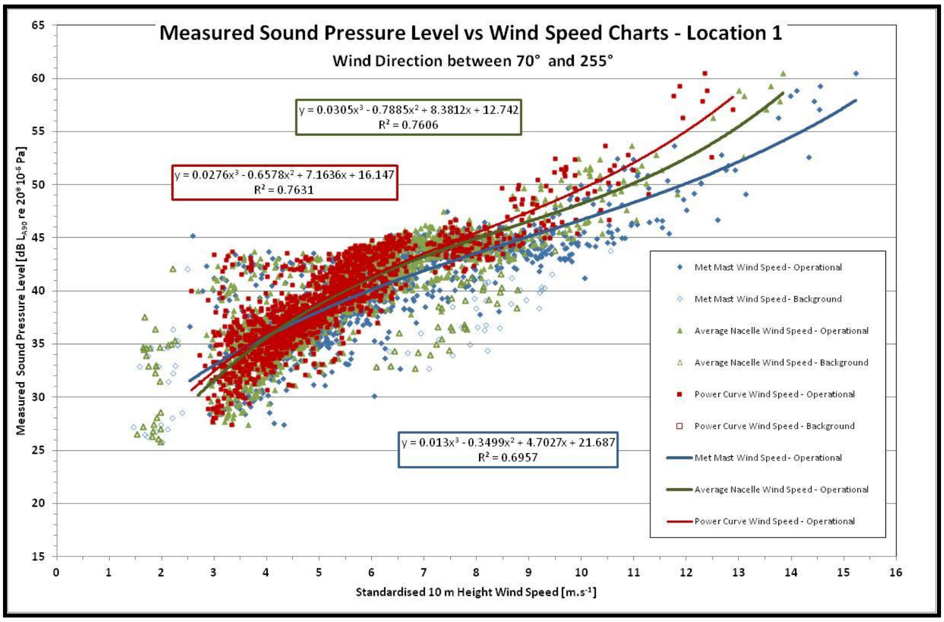

Figure 7: Wind Farm 2 Noise Assessment with 10 m Height Wind Speed standardised from Met Mast Anemometer, Average of 10 Nacelle Anemometers and Average of Power Curve derived Wind Speeds including Data from a wider 'downwind' Angle.

It has previously been assumed by the author that nacelle anemometers are not reliable enough due to shadow effects of the blades and/or turbulences around the nacelle which could affect the readings of the nacelle anemometers. However, these charts suggest that for this wind farm site both methods show very similar results for the 'allowed' range of the power curve. At higher wind speeds the power curve derived wind speed results in higher noise levels at the same wind speed, i.e. showing lower wind speeds than the nacelle anemometers in the same period. Data correlated with the met mast wind speed is generally lower for the operational range of the wind turbines.

3.4 Comparing wind measurements with cup anemometers on met mast, anemometers mounted on wind turbine nacelle and power curve derived wind speeds on wind farm site 3

Wind Farm site no. 3 consists of five wind turbines of a similar size to the turbines at wind farm site no. 2. A met mast with hub height anemometers was available as well, situated upwind of the wind farm with respect to the noise measurement location. The anemometers mounted on the met mast are therefore considered to experience a free-field inflow in the assessed wind direction. This met mast had two anemometers mounted at hub height, so that the average of both readings was used apart from wind directions where a shadow effect from the mounting could be observed, similar to what was described in chapter 3.1 above. Where this was apparent, only data from the free-flow anemometer was used.

In addition to the hub height mounted met mast anemometer, measurements at 10 m were available as well.

Figure 8 shows results for operational and non-operational noise measurements correlated with standardised 10 m height wind speeds from the met mast (average of two anemometers), nacelle anemometer (average of five anemometers) and the power curve derived wind speed (average of the power output of five wind turbines). Furthermore a curve showing the 10 m measured wind speed from the met mast is shown as well.

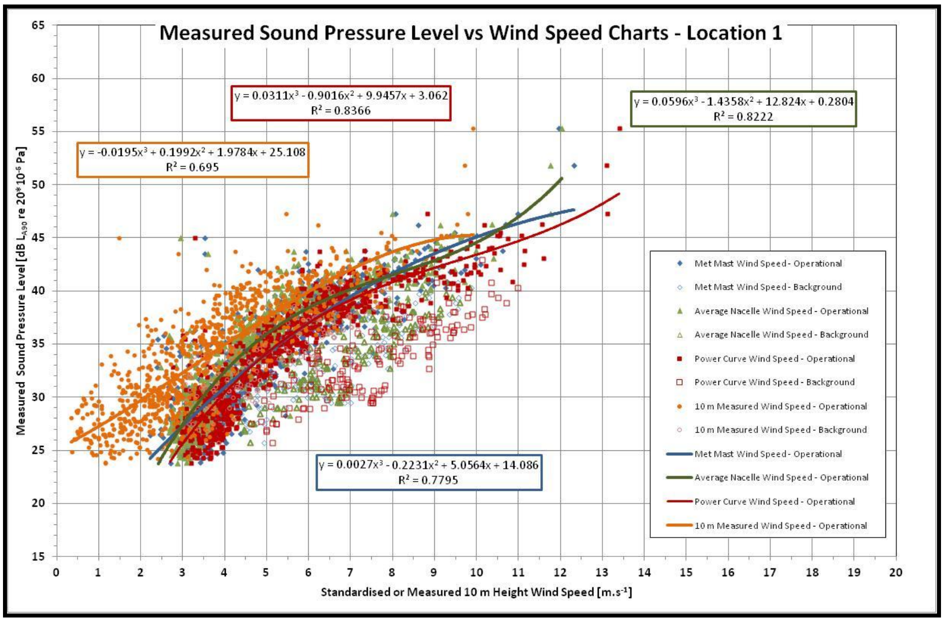

Figure 8: Wind Farm 3 Noise Assessment with 10 m Height Wind Speed standardised from Met Mast Anemometer, Average of 10 Nacelle Anemometers and Average of Power Curve derived Wind Speeds including Data from a wider 'downwind' Angle, and measured 10 m Height Wind Speed.

At this wind farm site, the power curve derived wind speed-noise curve shows a good correlation with the met mast anemometer wind speed curve up to 7 m/s when it correlates better with the nacelle wind speed curve. The power curve derived wind speed at this site is generally higher than the nacelle anemometers, hence shows lower sound pressure levels at the same wind speed.

The difference between the standardised wind speed curves and the measured 10 m height wind speed curve seems to tie in well with the suggestion of the GPG, to adjust the wind speed reference by subtracting 2 dB for turbines up to 60 m hub height when no wind shear data is available and predictions for standardised 10 m height wind speeds need to be compared with limits based on 10 m height measured data. (GPG page 23, section 4.5.4)

3.5 Further investigation

An uncertainty evaluation has not been carried out yet to determine whether all three methods would lie within the margin of uncertainty. Further wind farms have to be investigated in order to establish whether a general trend can be shown in order to suggest a preferred method for wind speed measurements for operational wind farm noise measurements.

Wind Farm 2 and 3 have similar size wind turbines, albeit with different hub heights, 80 m and 60 m. However, they show a different result. Until further wind farm sites have been assessed, it cannot be determined what causes the difference. It may be that one power curve was more conservative than the other. This will be investigated next. It may be site specific or turbine type specific. Stronger conclusions may be reached when more results become available.

These assessment have only been carried out for three wind farm sites to date, consisting of three medium sized, five and ten large sized wind turbines. Therefore no general statements can be made yet. More wind farm sites of various sizes and layouts are being assessed and results will be presented at the conference. An updated paper will be available for download after the conference at: http://www.hayesmckenzie.co.uk/publications.html

4. Conclusions

It has been shown for three wind farm sites, that the results of the average measured wind farm noise correlated with wind speed differ for different wind measurement methods. Not much difference has been found at wind farm site 1 between using the average nacelle anemometer wind speed and using the nacelle anemometer wind speed of just the wind turbine closest to the noise measurement location. However, it is expected that for more complex and larger wind farm sites the difference would be more noticeable. A maximum increase of 4 dB of the prevailing wind farm noise at standardised 10 m height wind speeds of 6 and 7 m/s has been found when comparing results with nacelle anemometer derived wind speeds against SoDAR derived wind speeds. However, further investigation will be carried out including other wind farm sizes and wind turbine types to find out whether this result can be considered conclusive.

At all three wind farm sites, it was shown that the noise curve correlated with nacelle anemometer wind speed is higher than the noise curve correlated with wind speed from either the met mast or SoDAR wind speed measurements for most of the wind speed range. Hence the 'alternative' wind speed measurement, i.e. not associated with the wind turbine directly, is higher than either the nacelle anemometer wind speed or power curve derived wind speed.

Differences have been found at two wind farm sites in the correlation between power curve derived wind speed and nacelle anemometer and met mast wind speeds. This needs further investigation to find the source of this discrepancy.

Further wind farm assessments with wind speed derived from the power curve versus wind speed measured at hub height, either from nacelle anemometers or a stand-alone device, will be included in the presentation and in the final paper published on the Hayes McKenzie website. The effect of measuring wind speed at 10 m height or using standardised 10 m height wind speed on the measured wind farm noise regression curve may also be further reviewed.

5. Disclaimer

It should be noted that the author is not, and does not claim to be, a specialist in meteorology or wind assessment. This paper is a description of observations made during wind farm noise measurements with various means of wind speed derivation. Updated paper available after Internoise 2014 (towards the end of 2014): http://www.hayesmckenzie.co.uk/publications.html

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