

SITE-SPECIFIC ADJUSTMENTS TO WIND TURBINE POWER CURVES

Andrew Tindal, Clint Johnson, Marc LeBlanc, Keir Harman, Elisabeth Rareshide, and AnneMarie Graves, Garrad Hassan America, Inc.

1 INTRODUCTION

This paper considers site-specific factors that may influence wind turbine performance. The focus of the paper is to consider how the performance of a wind turbine, which will usually be based on a power curve or power curves measured independently in accordance with the relevant standard [1] at a flat and benign test site, should be interpreted for the purpose of pre-construction energy predictions for wind farms. A particular focus is to assess how the sales power curve should be interpreted for a site with complex terrain or markedly different meteorological characteristics than those at a meteorologically benign test site.

2 SPECIFIC POWER CURVE ADJUSTMENT AND UNCERTAINTY FACTORS

2.1 Sensitivity of power curves to turbulence

A number of technical papers, e.g. [2, 3], discuss how wind turbine power curves are sensitive to turbulence intensity. A typical power curve for a pitch regulated machine might cut in at about 4 m/s, the power curve is concave between the cut in wind speed and approximately 10 m/s, and beyond 10 m/s the power curve becomes convex until rated power is reached. Increasing turbulence intensity will increase the machine's power in the concave region of the power curve and will decrease the machine's power in the convex region of the power curve. Thus changes in turbulence intensity will have opposing effects on the different parts of the power curve which, to an extent, will cancel each other out.

Most turbine suppliers recognise the potential sensitivity of the power curve to turbulence intensity and associate a supplied power curve with a specific turbulence intensity or turbulence intensity range. Owing to the opposing low and high wind speed effects described above and where the site turbulence intensity is not substantially different from that quoted for the supplied power curve, it is reasonable to use the supplied power curve for a pre-construction wind farm energy assessment without adjustment.

GH has undertaken detailed studies using data both from power curve tests and from ten-minute SCADA data recorded at wind farm sites. From these data sets, power curves have been derived for specific sectors binned on turbulence intensity. The sensitivity of the power curve to turbulence intensity has been assessed using these binned power curves. Some caution must be exercised in the interpretation of these data as it is possible that for periods of high turbulence intensity, other meteorological parameters, such as wind shear, are also varying. Nevertheless, such data do provide a good indication of the influence of changes in turbulence intensity on the power curve. Furthermore, by combining the binned power curves with realistic wind speed distributions for different wind speeds, the impact of turbulence intensity on annual energy production can be estimated.

Figure 1 below illustrates the power curves that result when the data are binned by turbulence intensity. This figure shows data from a particularly low turbulence site, and this plot may be considered an example of how the power curve changes when moving from low to medium turbulence intensity levels. Here low turbulence intensity is defined as approximately 0-5 %, medium is defined as approximately 5-10 %, and high is defined as approximately 10-15 %.

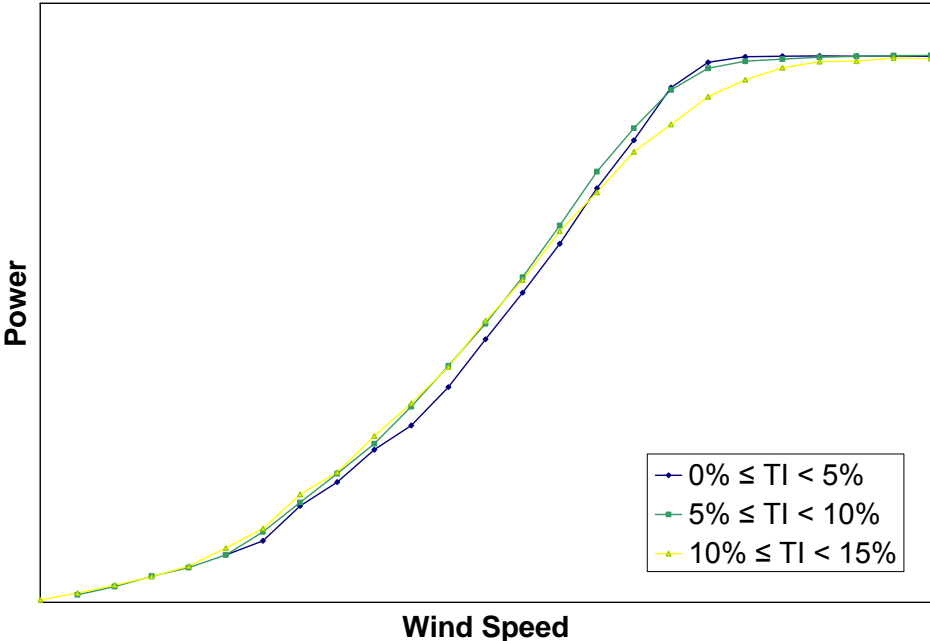


Figure 1 Power curves binned based on turbulence intensity

Figure 2 below presents power curves that have been derived for a wind farm site specifically selected to include some directions for which the turbulence intensity is high. The figure below demonstrates how the turbine power curve changes as turbulence intensity levels become particularly high.

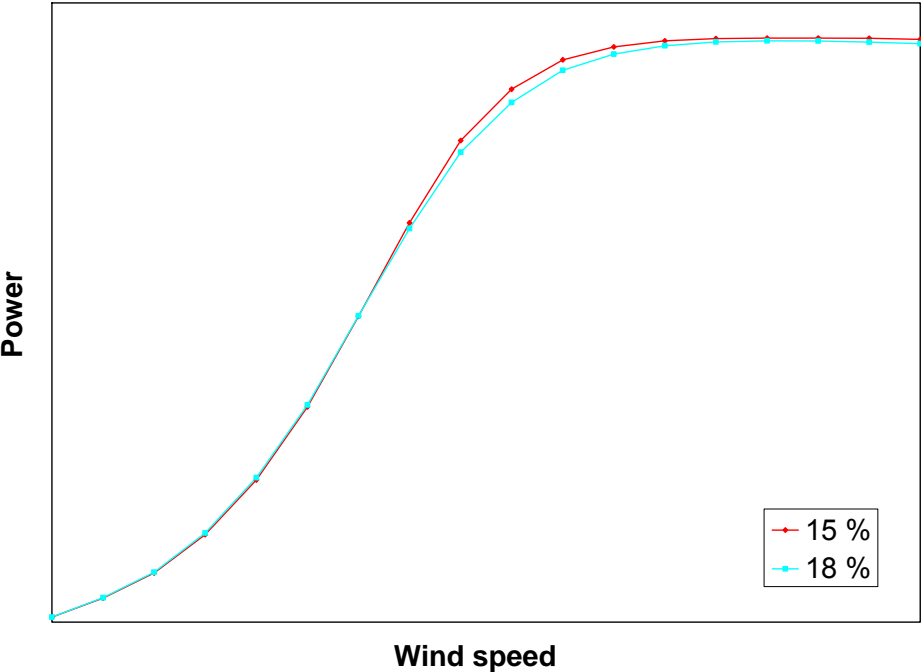


Figure 2 Power curves for 15 % and 18 % turbulence intensity

GH has reviewed of a number of data sets including those illustrated above to critically evaluate for what conditions there is potential for the power curve to be materially different, in terms of energy capture, from that supplied by the turbine manufacturer. Developing a detailed theoretical model to adjust a supplied power curve based on both turbulence intensity and wind speed would be possible if the exact turbulence intensity of the supplied power curve were known. However, this turbulence intensity is often unclear. Furthermore, such a model would require site-specific and turbine-specific assumptions about the turbulent structure of the wind and the operation of the turbine controller, respectively. It is therefore considered appropriate to apply a “higher level” model that only applies adjustments when it is considered that the net effect of changes in turbulence intensity on annual energy production is significant. Based on the assessment of the data sets described above, GH considers it is reasonable to assume that for low and medium turbulence intensity sites, the net effect on energy production of changes in turbulence intensity is small and therefore no adjustment to the turbine manufacturer’s power curve is merited - assuming that the sales power curve may be considered representative of medium turbulence levels. However, the studies have shown that as turbulence intensities increase beyond approximately 15 %, a net reduction in the energy production is observed as degradation of the “knee” of the power curves becomes severe.

GH therefore considers it appropriate to apply a high turbulence intensity adjustment factor to account for the above influence. The model applies an adjustment to the energy production of the wind farm when the predicted turbulence intensity, including wake effects, exceeds 15 %. The factor is sensitive to both turbulence intensity and annual mean wind speed. To provide an illustration for an approximately 7.5 m/s wind speed site with an average 18 % turbulence intensity (TI_{15}), the adjustment factor would reduce the energy production by approximately 1 %.

While GH believes that the above model will adequately address the issue of the sensitivity of the power curve to changes in turbulence intensity, if a site’s turbulence intensity is substantially different from the turbulence intensity of the supplied power curve, then the adjustment should be re-examined on a site-specific basis.

2.2 Sensitivity of power curves to complex terrain

Power curves measured in accordance with the IEC standard’s terrain requirements will typically have slopes of less than 3° within approximately 4-8 rotor diameters of the tested machine and slopes of less than 10° within at least 16 rotor diameters of the tested machine. For such sites it is reasonable to assume that the flow typically experienced by the wind turbine closely approximates horizontal flow.

Many wind farms are situated in more complex terrain. For many locations in complex terrain the flow no longer approximates horizontal flow, and there may be a significant degree of upflow or downflow.

Studies have been undertaken using both theoretical modelling techniques and measurements to assess how the performance of wind turbines changes with upflow angle. Risø has studied a 75 kW turbine operated at a range of yaw angles to measure the sensitivity of wind turbine power to off-axis flow [4]. It has been assumed that the wind turbine will experience similar effects with changes in upflow angle as are experienced with changes in yaw angle. Studies have also been undertaken in Japan which include measurements on a 100 kW wind turbine [5] to measure the influence of flow inclination on power.

These studies show that if there are severe upflow conditions induced by terrain, there can be significant reductions in the performance of wind turbines.

Before considering the impact of upflow angles on turbine performance further, it is necessary to understand the likely upflow angle induced by terrain of different complexities. A study aimed specifically at this issue [6] is useful in informing the likely variability of mean upflow angle with complexity of terrain. The study measured upflow angle at two sites. The first site had localised

terrain slopes that varied between 0° and 10°, while the second was more severe with slopes varying between 0° and 21°. From this study a significant correlation between upwind slope and upflow was identified, and the data indicated that the mean measured upflow was approximately $\frac{1}{3}$ of the upwind terrain slope. As the study is relatively old, the measurements were made at only 25 m height, and there were some indications, as would be expected, that upflow angle reduced with height above ground level. From this work it is considered that a reasonable model for upflow is to assume that the upflow angle at the height of typical modern wind turbines is $\frac{1}{4}$ of the angle of the localised slope. This assumption is broadly consistent with what GH has observed on sites with steep slopes where upflow angle is measured.

Within [5] it is estimated that a wind turbine experiencing a constant upflow of 10° at hub height would have an annual energy production approximately 5 % lower than that of an equivalent site with horizontal flow. At a wind farm site the situation is more complex because the location where the wind speed is measured relative to the turbine locations and the specific cup anemometer's response to variations in flow inclination may affect how the wind speed measurements reflect the horizontal versus the "vector scalar" components of the wind speed.

It is clear from the above that for complex terrain sites that experience substantial upflow, it is appropriate to apply an upflow power curve adjustment. However, establishing the appropriate magnitude for an adjustment is a challenge.

GH has developed a model with the following key attributes:

- The model is only applied for sites that are considered complex.
- The terrain slopes in the vicinity of each wind turbine are appraised. It is assumed that at turbine hub height the upflow angle is $\frac{1}{4}$ of the localised terrain slope, and an average terrain slope is defined with due consideration of the "energy rose" at the turbine location.
- An upflow adjustment factor is then assigned based on the average terrain slope on a per turbine basis and aggregated to get the wind farm effect.

It is acknowledged that there are several pragmatic assumptions and simplifications included within the above model. GH will refine the model further as more data become available. The upflow power curve adjustment factor model accounts for the likelihood that the average yaw error of the wind turbine may be marginally higher in complex terrain than in simple terrain.

The magnitude of adjustment for an example site illustrates the typical magnitude of effect in complex terrain. A wind farm with a line of turbines on the edge of a 20° escarpment with a uniform wind rose would have an upflow power curve adjustment of 99.4 %. The same site with a unidirectional wind rose that constantly blows up the escarpment would have a power curve adjustment factor of 97.5 %. Clearly this factor must be determined on a site-specific basis.

An attempt has been made to observe the influence of upflow on the power curve using measured SCADA data. This comparison did not reveal significant differences between the power curves for a turbine located in steep terrain compared with one in more moderate terrain. However, the nacelle anemometer wind speed measurements on which the power curves are based are notoriously sensitive to upflow, and it is considered that this is why it was not possible to isolate this effect from the available SCADA data. GH will seek a site where a suitable free stream mast with upflow measurements is available to further investigate this effect.

2.3 Sensitivity of power curves to shear

GH has undertaken internal studies using the GH Bladed wind turbine model to investigate the sensitivity of theoretical power curves to variations in wind shear. From these studies it is concluded that the power produced by wind turbines is not particularly sensitive to variations in shear where an

idealised model of wind shear is assumed. From these studies GH considers it appropriate to apply a site-specific power curve factor only where, averaged over the long term, there is evidence that the wind shear above hub height may be significantly different than the wind shear below hub height. There is seldom data available to measure the variation of wind speed above the hub height of the machine. This is an area where remote sensing techniques may start to provide robust data to define the detailed wind shear patterns above the turbine hub height. Where such data are available, a detailed view can be taken regarding whether a wind shear based power curve adjustment factor is merited at a specific site.

2.4 Blade fouling and icing

The estimation of icing effects on wind turbines is a site-specific issue that GH has considered in other papers.

GH typically applies a blade fouling and degradation factor of 99.5 % to account both for fouling of the blades by dirt and insects before blades are cleaned by sustained periods of rain and for the degradation of the aerofoils over time. For sites that are relatively arid or where there are known blade degradation issues, this factor is increased to 99 %. While these estimates are largely pragmatic, the findings of [7] and [3] broadly support the above estimated adjustment factors. However, it is noted that a higher allowance should be made for exceptional sites where blade fouling or degradation can be a severe issue.

2.5 Power curve measurement blockage effects

Over the past decade considerable advances have been made in achieving consistency in the measurement of wind turbine power curves. There has been a range of documents that have provided guidance on best practices for power curve measurements over this period. However, since publication in 2005, the IEC standard is now widely accepted as the definitive guidance for power curve measurements [1].

Predicting the performance of wind turbines from theoretical aerodynamic models is notoriously difficult. It is common practice to validate and refine predictions of wind turbine power curves made with computational models by using measured data. This enables the theoretical models to be used, for example, to present the power curve of a wind turbine at different air densities. However, owing to the comparison with measurements, such computationally derived power curves may still be considered based on measured power curve data. Additionally with the now universal acceptance of the IEC standard, it may be considered that the power curves for all commercially available wind turbines are referenced to the measurement techniques within the IEC standard.

The measurement of wind turbine power curves is also notoriously difficult, and even when current best practice is followed as defined by [1], the uncertainty in the measured power curve is significant. For a typical wind turbine at a typical wind farm site, the uncertainty in a measured power curve may exceed 5 % of the annual energy production of the wind turbine.

This paper reviews how power curves derived in accordance with the IEC standard should be interpreted for use in pre-construction energy analysis.

The IEC standard provides guidance on the location of the meteorological mast relative to the test turbine as follows:

“Care shall be taken in locating the meteorological mast. It shall not be located too close to the wind turbine, since the wind speed will be influenced/changed/affected in front of the wind turbine. Also it shall not be located too far from the wind turbine, since the correlation between wind speed and electric power output will be reduced. The meteorological mast shall be positioned at a distance from

the wind turbine of between 2 and 4 times the rotor diameter D of the wind turbine. A distance of 2.5 times the rotor diameter D is recommended.”

Thus the location of the mast is a compromise between mitigating the upwind reduction in wind speed due to the presence of the wind turbine (blockage effect) and achieving a strong correlation between wind speed and electric power.

It is reasonable to assume from the above that, due to the compromise that must be reached in defining the upstream distance of the mast from a wind turbine, a measurement 2.5 D upstream of the wind turbine includes a small reduction in wind speed due to the presence of the wind turbine when compared with the free stream condition. The estimated reduction in wind speed due to the presence of the wind turbine is not directly stated within the standard. The issue is illustrated schematically in Figure 3 below:

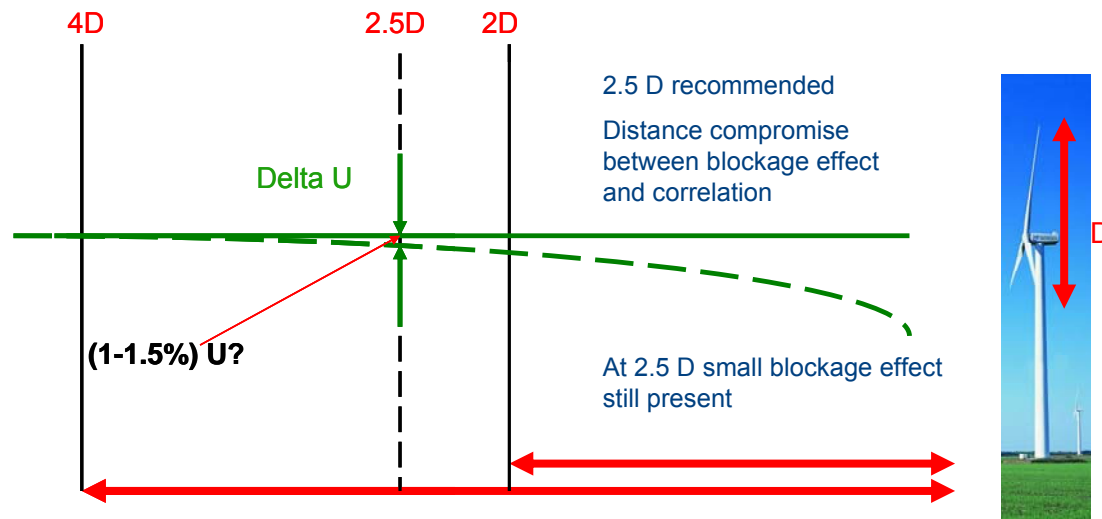


Figure 3 Blockage effect schematic

Frandsen has estimated the blockage effect from a wind turbine and from groups of wind turbines and published the results of an analytical assessment of this issue [8]. It is predicted that the reduction in wind speed 2.5 D upstream of a typical single wind turbine is 1 % [8]. The blockage effect upstream of a mast when the turbine is within a row of wind turbines is predicted to be substantially greater than that of a single turbine.

Although the IEC standard does not provide an explicit estimate of the blockage effect experienced 2.5 D upstream of a turbine, it does consider the issue of the blockage effects of lattice masts. Annex G of the IEC standard defines best practices to ensure that anemometers are not unduly influenced by the blockage effect of a meteorological mast. Using data within Annex G, if a lattice meteorological mast with a density of cross beams is assumed such that the thrust coefficient of the mast is broadly similar to that of a wind turbine at medium wind speeds, then reduction in wind speed 2.5 D upstream of a lattice mast is estimated to be approximately 1.5 % of wind speed. Furthermore, numerous assessments of anemometers mounted at such distances from lattice towers by GH have confirmed that 2.5 D upwind from a lattice tower there is indeed a significant blockage effect.

It therefore appears reasonable, based on the analytical work of Frandsen et al [8] and the analogy with the effect upwind from a lattice meteorological mast, that the wind speed 2.5 D directly upstream of a wind turbine is in fact likely to be 1 to 1.5 % less than the free stream wind speed. This is a

significant observation in the context of using a power curve derived in such a way for a pre-construction estimate of the energy production of a wind farm.

For a typical power curve test where a reasonably wide measurement sector is used, the above blockage effect will only occur for the sector where the mast is upwind of the wind turbine. For other sectors there will be a substantially reduced effect. However, the IEC standard also states:

“In most cases, the best location for the meteorological mast will be upwind of the turbine in the direction from which most valid wind is expected to come during the test.”

It is therefore reasonable to assume that for a significant proportion of the data used within most power curve tests, the wind speed measurements include a blockage effect of 1 to 1.5 %. Of course it is widely accepted that there is significant uncertainty in power curve measurements. However, the concern here is that the above effect will be manifested as a bias rather than simply as uncertainty.

As discussed above the substantial majority of all power curves used for modern wind turbines may be assumed to be referenced, either directly or indirectly, to measurements made in accordance with [1]. GH therefore considers it appropriate to adjust for the inherent blockage effect in the power curve measurements when using supplied power curves for future pre-construction estimates of the energy production of wind farms. The wind measurements made on pre-construction wind farm sites do not include such a blockage effect and therefore an adjustment is required before they may be compared on a like-for-like basis with wind speed measurements within the power curve test.

To precisely estimate and correct for the influence of blockage effects on any individual wind turbine power curve is a task that requires a detailed understanding of the derivation of the wind turbine power curve and full availability of the measured power curves that were used to define the wind turbine power curve. Such information is generally not available. GH has therefore decided for future wind farm energy prediction estimates to apply a “Generic power curve adjustment” factor of 99% to account for the blockage effect discussed above.

A value of 99 % for the Generic power curve adjustment factor as the effect on energy production for a typical wind farm site has been assumed based on the following assumptions:

- At 2.5 D upstream of a wind turbine, the meteorological mast is directly upwind of the turbine rotor for a direction sector of 22.5°. For this sector it is assumed the blockage reduces wind speeds by 1 to 1.5 %.
- It is assumed that such an influence on wind speed would have an effect of 2 to 3 % on wind farm energy production using typical wind speed to energy production sensitivity ratios.
- It is assumed that the above energy effect is mitigated in a power curve test because the measurement sector typically includes sectors that are not blocked.

GH has taken data from a power curve measurement in a particularly flat location where it may be expected that in the absence of the wind turbine, the wind speed recorded at the mast and turbine location would be the same. The power curve has then been separately derived for the sectors that are directly upstream and are not directly upstream of the turbine. The results are presented in Figure 4 below. Due to the uncertainties in the measurement of any individual turbine’s power curve, the results of this check are not considered definitive. Nevertheless, the power curve derived when the mast is directly upstream of the turbine is better than that derived from the parts of the sector that are not directly upstream of the turbine. It is estimated that, depending on the annual mean wind speed at the site, the difference in annual energy production between the two power curves is between 1 and 1.5 %. This further supports the need to apply such an adjustment factor.

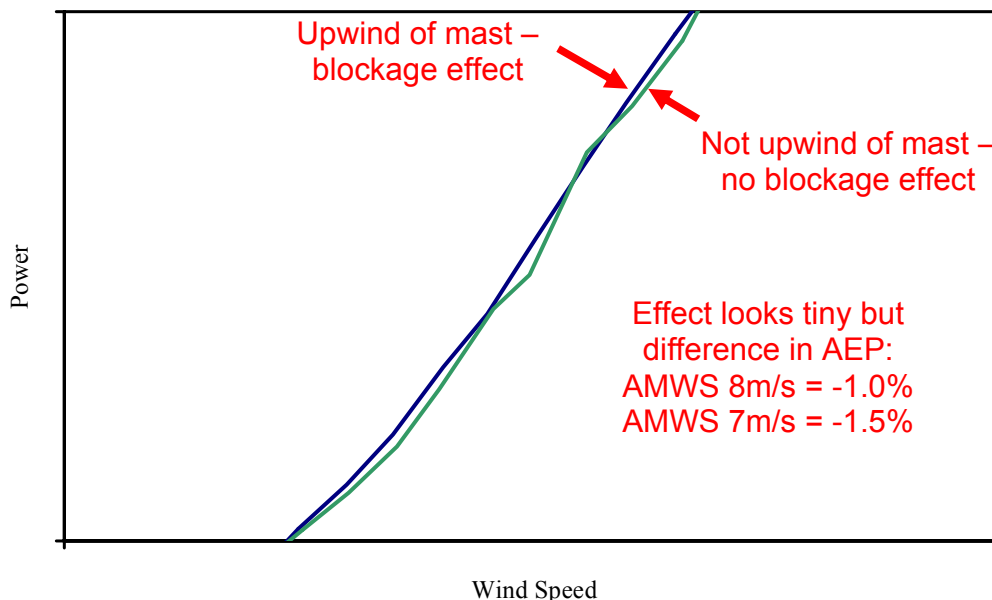


Figure 4 Blockage and non-blockage effect power curves – medium wind speeds

It is stressed that the above factor does not imply that power curves have not been measured correctly. It rather is an issue of how a power curve measured in accordance with the IEC standard should be interpreted in the context of pre-construction energy assessments.

In the usual way for a project at financial close where there is a large body of documentation associated with the power curve contractual arrangements, it may be appropriate to adjust the above assumption on a site-specific basis. In addition, if there are a significant number of independently measured power curves available for a machine, it may be appropriate to amend this assumption.

Though it is not directly the subject of this paper, based on the calculations undertaken by Frandsen [2], care is required in the selection of suitable wind turbines for power curve measurements. When a turbine in the middle of a row of turbines is tested, the resulting measured power curve may be materially different from that measured on a single turbine, all other things being equal.

2.6 Power curve and availability uncertainties

Most wind farm projects have specific arrangements within the contract terms to warrant specific levels of turbine performance and availability. Additionally the future availability of a wind farm will be dependant on many factors, including the O+M arrangements and budgets set. The actual performance of the wind turbines and the availability may be different from those assumed in a pre-construction energy analysis, and these parameters are therefore subject to uncertainty. However there are uncertainties that depend on how the wind farm is operated in future and therefore differ from the other parameters considered within the uncertainty analysis. Furthermore, at least in a financial sense, the uncertainty distributions are potentially non-linear with liquidated damages payable if warranted levels are not met.

In order to acknowledge the uncertainty in both the power curve adjustment factors described above and in all loss factors, including issues such as availability, it is considered appropriate to include a term in the uncertainty analysis to account for these effects. Although these effects are different from other uncertainties in that many of them depend on how the wind farm is operated, it is considered

appropriate to assign an uncertainty. Clearly the assigned uncertainty may prove to be incorrect if the wind farm is operated differently from pre-construction expectations. An uncertainty of 2 % on energy production might be typical for a wind farm with an assumed normal distribution. It is accepted that this allowance is a compromise. In parallel with this allowance, it is recommended that suitable sensitivity studies are undertaken within the financial model to assess the impact of major events such as generic defects in the turbine technology that are outside the range of the power curve and availability uncertainty assumptions included within a pre-construction energy assessment uncertainty analysis, which is more focused on the accurate prediction of the wind resource at the site and the likely future variability of the wind.

3 SUMMARY OF POWER CURVE ADJUSTMENT FACTORS

This paper has considered site-specific power curve adjustments for meteorological conditions and interpretation of turbine power curves measured in accordance with the IEC standard [1] for pre-construction energy assessments. The key findings from the investigation of these issues are summarised below:

- Analysis of relevant data sets has demonstrated that for sites with particularly high turbulence levels, there is potential for reduction of the energy production of the wind farm when compared with lower turbulence sites. A model has been proposed to apply a turbulence power curve adjustment factor for sites where the predicted turbulence levels, including wake effects, are more than 15 %. For example, the model defines a reduction in energy of 1 % for a site with 18 % turbulence.
- It is argued that for sites with significant upflow there is the potential for reduction of the energy production of the wind farm when compared with flat terrain sites. A model has been developed where sites are characterised into simple and complex terrain categories. For complex terrain sites, an upflow power curve adjustment factor is applied. The average upflow is estimated using a model based on a directional definition of terrain slope for each turbine, the site wind rose, and an assumed dependence of upflow to terrain slope. For example, for an escarpment site with 20° slopes, the model defines a reduction between 0 and 1 %, which might increase for steeper slopes or for slopes strongly aligned with prevailing wind directions.
- It is argued that a site-specific power curve adjustment factor for wind shear is only appropriate for those sites where there is evidence that the wind shear is markedly different above the turbine hub height than below the turbine hub height. It is seldom the case that there are data available to demonstrate such a trend, and it is therefore unusual that the application of such a factor can be justified.
- A model is defined for blade fouling and degradation which applies a factor of 0.5 % for the majority of sites but increases to 1 % for particularly arid sites or sites where there are known to be significant occurrences of blade fouling. The issue of icing of turbines is not considered here but is assessed in other GH publications.
- It is considered that the definition of wind speed provided within wind turbine power curves based on the widely adopted international standard IEC 61400-12-1 effectively includes a blockage effect from the presence of the wind turbine. Such a blockage effect is not present for wind speed measurements made on pre-construction wind farm sites. To enable a like-for-like comparison between the site wind speed measurements and the definition of wind speed within the power curve, an adjustment is necessary. To account for this effect, a generic power curve adjustment factor of 99 % is applied. It is stressed that this does not

imply that the power curve has been measured incorrectly, but rather that the power curve needs to be appropriately interpreted in the context of pre-construction energy assessment.

- An allowance for the uncertainty in the power curve and availability of the wind turbine is made, which is typically 2 % of the energy production of the wind farm. Although this accounts for some of the uncertainty in the loss factor parameters, several loss factors (e.g. availability) are strongly dependant on the operational regime of the wind farm. Therefore these issues are considered within the financial model of the wind farm with due consideration of the O+M and contractual arrangements of the wind farm.

It is accepted that the above models are pragmatic models, and it is anticipated that as more data become available, the above models will be refined.

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