VALIDATION OF GH NORTH AMERICAN ENERGY PREDICTIONS BY COMPARISON TO ACTUAL PRODUCTION

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1 INTRODUCTION

Garrad Hassan (GH) has been predicting the energy production of wind farms for fifteen years. Predictions have now been produced for over 80,000 MW of plant internationally, and many of these projects have gone forward to construction and have now operated for considerable periods. This paper focuses on the validation of energy production assessments performed by GH for wind projects in North America.

In order to assess the accuracy of these predictions, GH maintains an internal database which allows the actual production of wind farms to be compared with pre-construction projections. Using the information within this database, GH has conducted a high level investigation of how these constructed wind farms have performed in relation to the original GH pre-construction predictions. This investigation has been designed to compliment a range of more detailed validations that GH conducts on individual aspects of its methodologies and models.

GH has previously published energy validation results for North America [1]. This paper presents the latest validation results, and it is GH's intention to continue to maintain the energy validation database and to publish updated validation results.

To overcome issues associated with different periods of data being available from the various wind farms, each year of actual production data has been considered separately, and compared against the GH net energy output central estimate (P50) and 1 year 90 % probability of exceedence level (P90).

It is the aim of this work to be able to evaluate as large a volume of validation data as possible. For some wind farms only "high level" data are available, such as monthly sub-station meter readings with no detailed information on wind farm availability or performance. Wind farms with only high level data have been included within the analysis. However, where wind farms are known to have been affected by gross issues such as very poor turbine or grid availability, or such issues are apparent from comparison with data from nearby wind farms, such wind farms have been excluded from the assessment. Such exclusions of wind farms from the database is inevitably somewhat subjective, however, the results are also presented in this paper for the subset of data for which the availability is known.

The results of a previous comparison of actual to projected energy production for North American wind farms identified that, on average, across the data available at that time there was a tendency for energy production to be over-predicted. Following publication of that paper GH have undertaken a critical appraisal of all aspects of energy analysis methodology and assumptions to attempt to identify potential sources of bias in an analysis. As a result of this process some factors have been identified where amendments to analysis methodologies and assumptions have been made. Some amendments are generic and applicable to all GH analyses, while some reflect current North American market conditions. These areas are described within this paper.

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2 ENERGY VALIDATION RESULTS FOR NORTH AMERICA

Results for the whole of North America have been considered. The database includes results from 41 wind farms with operational periods which vary from 1 year to 8 years. There are currently a total of 113 wind farm years in the validation database.

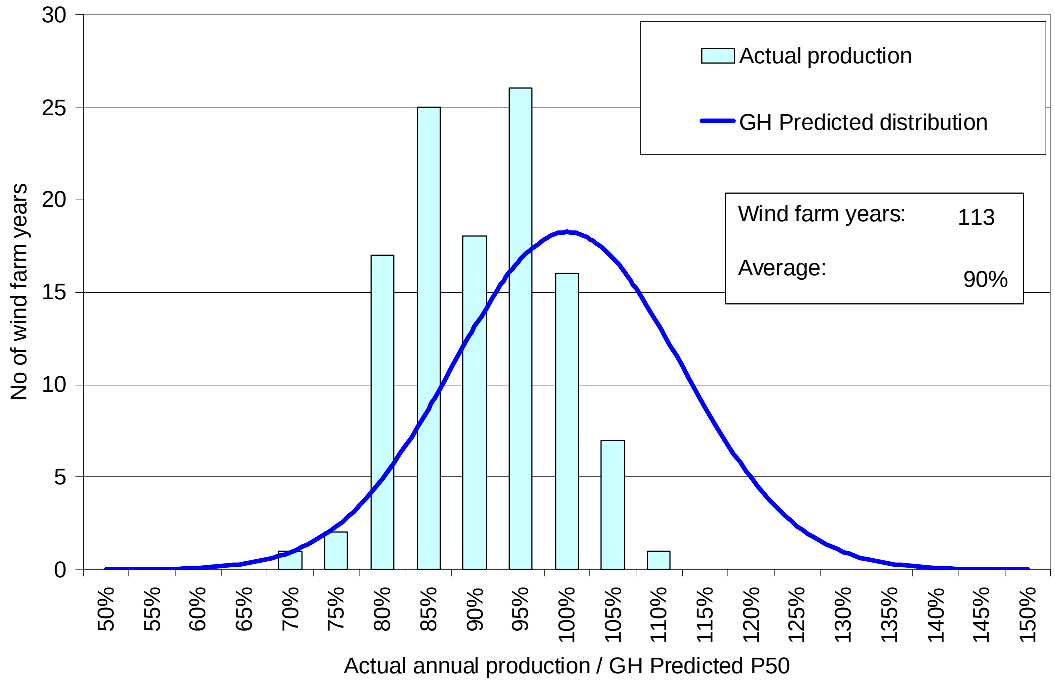


Figure 1 Distribution of annual production relative to GH projected central estimates

The distribution of annual energy production, relative to the GH central estimate, for the 113 wind farm years in the database is presented in Figure 1. It can be seen that on average wind farms have produced 90 % of pre-construction estimates.

The potential causes of the above discrepancy from the "ideal" 100 % result are briefly summarised below.

Windiness of operating period.

It is noted that there are a substantial number of wind farms for which data are available from Texas and, for example, Texas generally experienced a low wind year in 2007. Windiness of the period therefore may explain some of the difference. This is considered further below.

Wind resource prediction error

It may be that bias has been introduced in the different elements of the wind speed assessment process including; wind speed measurement bias, long term wind speed adjustment, extrapolation to hub height, and wind flow modeling.

Energy loss factor prediction error

It may be that bias has been introduced by differences in estimated and actual energy loss factors including; wake loss modeling, availability, electrical losses, turbine performance, environmental losses and losses through curtailment.

As discussed above for a subset of the full data set availability data are available, and these data have been used to adjust the actual production of the wind farms to be consistent with pre-construction estimates of availability. The purpose of this exercise is to assess to what extent such differences may explain the discrepancy. The distribution of actual energy production compared with GH pre-construction energy estimates is presented in Figure 2 for the subset of 70 wind farm years for which availability data were available.

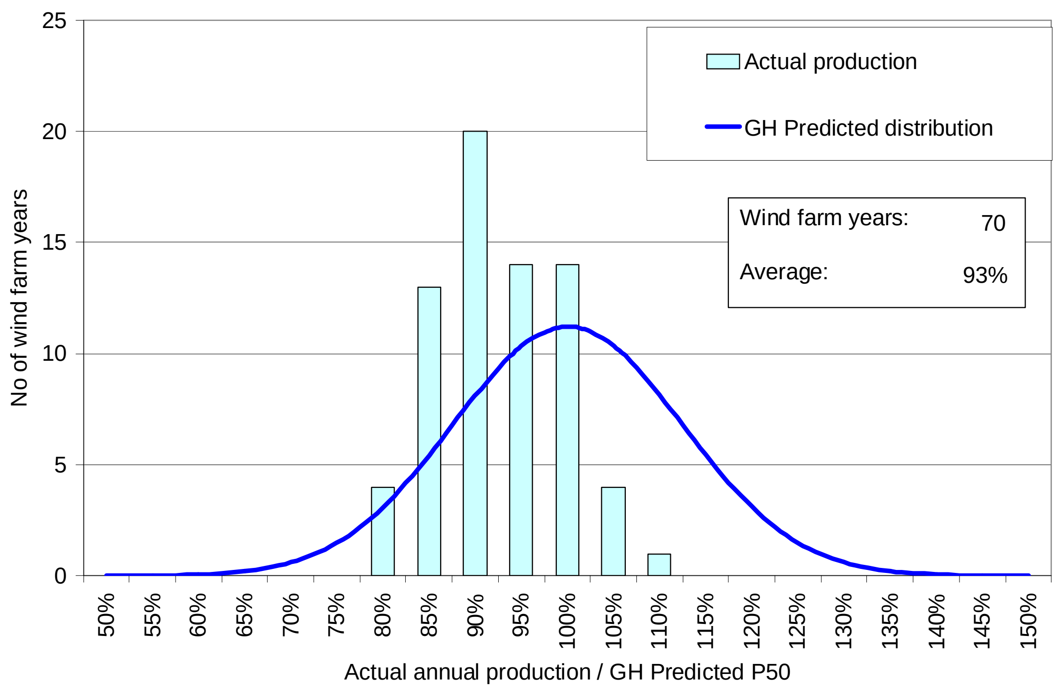


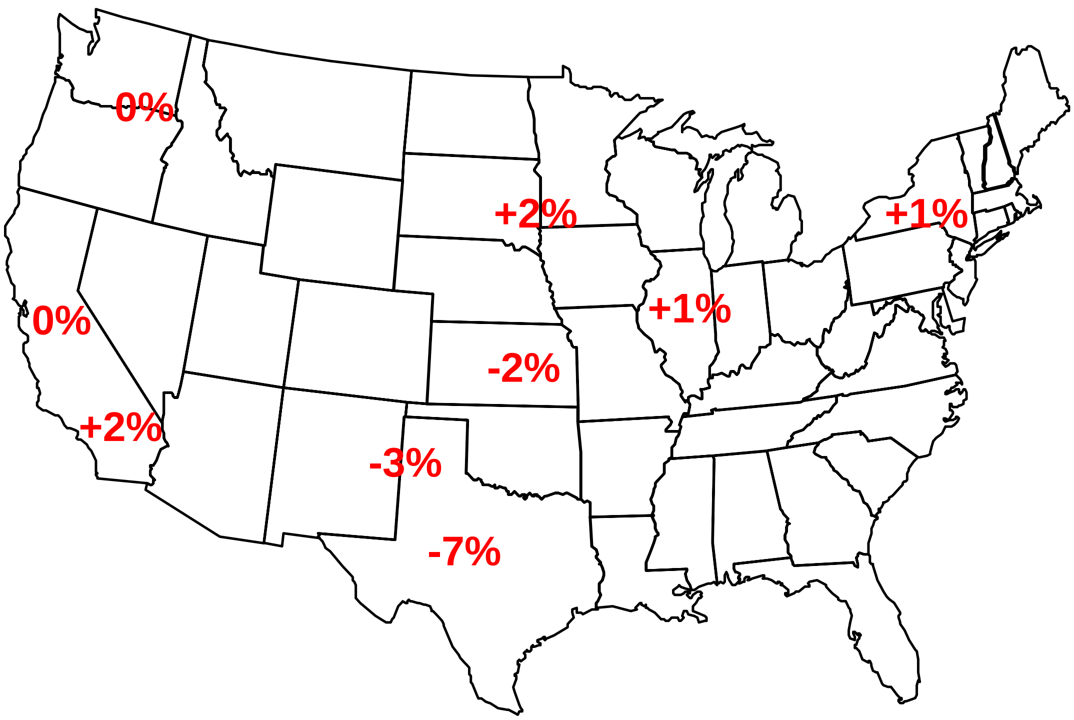
Figure 2 **Distribution of annual production relative to GH projected central estimates including availability adjustment for a subset of 70 wind farm years**

It is noted that when such an adjustment is made the average production increases to 93 % of the pre-construction value. Differences in actual availability from pre-construction availability estimates therefore explain some of the observed discrepancy. Additionally it can be seen that the availability correction has made a material difference to the tails of the distribution, although it is also noted that the data set is relatively small to read too much into this part of the distribution. The issue of current availability trends in North America is discussed further below.

In a previous paper [1] there was significant discussion of legacy issues, such as the prevalence of poor mounting arrangements of sensors – the so called "stub mount" effect causing a significant but difficult to quantify bias in the predictions of wind farm energy production.

In order to allow a focus on the most up to date measurement norms and analysis techniques GH have focused on the production of projects in 2007. A key question raised above was what impact has windiness had on the results observed. In order to address this question GH have attempted to define a windiness index for each of the key wind energy regions in North America. Such windiness indices have generally been based on available sources of ground based wind speed measurements. While careful checks have been made to ensure the consistency of the data and the relevance of the wind data to wind farms in the region in question, it is stressed that the results of these indices are only indicative in nature and intended to be used only in this "high level" assessment to attempt to understand the observed discrepancies between actual and projected energy production.

The indicative windiness indices for different regions are presented on a map of North America in Figure 3 below.



Note: indices are windiness – energy variations will be larger

Figure 3 Indicative windiness indices for key US wind power regions in 2007

The 2007 energy production data have been adjusted for windiness using the above indicative indices and, for the subset of data for which availability is available, adjustments have also been applied to adjust production levels to pre-construction availability assumptions. The results of this process are presented in Table 1 below.

	All data (41 wind farm years)	Windiness adjusted (41 wind farm years)	Windiness and availability adjusted (27 wind farm years)
Average ratio Actual/predicted	90%	92%	**96%**

Table 1 Comparison of average to predicted energy production for 2007 data and the effect of correcting production for windiness and to pre-construction availability levels

It can be seen from the above that when the data from the most recent year are considered and when adjustments are made for the influence of windiness and of availability then the average ratio of actual to the predicted energy reduces to within 5 % of the ideal 100 % result.

Although the number of wind farms in the GH database in any given year for years prior to 2007 is somewhat limited, GH has also undertaken a similar process to adjust for observed windiness and availability for all production years prior to 2007. The outcome of this exercise show similar results overall, with the average ratio of actual output to predicted output of approximately 94 % to 96 %.

3 CRITICAL APPRAISAL OF METHODS

GH has undertaken a rigorous evaluation of what elements of energy analysis may lead to a bias in the result. This has involved a very detailed assessment of the 10 minute SCADA data from a range of North American and other wind farms. This process has identified areas where there is potential for bias to be introduced, and where appropriate, amendments have been made to assumptions and methodologies.

The key issues from this process are presented below:

Availability

A previous GH publication [2] has identified the material “ramp up” in availability which is currently observed for North American wind farms. Figure 4 below presents an updated graph showing how the availability levels vary for the North American wind farms over time from construction compared to the equivalent characteristic for wind farms from Europe.

The larger data set which is now available indicates that on average, even by year 4, availability levels of only approximately 96 % are being achieved. Based on this new information GH has amended the availability ramp up characteristic which will typically be applied to North American wind farms, and the characteristic is presented on Figure 4. A detailed discussion of potential causes of the lower availability levels achieved in North America compared with Europe was given in [2]. It is considered that there are a number of reasons why the availability of wind farms will improve with time and therefore GH considers that a “ramp up” is the appropriate model for wind farm availability. Many North American wind farms experience either relatively extreme cold temperature or relatively extreme hot temperature conditions or both cold winter and hot summer conditions. It is considered that such an environment does make faults more likely and more difficult to resolve. Additionally there tends to be a relatively high incidence of meteorological events which may impact availability such as hail storms and lightning. GH have therefore reduced the availability level which the wind farm is assumed to ramp up to until such time as the availability data demonstrate this assumption is no longer appropriate for the North American market. It is stressed that when a full technical review is undertaken this characteristic will be considered on a site specific basis with a detailed consideration of the specific technology and specific O & M arrangements.

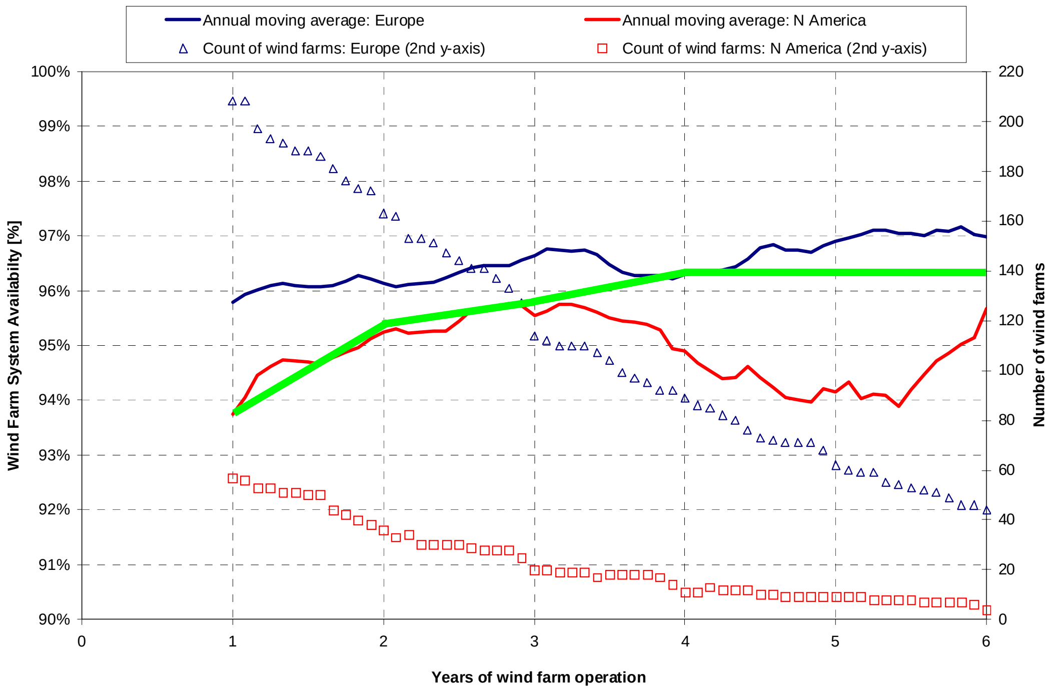


Figure 4 **Comparison of availability with time for North American and European wind farms – Thick green line generic future availability ramp up assumption**

Power curves

GH have used power curve test data and wind farm SCADA data to undertake a critical appraisal of how the turbine manufactures' sales power curve should be interpreted in the context of a pre-construction energy analysis. A comprehensive description of this work and the findings from it are provided within a separate paper presented at AWEA WINDPOWER 2008 [3].

The key aim of the paper was to consider the site specific power curve adjustments which may need to be applied to pre-construction energy production estimates due to the meteorological conditions at a specific wind farm site. The paper also considers how a turbine power curve measured in accordance with the IEC standard should be interpreted in the context of a pre-construction energy assessment. The key findings from the investigation of these issues are summarised below:

Effect of turbulence on a power curve

Analysis of relevant data sets, as described in [3], has demonstrated that for sites with particularly high turbulence levels there is potential for the energy production of the wind farm to be reduced 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—inclusive of wake effects—are more than 15 %. As an example the model defines a reduction in energy of 1 % for a site with 18 % turbulence intensity. A comparison of power curves for 15 and 18 % turbulence intensity to illustrate the degradation of the knee of the power curve for high turbulence levels is presented in Figure 5.

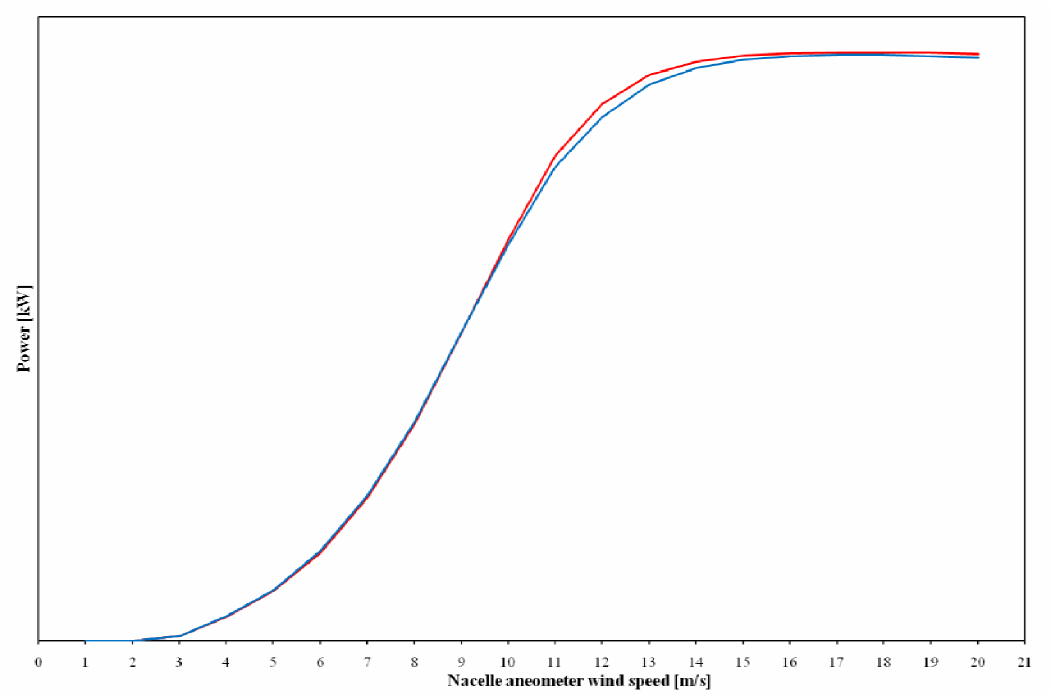


Figure 5 **Example of the degradation of the knee of the power curve for an 18 % (blue line) turbulence intensity site compared with a 15 % (red line) turbulence intensity site**

Effect of upflow on power curve

It is argued in [3] that for sites with significant upflow there is the potential for the energy production of the wind farm to be reduced when compared with flat terrain sites. A model has been developed where sites are characterised into simple terrain and complex terrain categories. For complex terrain sites an upflow power curve adjustment factor is applied. The average upflow is estimated using a model for which the inputs include a directional definition of terrain slope for each turbine, the site wind rose and an assumed dependence of upflow to terrain slope. As an example for an escarpment site with 20 degree slopes and a fairly uniform wind rose the model defines a reduction between 0 and 1 % which will increase beyond that level for steeper slopes or for slopes strongly aligned with prevailing wind directions.

Interpretation of a power curve measured to International Standard IEC 6-1400 Part 12

It is considered that the definition of wind speed provided within wind turbine power curves based on the widely adopted international standard IEC 6-1400 Part 12 effectively includes a blockage effect from the presence of the wind turbine. The issue is illustrated in the schematic diagram presented in Figure 6 below.

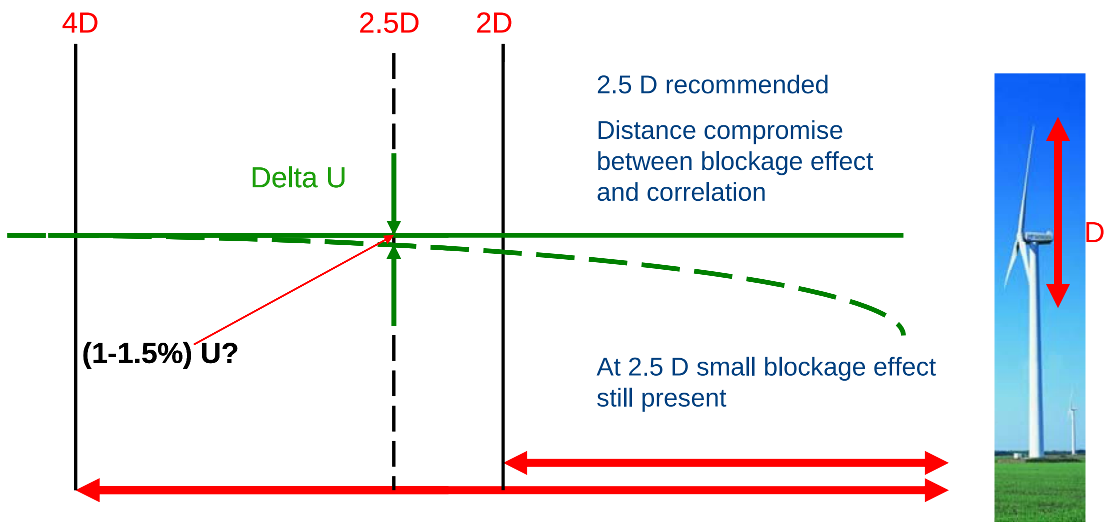


Figure 6 **Blockage effect schematic**

Such a blockage effect is not present for wind speed measurements made on pre-construction wind farm sites and 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 is not implying the power curve has been measured incorrectly, rather that the power curve needs to be appropriately interpreted in the context of a pre-construction energy assessment. A more comprehensive discussion of this issue is provided in [3].

Are turbines performing as they should?

In 2007 and 2008, GH has undertaken a large volume of highly detailed analyses based on 10-minute SCADA data to assess the performance of North American wind farms. From this it is concluded that for significant periods of time for significant numbers of wind turbines the data demonstrate material performance deviations from the expected sales power curve of the machines. It is considered that some of these issues are caused by teething hardware issues, but of more importance typically are software issues which cause the machines to not reach their intended power curve or operate in a non-optimal way. It is considered that it takes time and focus to ensure wind turbines continuously operate as they should. GH has concluded that these performance issues have played a role in the discrepancy between actual and expected energy production. In order to capture these effects for future assessments, GH considers that while there is a ramp up in availability it is also likely that there will be non-optimal control of the machines. GH has therefore assumed that for the same period as the assumed availability ramp up, in this case four years, an allowance will be made for power curve teething issues. A typical allowance for this factor is an effect of 1 % on annual energy production during the period of ramp up. Operational data from wind farms will continue to be reviewed and as typical trends with regard to this issue change then the assumption will change. Additionally, where detailed information about the O&M arrangements has been reviewed this assumption may be changed. An example of the effect is illustrated in Figure 7 below.

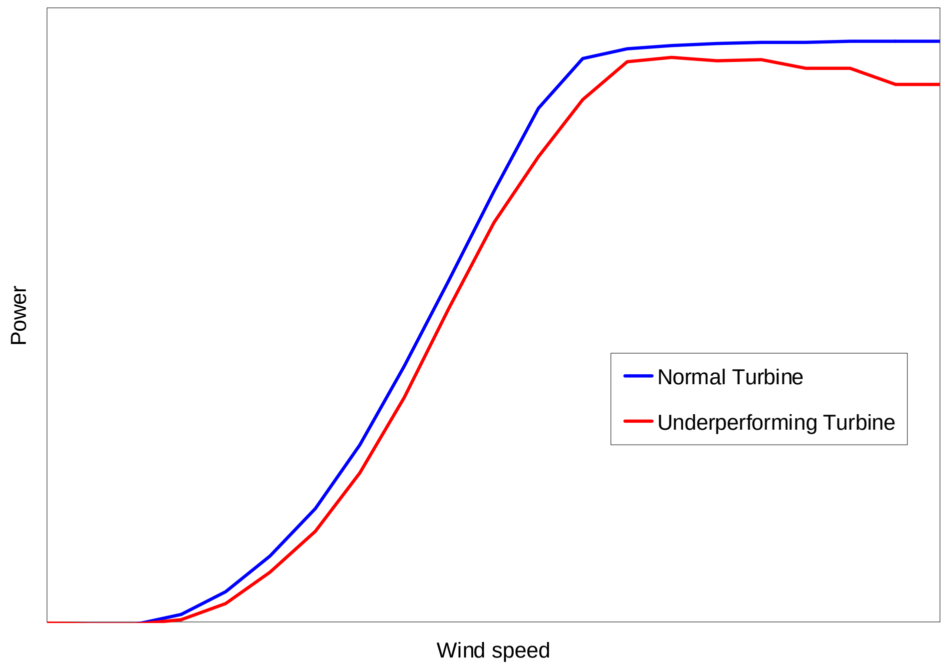


Figure 7 Comparison of normal operation of a turbine with a period of under performance thought to be used by controller related issues

Large wind farm wake effects

Wind turbines extract energy from the wind and downstream there is a wake from the wind turbine where wind speed is reduced. As the flow proceeds downstream there is a spreading of the wake and the wake recovers towards free stream conditions. The wake effect is the aggregated influence on the energy production of the wind farm which results from the changes in wind speed caused by the impact of the turbines on each other. GH has generally used an "eddy viscosity" based wake model within the GH WindFarmer computational model [4, 5] to predict wind farm wake effects. This model has the benefit over the simpler PARK model developed by Risø Laboratory in Denmark in that the site specific turbulence intensity, which wake recovery is sensitive to, is a direct rather than indirect input into the model.

Much of the original validation of the eddy viscosity wake model within WindFarmer was undertaken on what now would be considered to be medium sized wind farms, and as data from large wind farms has become available such data are clearly valuable to extend the validation of the model. Recently constructed large offshore wind farms provide a unique validation data source as the extreme flatness and homogeneity of the sea, when compared with even relatively flat onshore sites, allow differentiation between wake effects and terrain effects which is generally very difficult to achieve onshore.

Validation of wake loss models against actual production from large offshore projects indicates that wake loss models are under-predicting the actual wake impacts under some scenarios [6]. There is currently significant debate over the physical mechanisms which may be causing the observed results to deviate from the predictions obtained with a conventional wake model for large offshore wind farms. GH is currently involved with internal and externally funded research projects aimed at improving modeling techniques for large offshore wind farms. For onshore wind farms, due to the difficulties of differentiating wind speed changes due to wake effects from those due to terrain effects, the quality of the data sets available for validation of wake effects for large onshore are lower. However, it seems likely that the mechanisms which are causing under prediction of the wake effects for large offshore wind farms will also be experienced for large onshore wind farms at least to a certain degree. For large offshore wind farms where under-prediction is observed the following criteria are present:

- The wind farms of approximately 100 MW or more;
- The ambient turbulence is low;
- Many of the turbines have a large number of upwind turbines for significant wind directions.

Given the potential concerns that the standard wake models may start to under-predict the wake effects for onshore wind farms as wind farms become large, GH has developed a pragmatic large wind farm wake model. The large wind farm wake model makes an adjustment to the results obtained with the standard wake model. The model considers the proportion of turbines which may be considered to be in a "deep array" situation similar to that seen at the large offshore wind farms used for the validation work described above. A wake adjustment factor informed by the validation results from the large offshore wind farm is then applied. Ambient turbulence intensity and wind rose are parameters within the model.

Conventional wake models under-predict the energy production of the current largest offshore wind farms by approximately 2.5 %. The result of applying the above large wind farm wake model will reduce the predicted energy production of the wind farm by between 0 and 2.5 %, depending on the specifics of the wind farm. It is stressed that this is a pragmatic model and more sophisticated modeling techniques are in development.

4 CONCLUSIONS

GH maintains an internal energy production validation database which contains actual wind farm production data and GH pre-construction energy projections. The database contains only “high level” information which, as a minimum, includes monthly wind farm production and in some cases more detailed information such as availability.

It is only by looking at large volumes of data that a scientific view on the typical accuracy of predictions can be made. This paper has presented the current results from the energy validation database containing 113 wind farm years of data from North America. GH has focused particularly on the performance in 2007, for which the production of 41 wind farms is considered.

The “raw” results show that predictions have, on average, been over-predictions. Focusing on 2007 production data after adjustments are made to attempt to adjust for windiness in the different regions and to correct availability levels to pre-construction estimates, the predictions are within 5 % of the actual result.

GH has gone through a process to assess what elements of energy analysis may lead to a bias in the result. This has involved comprehensive and rigorous assessments of the 10-minute SCADA data from several North American and other wind farms. This process has identified areas where there is potential for bias to be introduced, and some amendments have been made to assumptions and methodologies where appropriate.

A database of wind farm availability data has been assessed to evaluate what average availability levels are being achieved for wind farms in North America. From this, is concluded that a "ramp up" in availability levels is observed, and GH have revised standard availability assumptions used for pre-construction assessments in light of the latest availability data.

For the period over which availability is ramping up it is frequently observed that wind farms have material loss of energy caused by incorrect setting of wind turbine hardware and software resulting in periods of degraded power curve performance.

GH has critically reviewed the interpretation of the sales power curve as a potential source of bias in energy assessments. From this it has been concluded that, on a site specific basis, adjustments are required to the sales power curve to account for high turbulence and steep slopes. Additionally to account for the potential for "blockage" from the turbine when power curve measurements were originally undertaken an adjustment factor will now be applied.

The validation of conventional wake models was undertaken on what would now be considered to be small to medium wind farms. Data recorded at the largest offshore wind farms—which provide excellent data sources for validation of wake models due to the absence of terrain effects—indicated that there is a tendency for wake models to under-predict the wake losses for the largest offshore wind farms. There is a concern that these influences may also extend to the largest onshore wind farms. GH is therefore now applying a large wind farm wake model adjustment and is working along with many of the leading wind energy research organisations to refine wake models in light of these data.

The net result of the above amendments to GH loss factor assumptions is to reduce the predicted Annual Energy Production by 2 to 5 % depending on the specifics of the site.

It is stressed that high quality wind measurement campaigns are of vital importance for robust wind farm energy production estimates.

5 REFERENCES

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