UNCERTAINTY OF ANNUAL ENERGY PRODUCTION FOR A SPECIFIC TURBINE MODEL BASED ON A SET OF IEC 61400-12 MEASUREMENTS

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Abstract

The IEC 61400-12 is the base of almost any power curve warranty of the past years. As a standard, one or more turbines of a new wind farm project are tested for power performance after commissioning of the wind farm. From the power performance measurements that have been performed by DEWI, 8 measurements according to IEC 61400-12 [1] and MEASNET [2] of the same turbine type were compiled and used for a comparison of the annual energy productions (AEP). The result shows a very small standard deviation of the AEP values at typical wind conditions, although the site conditions varied significantly. By contrast the mean measurement uncertainty of all 8 measurements is clearly higher than the standard deviation of all AEP values. The uncertainty of the single measurements was thereby calculated according to IEC [1] and MEASNET [2]. Thus the uncertainty calculation according to these standards implicates too high measurement uncertainties and the calculation methods should be adapted.

By considering lower uncertainties of the power curve the overall uncertainty for an investor would be significant lower, implicating an increased P_{90} theoretically.

Concerning power performance guarantee contracts the study shows that for wind farms in complex terrain not only the AEP of single turbines should be considered, but an average AEP based on two or three IEC measurements.

1. Introduction

The present study demonstrates that power performance measurements according to IEC 61400-12 [1] and MEASNET [2] can be performed also at complex sites with high quality.

Therefore the considered measurements do not confirm the general opinion that the IEC 61400-12 (often in combination with the MEASNET guidelines) for assessing the power curve has limitations regarding the differentiation of site specific influences on a power curve measurement.

2. Power Performance Measurements

8 power performance measurements according to IEC 61400-12 [1] and MEASNET [2] of the same turbine type were compiled. All relevant turbine parameters as blades, generator type etc. were the same. These turbines were located in five different sites in complex terrain so that site calibrations were required for all turbines. All site calibrations were performed by means of measured ones.

The average terrain slopes range from about 3 to 12 degrees in the measurement sectors for the power performance measurements, outside the measurement sectors also higher terrain slopes are observed. Although the site conditions are complex and therefore not as good as those sites which are usually used for prototype development and testing, the comparison is facilitated as the measuring conditions were identical respectively very similar: The same type of cup anemometer, wind vane, temperature and pressure sensor was used. The mast was of tubular type for each measurement, the top height varied by some meters because the turbine hub height was slightly different.

The comparison of the 8 power curves (see Figure 1) shows only small differences between the single measurements.

Concerning the cp values (see Figure 2) there are some differences in the partial power range between

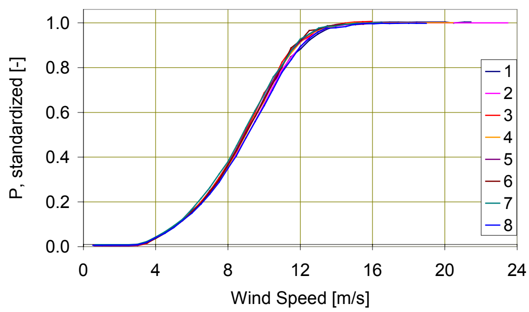

Figure 1: Comparison of Power Curves

the single power curves. The maximum difference between the maximum cp values for all 8 measurements is 5 %. Considering that the turbine No. 7 shows a comparably better power curve and

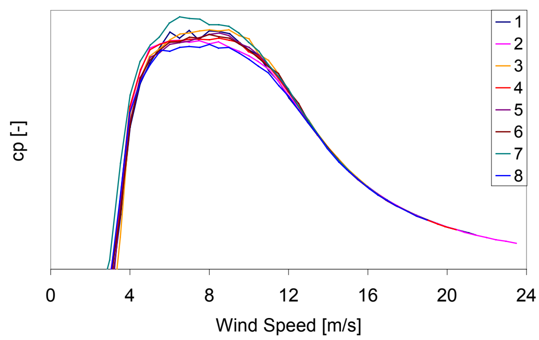

Figure 2: Comparison of cp values

comparing only the remaining 6 power curves, the maximum difference between these maximum cp values is just 3 %.

The low spreading of the 8 power curves is an indication of their high quality and demonstrates that also at complex sites power performance measurements can be very well performed with a representative result.

The high quality of these power performance measurements is also reflected by the low mean deviation of the individual AEP values (see Figure 3). For an annual average wind speed of 6 m/s the standard deviation is only 2.6 % for all 8 measurements. All presented AEP values in this study are extrapolated AEPs (Rayleigh distribution).

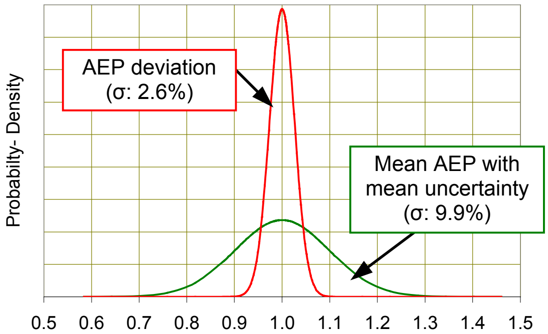

Figure 3: Mean deviation of AEP values and mean total measurement uncertainty for the 8 measurements, for an annual average wind speed of 6 m/s.

DEWI gained similar results from a measurement where a complete wind farm of 9 turbines was assessed with a combination of IEC compliant measurement and nacelle anemometry. For this wind farm the standard deviation of all AEPs was 2.6 %, too, for an annual average wind speed of 5.8 m/s.
Obtaining nearly the same results in terms of AEP deviation for 5 different wind farms in complex terrain in comparison to only one wind farm, is again an indication for the high precision of the considered 8 power performance measurements.

Compared to the mean deviation of the individual AEPs the total uncertainty of all 8 measurements is much higher (9.9 %, see Figure 3). This uncertainty was compiled from the single uncertainties of the individual measurements by means of equation 1.

$$u_{total} = \sqrt{\frac{\sum_{i=1}^{8} u_i^2}{8}} \qquad \text{(Equation 1)}$$

where u_{total}: mean uncertainty of all measurements
u_i: uncertainty of single measurement

The individual measurement uncertainties were calculated according to IEC 61400-12 respectively MEASNET (see section 4).

The deviation of the individual AEPs from the mean AEP is presented in detail in Figure 4.
Especially turbines of one wind farm (No. 1 to 3 and No. 7 and 8) deliver different AEPs, but the mean AEP of the measured turbines in one wind farm is again close to the mean of all AEPs of the other wind farms.

Therefore it is advisable to perform always more than one power performance measurement in a wind farm in complex terrain. Furthermore the mean AEP compiled from these measurements should be the base of power performance guarantee contracts which are sometimes based only on AEPs of single turbines.

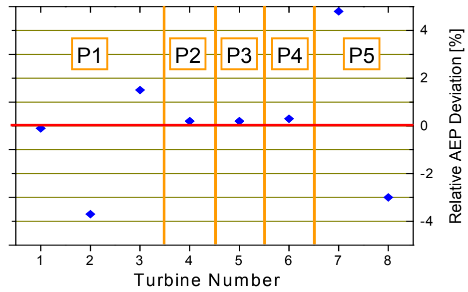

Figure 4: Individual AEP deviation from mean AEP for an annual average wind speed of 6 m/s. The different wind parks (Px) are groupd in addition.

3. Influence of Characteristic Parameters

The influence of different characteristic external parameters on the relative deviation of the individual AEPs from the mean AEP of the 8 measurements (see Figure 4) were investigated.

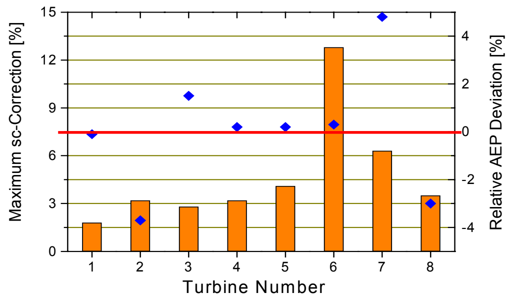

Figure 5: Influence of the maximum correction of site calibration on the individual AEP deviation from mean, for an annual average wind speed of 6 m/s.

The maximum correction of the site calibration does not show significant correlation to the relative deviation of the individual AEPs from the mean AEP (correlation coefficient R^2: 0.07).

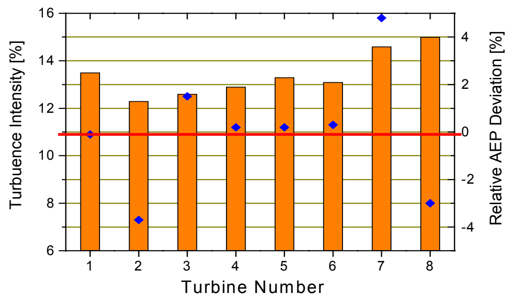

Figure 6: Influence of the turbulence intensity on the individual AEP deviation from mean, for an annual average wind speed of 6 m/s.

There is some small correlation visible between turbulence intensity and AEP deviation. Sites with turbulence intensities higher than 14 % have higher relative deviations from the mean AEP. But as also turbines at sites with a comparably lower turbulence intensity shows an AEP with a higher deviation, no definite correlation can be assessed in terms of turbulence intensity (correlation coefficient R^2: 0.04).

The average distance between reference mast and turbine was 2.5 D for the 8 measurements, which is the IEC recommendation (D: turbine rotor diameter). The single distances range from 2.2 D to 2.9 D. Between these distances and the relative AEP deviation there is some correlation (see Figure 7). The AEPs of those turbines for which the distance between reference mast and turbine shows higher fluctuation from the recommended distance of 2.5 D, higher relative AEP deviations from the mean AEP are observed.

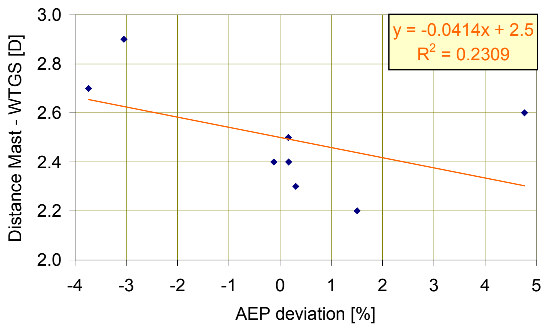

Figure 7: Influence of the distance between turbine and reference mast on the individual AEP deviation from mean, for an annual average wind speed of 6 m/s.

The width of the measurement sectors can be devided into two different classes for the compiled measurements: 20 to 30 degrees and 60 to 70 degrees sector width. Measurements with a larger measurement sector show only small deviations of the individual AEPs from the mean AEP. Higher deviations are observed for smaller sectors.

The analysis of the influences of flow inclination at the site does not show a direct correlation. An inclined flow at the turbine location seems to have no significant influences on the deviation of the individual AEPs from the mean AEP. This corresponds to the known fact that a plane like a rotor is less influenced by external impacts than a single point like an anemometer.
In contrast an inclined flow at the reference mast tends to cause a higher deviation from the mean AEP. It is a known issue that the available cup anemometers have limitations regarding inclined flow. To assess the vertical component of the wind speed at the site in addition it is therefore recommended to perform measurements by means of three dimensional wind measurements.

Additional parameters like density conditions at the site, last complete bin of the power curve and power curve dependency on the wind direction do not show significant correlations to the relative deviation of the individual AEPs from mean AEP.

4. Assessement of Measurement Uncertainty

The large difference between standard deviation of individual AEPs and total uncertainty of all AEPs (see equation 1) has already been presented in Figure 3. Table 1 specifies this result for other annual average wind speeds.

u	Standard Deviation of mean AEP	Averaged Uncertainty see (see equation 1)
[m/s]	[%]	[%]
6	2.6	9.9
7	1.9	7.8
8	1.6	6.4

Table 1: Comparison of AEP uncertainty for different annual average wind speeds u (Base: 8 WTGS).

Generally it should be expected that the average uncertainty reflects the standard deviation of the individual AEPs. But the present results indicate that the measurement uncertainties calculated according to IEC respectively MEASNET are too high compared to the standard deviation of the AEPs. Therefore the uncertainties for these measurements should be calculated lower.

4.1. Measurement Uncertainty of Site Calibration

One type of uncertainty was analysed in detail within the present study: The uncertainty of site calibration. This type of uncertainty was choosen because it clearly differs for all 8 measurements. The other uncertainty contributions were quite similar to each other due to the similar installation of the measurements.
Both standards, the IEC [1] and MEASNET [2], consider two different methods for calculating the site calibration uncertainty. The calculation according to IEC bases only on the maximum correction of the site calibration. The calculation according to MEASNET is more specific, as the uncertainty of the anemometer calibration and data acquisition system as well as the statistical uncertainty of the single site calibration factor in each wind direction bin are considered.
It should be noted that the MEASNET method is identical for the new IEC 61400-12-1 [3].
As the IEC [1] and MEASNET [2] were used for the 8 power performance measurements, the worst case of both standards in terms of the site calibration uncertainty, i.e. the particular highest uncertainty, was considered for the measurement uncertainty calculation. Therefore the average total uncertainties presented in Table 1 consider two different calculation methods for the site calibration uncertainty.
In order to identify whether one of the two calculation methods delivers more realistic, i.e. lower measurement uncertainties, the calculation of the measurement uncertainty was repeated (see Table 2).
Thereby only 6 turbines were considered because the site calibration of two turbines was performed by another measuring institute. As detailed information on the site calibration measurement itself were missing, an uncertainty calculation according to

MEASNET respectively IEC 61400-12-1 could not be performed for those two turbines.

u	Standard Deviation of mean AEP	Averaged Uncertainty[1] (IEC 61400-12)	Averaged Uncertainty[1] (IEC 61400-12-1/ MEASNET)
[m/s]	[%]	[%]	[%]
6	3.1	7.8	7.7
7	2.3	6.3	6.0
8	1.9	5.2	4.9

Table 2: Comparison of AEP uncertainty for different annual average wind speeds u (Base: 6 WTGS). The site calibration uncertainty was calculated by using two different methods, according to IEC 61400-12 and IEC 61400-12-1/ MEASNET.

The results of the remaining 6 turbines still demonstrate the large differences between the mean deviation of the individual AEPs and the calculated average total uncertainties.
Both the calculation method according to IEC 61400-12 and according to IEC 61400-12-1 in terms of the site calibration uncertainty deliver too high total uncertainties under these conditions. No significant differences between the site calibration uncertainty according to both standards were observed in terms of the total uncertainty. One may state that the IEC 61400-12-1 is more realistic because the resulting average uncertainties are slightly lower. But in fact it was observed that the complexity of the terrain directly influences the level of the site calibration uncertainty. For highly complex sites the site calibration uncertainty calculated according to IEC 61400-12 is comparably higher, whereas this uncertainty calculated according to the new IEC 61400-12-1 is higher for not so complex sites.
As three of the compiled 6 measurements are located in highly complex terrain and three in terrain of moderate complexity, these effects are averaged out.

Therefore it is advisable to further improve the IEC standard in order to render the calculated total measurement uncertainty of power curves more realistic.

5. Financial Risk Analysis

Decreased uncertainties of power curves can have significant effects on the financial risk analysis of wind farm projects.
Two exemplary energy yield assessements were conducted for an exemplary wind farm (see Figure 8), considering different total uncertainties. The first energy yield assessment was performed considering a total uncertainty of 11 %, including a power curve uncertainty of 8 %. The second energy yield assessement was calculated with a total uncertainty of 8 %, including a power curve uncertainty of 3 %. The other uncertainty components were the same for both assessments in order to demonstrate the impact of only the power curve uncertainty.
By reducing the power curve uncertainty by 5 % for the present example the P_{90} is increased from 8.6 to 9.0 GWh/a. Thus the P_{90} is increased by 5 %.

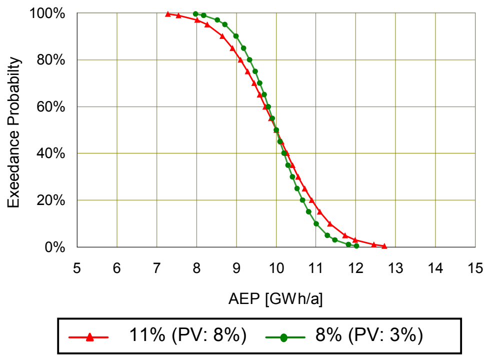

Figure 8: Energy yield assessement with different uncertainties. Wind farm: 5 turbines à 2 GWh/a energy production.

An increased P_{90} within this range would have significant effects on the financial risk analysis of wind farm projects.

6. Conclusions and Outlook

1. The present study demonstrates that also at complex sites high quality power performance measurements can be performed. Nevertheless some deviations are observed for the considered 8 power curves in terms of cp, but the deviation of the individual AEPs from the mean AEP is less than 5 %. This deviation is often the maximum allowable deviation in guarantee contracts.
2. More than one turbine should be measured in a wind farm in complex terrain. Furthermore power performance guarantee contracts for wind farms in complex terrain should be based on the mean AEP calculated from AEPs of two or three IEC measurements.
3. Parameters like the distance between turbine and reference mast and the measurement sector width as well as partly the turbulence intensity and inclined flow conditions indicate to influence the resulting AEP value of a turbine.
4. The calculation of the measurement uncertainty according to IEC 61400-12 and MEASNET delivers too high uncertainties. For the considered measurements the standard deviation of the individual AEPs from the mean AEP is much lower. Therefore it is advisable to further improve the IEC standard in order to obtain lower and more realistic measurement uncertainties.
5. If reduced uncertainties of power curves can be assessed, this would have significant effects on the financial risk analysis of wind farm projects by an increased P_{90}.

7. References

[1] IEC 61400-12: Wind turbine generator system – Part 12: Wind turbines power performance testing 1998

[2] MEASNET: Power Performance Measurement Procedure, 2000

[3] IEC 61400-12-1 Ed.1: Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, Dezember 2005

[1] The averaged uncertainty was calculated by means of equation 1.