

EFFICIENT WIND FARM PERFORMANCE ANALYSIS

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Summary

Deutsche WindGuard has analysed the energy yield of a large number of wind farms during the last couple of years. In many wind farms relatively high losses due to technical non-availability of the wind turbines have been found. This type of energy loss is very dependent on the type of wind turbine. Two cost effective and efficient methodologies for power curve analysis have been developed and fine-tuned. Within many wind farms the wind turbine power curve has found to be no significant problem. However, there are wind turbine models on the market with large deviations of the power curve among the individual machines. From this experience follows the recommendation, in case of doubts about the power curve, to perform a power curve verification at every single machine within a wind farm instead of at exemplary turbines. The most frequent and most significant source of wind farm energy production below expectations has found to be too high wind potential expectations.

1 Introduction

A lower than expected wind farm energy yield may be due to lacking wind potential, non-sufficient technical availability of wind turbines (WT), a non-sufficient WT power curve or a combination of these originates. During the last couple of years Deutsche WindGuard has analysed a large number of wind farms regarding the performance in terms of energy production. Based on that experience cost effective and efficient methodologies for wind farm performance analysis have been developed.

2 Verification of Technical Availability

Two key problems regarding the validation of technical availability of WTs have been identified:

- The definition of technical availability as given by many WT manufacturers and as implemented in the automatically analysis of many WT control systems is not appropriate for the analysis of technical losses due to wind turbine breakdowns. A proper definition would count any standstills of the turbine, where the turbine is not ready for production, as not available times. However, manufacturers often count maintenance times also as available, and then the problem is to distinguish between true maintenance times and breakdowns due to true errors of the wind turbine.
- The percentage of downtimes is often lower than the percentage of energy loss due to downtimes, because most WT breakdowns occur more likely at high wind conditions.

Both problems often lead to too optimistic figures about the loss due to wind turbine non-availability. The true energy loss due to non-availability at the present stage of modern WTs is for the most turbine models in the order of 92-97 % (Figure 1). From a large number of analysed modern wind farms only WTs from one manufacturer reach consistently a technical availability above 98 % in terms of energy production (green bars in Figure 1). Also many of the smaller stall controlled WTs often reach availabilities

above 98 % in terms of energy production (pink bars in Figure 1).

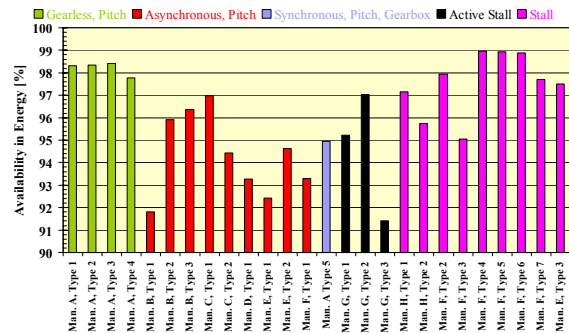


Figure 1: True technical availability in terms of energy production for different types of WTs.

Generally, a high correlation of energy production among wind turbines within the same wind farm is observed (Figure 2).

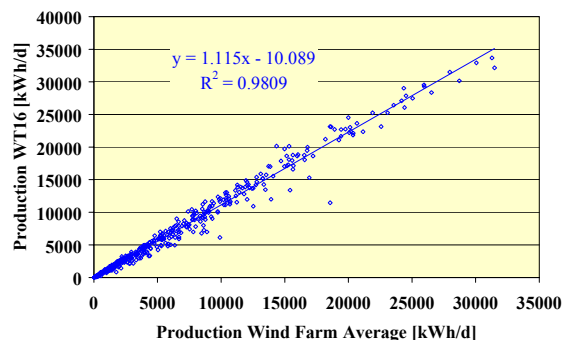


Figure 2: Example of relation between the daily energy production of a WT with the energy production averaged over 20 other WTs of the same wind farm, if all WTs are in operation.

Due to this fact the energy loss due to non-availability can usually be evaluated from the production of neighbouring WTs during the periods of standstill of the investigated turbine with a sufficient accuracy. For this purpose it is useful to evaluate a relation

between the energy production of the investigated turbine and the other WT's within the wind farm during periods where all WT's are available. These relations can then be applied during periods of standstills in order to transfer the energy production of the operating turbines to the non-available WT's.

3 Power Curve Verification

The present standards for power curve evaluation IEC 61400-12 [1] and its revision IEC 61400-121 [2] foresee to measure the WT power curve with the help of a meteorological mast, which reaches hub height and is placed about 2-4 rotor diameters away from the WT. In the practice of WT power curve verification this method is linked to the following problems:

- The cost for masts reaching hub height are high,, especially at today's multi megawatt machines. Also the circumstances linked to the mast erection are often a real hurdle.
- Only up to two WT's can be measured with one mast.
- The measurements can be time consuming due to limited wind direction sectors with the tested WT and the met mast both exposed to free wind conditions.

The typical situation is that the wind farm projects under investigation already suffer from lower than expected energy yields, and thus often there are not much financial resources available for the analysis of the power curve. Also the time needed for the power curve verification is often a critical factor.

3.1 Integral Power Curve Verification

The so-called integral power curve analysis often makes use of an already existing reference data source, and by this it overcomes the typical problems linked to the IEC-method (Figure 1). The term "integral" denotes the fact that the WT power curve is analysed as integral over a wind regime during a reference period. The available wind conditions are gained from the energy production of neighbouring WT's, met masts or a combination of both. The wind conditions are transferred from the reference data sources to the investigated wind farm via flow modelling and wake modelling. Often the uncertainties of the methodology can be minimised by a weighted combination of different independent wind data sources. On the bases of the transferred wind regime and the guaranteed power curve a target energy yield for the reference period is calculated for the investigated WT's under the assumption of 100 % technical availability of the WT's. This target energy yield is compared to the sum of the real energy yield of the investigated WT's during the reference period plus the in advance determined loss due to non-availability of the investigated WT's. The difference between the target energy yield and the real energy yield (plus non-availability losses) can be due to a deviation of the power curve from the guaranteed power curve, or it can be due to uncertainties of the methodology. Thus, the methodology should always

be accompanied by a detailed uncertainty analysis and the results of the comparison must be interpreted under consideration of the uncertainties.

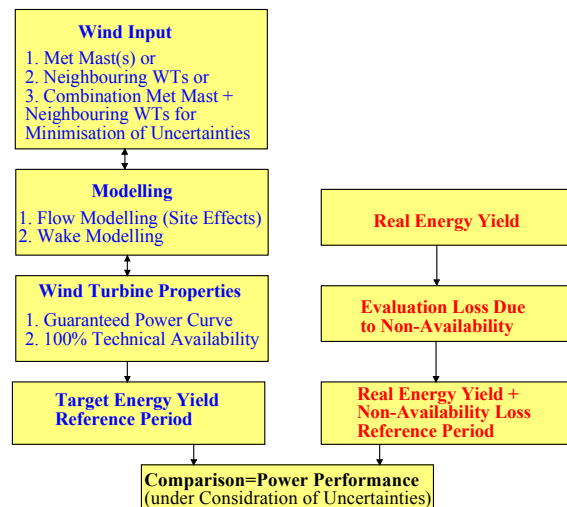


Figure 3: Principle of integral power curve analysis

An example result for an integral power curve analysis is shown in Table 1. In this example large deviations of the power curve of the single wind turbines within the wind farm appeared. Despite the quite high standard uncertainty of the methodology for single turbines the red marked turbines do not reach the guaranteed power curve with a probability higher than 70%. In the shown example, shortly after we finished the analysis, we became aware of the fact that the identified critical WT's all were equipped with different rotor blades than the uncritical WT's.

From a large number of applications the following experience has been gained by the application of the integral power curve analysis:

- Regarding the details of the methodology there are a number of different techniques available, which have to be chosen case sensitive.
- The methodology is well suited for the identification of problematic turbines and is thus a good and low priced starting point for a wind farm analysis. The technical origin for a lower than expected power performance can often be identified by an analysis of the physical properties of the WT's [3].
- The uncertainty of the integral power curve analysis is often a little bit higher than the uncertainty of the IEC-method. The uncertainty usually increases with the complexity of the terrain.
- In many wind farms a homogenous power curve among the WT's has been observed, close to the guaranteed power curve.
- There are a few types of WT's currently on the market with strong fluctuations of power performance among the turbines, what is often due to variations in rotor blades or variations in the WT control settings. Due to this, it does not make sense to verify only the power performance of single WT's (as example) in a wind farm.

WT	Rotor Blade Type	Deviation	Standard Uncertainty	Level of Non-
		Real Yield - Target Yield	Comparison	Exceedance of
		[%]	Real and Target Yield	Target Yield
			[%]	[%]
WT 1	A	-2.4	13	57
WT 2	A	2.4	14	43
WT 3	A	9.4	14	25
WT 4	B	-12.3	12	83
WT 5	C	-10.1	12	80
WT 6	C	-8.9	12	77
WT 7	C	-9.5	13	77
WT 8	C	-0.5	13	52
WT 9	B	-13.6	11	89
WT 10	C	-14.2	11	90
WT 11	C	1.2	11	46
WT 12	C	-2.3	12	57
WT 13	C	-3.7	11	63
WT 14	C	-7.3	12	72
WT 15	A	2.7	11	41
WT 16	B	-12.4	11	86
WT 17	B	-6.5	11	72
WT 18	A	6.5	12	30
WT 19	A	-0.6	13	52
WT 20	A	6.0	13	32
WT 21	A	9.1	14	26
Wind Farm		-3.3	9	64

Table 1: Result of an integral power curve analysis

3.2 Relative Power Curve Verification

The Relative Power Curve Evaluation aims to compare the power curve of a WT during different periods of time in order to observe possible changes, e.g. for evaluating the success of an optimisation of the WT. In order to save cost, SCADA-data can be used for the power curve analysis.

One possibility to realise a relative power curve analysis is to evaluate the wind conditions incident to the rotor on the bases of the nacelle anemometer, corrected to the ambient wind conditions. This has already been described in former publications [3], [4]. Another possibility consists of a side-by-side testing of turbines. Condition for this is that a neighbouring WT exists, whose power curve did not change over the time (denoted as reference turbine). Basic strategy of the side-by-side testing is to compare the relation between the power output in terms of 10-minute averages of the reference turbine and the turbine to be investigated (denoted as test turbine) before and after the change of the test turbine.

An example for a relative power curve measurement is the prototype testing of the new Enercon E-70 E4 machine. Here a neighbouring turbine of type Enercon E-66/18-70-3 served as reference turbine (same hub height as the E-70 E4 prototype). In a first phase of the measurements the E-70 E4 was equipped with the same type 3 rotor blades than the reference turbine. In this first phase the power output of both turbines was nearly equal (Figure 4, black points). Then the rotor blades of the E-70 E4 have been changed against the new design E4 and the power output of the E-70 E4 increased about 14 % compared to the old blades over the entire power range below rated power (Figure 4, red points).

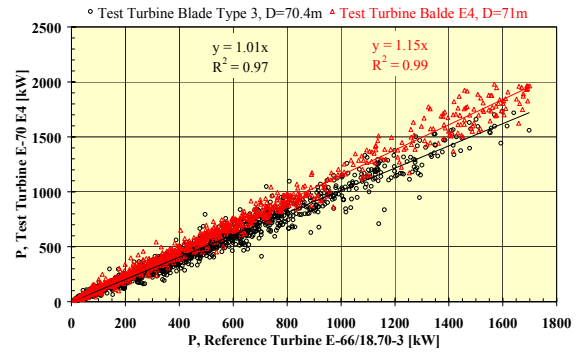


Figure 4: Relation between 10 minute averages of power output of a Enercon E-70 prototype (test turbine) to a neighbouring reference turbine before and after the exchange of rotor blades from type 3 to type E4 at the test turbine.

The relative change of the power curve of the test turbine in terms of power output versus wind speed can also be evaluated with the relative power curve, methodology, only by using SCADA-data. Details about this technique will be presented in reference [5]. The power curve of the Enercon E-70 E4 prototype after the exchange of the rotor blades to the blade type E4 has been analysed with a met mast according to the IEC-standard and by means of the relative power curve using the neighbouring turbine as reference. As can be seen from Figure 5 the raw data of the two power curve evaluations is in good agreement. Also the change of the power curve due to the change of rotor blades as evaluated with the met mast and by means of relative power curve evaluation using the neighbouring turbine as reference is in good agreement (Figure 6). The change of power curve as evaluated by using the relative power curve method is more uniform over the wind speed range than the evaluation via met mast, what might be more realistic.

The following experience has been gained by the application of the relative power curve analysis:

- It is well suited to analyse changes of the power curve of wind turbines.
- It is cheap to apply, as only SCADA-data is needed. Cost for any additional measurements are avoided.
- Usually a larger wind direction sector can be applied than by using a met mast. However, the applicable sector is often smaller than by using nacelle anemometry.
- No air density normalisation is needed, as the procedure is self-normalising.
- The method is less sensitive to site effects than measurements with masts, especially regarding turbulence and wind shear effects on the power curve.
- If more than one reference WT is available, uncertainties can be further reduced.
- Above rated power of the reference turbine no information about the wind speed is available. However, at modern actively controlled WTs this is not very relevant.
- With increasing distance between the test turbine and the reference turbine the correlation of wind

conditions as seen by both turbines decreases. The scatter of power curve raw data is higher than by using nacelle anemometry.

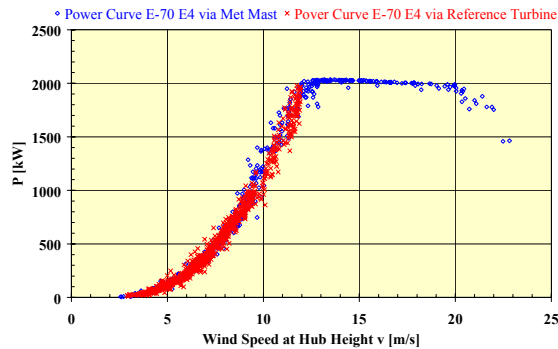


Figure 5: Power curve raw data of Enercon E-70 E4 prototype after change of rotor blades to type E4 as evaluated via met mast (blue) compared to the relative power curve evaluation using the neighbouring turbine as reference (red).

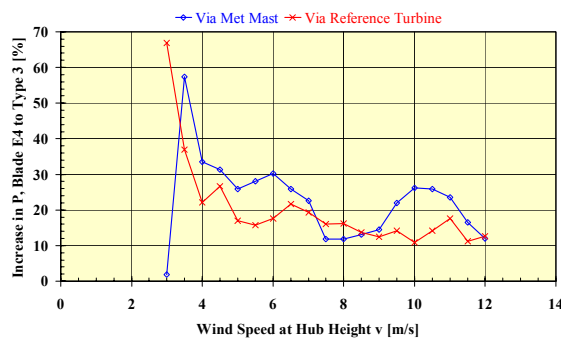


Figure 6: Increase of power curve of the Enercon E-70 E4 prototype due to the change of rotor blades as evaluated via met mast (blue) and via relative power curve evaluation using the neighbouring turbine as reference (red)

4 Verification of Wind Potential

After an analysis of energy production losses due to non-availability and power curve the site-specific wind potential can be verified by the principle of exclusion. Basically the sum of the real energy yield and production losses due to non-availability and power curve are correlated to a long term period. This possible long term energy yield is then compared to the expected energy yield. The difference can be due to a deviation between the real wind potential and the expected wind potential or it can be due to the uncertainties of the evaluation. As a consequence the results must be interpreted under careful consideration of the uncertainties.

5 Conclusions

The following conclusions can be drawn:

- Technical availability is a point of definition and loss due to non-availability should be evaluated in terms of energy production instead of percentage of non-availability in time.

- Integral power curve analysis is a good starting point for a wind farm analysis and offers valuable information for low cost.
- Relative power performance evaluation is ideal for tracking changes of WT power curves and also for investigating the success of optimising WTs.
- Often the site-specific wind potential is overestimated (most frequent origin for lower than expected energy production).
- Often a relative high loss due to non-availability has been observed in the order of 5-10%. However, this is very dependent on the type of WT.
- The WT power curve is often no significant problem. This however is very dependent on the type of WT, the blade configuration and control settings. It is recommended, in case of doubts about the power curve, to perform a power curve verification at every single machine within a wind farm instead of at exemplary turbines.

6 Acknowledgement

Thanks belong to Enercon for the permission to present results from the measurements at the Enercon E-70 E4 prototype and for making available SCADA-data for this work.

7 References

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- [4] A. Albers, H. Klug; Power Performance Verification; proceedings of EWEC1999, Nice
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