Wind Farm Performance Verification

Albers, Axel; Gerhard Gerdes; DEWI

1. Introduction

The economy of a wind farm relies mainly on the available wind potential and the wind turbines' (WT) power performance and technical availability. Recently complains were reported to DEWI from different wind farms about lower than predicted energy production. Without a wind farm performance verification there remains often a large uncertainty about the origin for failing energy production, especially during periods with lower than average wind potential. Hence, it must be recommended to manifest a wind farm performance verification in the contract between developers, financiers and manufacturers.

A performance verification can serve to test the WT power curve guaranteed by the manufacturer and to prove the site assessment including wake effects established by the developer. Wind turbines with unsatisfying performance within a wind farm can be identified and optimised. Furthermore, a long term monitoring of the wind farm performance can help to get aware of performance changes due to ageing and to verify the turbines' availability also guaranteed by some manufacturers. Generally, an optimisation of the power performance by just 1 % will shortly return the cost for a long term verification of the WT operational characteristics.

2. Causes for Unsatisfying Energy Production

Possible reasons for a discrepancy between real and predicted wind farm energy production are:

- **Insufficient wind resource assessment.** Often not an unsatisfactory power performance of the wind turbines but an inadequate site assessment is the source for lower than expected energy production. In many cases the wind resource is estimated by meteorological model calculations based on wind data from a meteorological base station in some ten kilometres distance and with often unknown quality and conditions of measurement. Especially in complex terrain the question arises if data from a meteorological station are representative for the investigated site; the wind climate can change drastically on short distances, e. g. 1 km. Furthermore, wind data offered by most meteorological services often attribute to higher uncertainties than required for wind engineering and are often measured at too low heights (mostly 10 m). Another source of uncertainty is the application of flow simulation codes not designed for the terrain in question (terrain inclination, atmospheric stability, transitional region between land and sea) as well as uncertainties in the modelling of wind farm effects (mutual shadowing of wind turbines)
  The uncertainties attributed to energy predictions can be reduced drastically by performing wind measurements at the potential wind farm site at least for the period of one year.

- **Differences in annual wind potential.** According to Ref. [1] the technical available wind potential can change from year to year by about 10 %. Sometimes wind indices (see Ref. [1]) are taken into account when comparing the real wind farm production within a certain period to the long term prediction. It must clearly be stated, that a global wind index describing the yearly wind potential fluctuations for single wind farm locations does not exist. The annual differences in wind potential can be very site specific, they may vary drastically within some ten kilometres distance, and hence a wind index should not be applied to judge the energy production data. Accurate input data for an evaluation of the energy potential during certain periods can be gained from a long term monitoring of wind conditions directly at the wind farm location during the whole lifetime of the wind farm.

- **Differences between real and guaranteed WT power curve.** Unfortunately, some manufacturers still promise unrealistic optimistic power curves to their clients which have not been measured according to quality insuring international accepted guidelines. High reliability and quality of measured power curves are guaranteed by qualified institutions only (accreditation according to EN 45001, MEASNET-members [2]). Most WT manufacturers offer their products based on power curves measured at prototype turbines. Thus a further source of uncertainty can origin from differences between the individual wind turbines and the prototype, e. g. due to non-optimal wind turbine settings. The example shown in Fig. 1 demonstrates that e. g. a small error in the rotor blade's pitch angle can result in a significant reduction of the annual energy production of the wind turbine. As a consequence it is recommended to verify the WT power curve on the bases of measurements in order to optimise the WT operation and to prove the power curve guaranteed by the manufacturer. The power performance of wind turbines can also be effected due to ageing of the turbines (wear-off of material) or by environmental impact (rotor blade acridition, dirt on rotor blades). Such effects can be identified by monitoring the WT power performance over the whole lifetime of the wind farm in order to initiate appropriate action, e. g. exchange of components, cleaning of rotor blades.

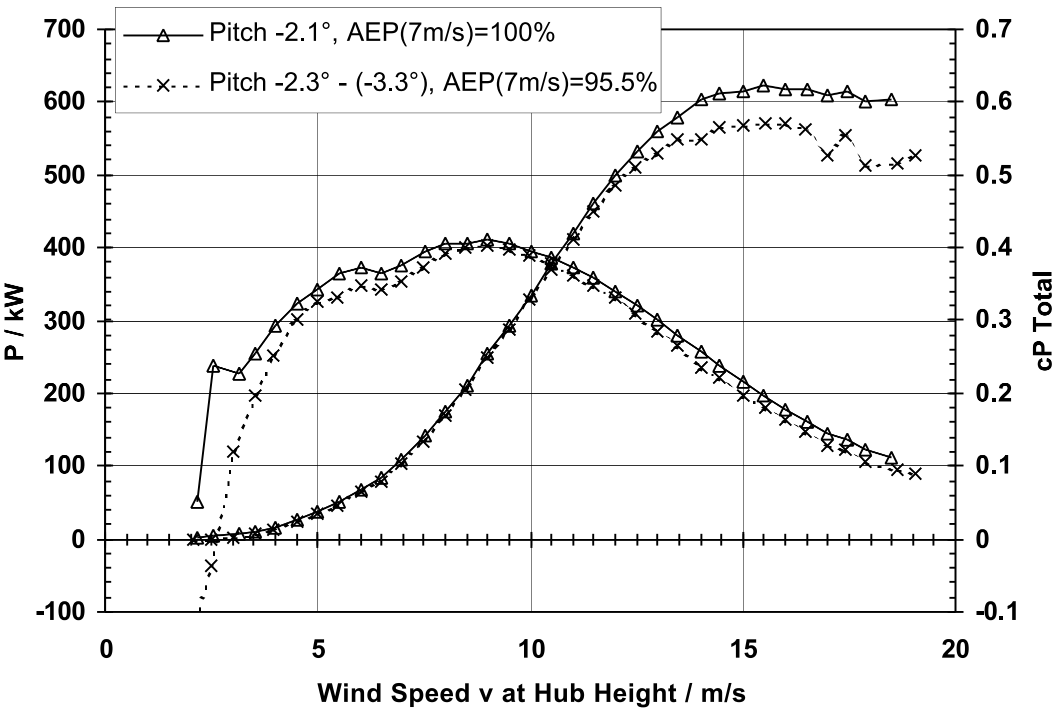

Fig. 1: Power curves of a stall regulated WTGS for different pitch settings. A small imbalance between the pitch angles of different rotor blades of about 1° leads to a decrease of about 5 % in the annual energy production.

- **Lower than expected technical WT availability.** The predicted energy production of a wind farm usually relies on a certain level of technical availability of the wind turbines. Most WT manufacturers also guarantee the level of technical availability to their clients (e. g. WT during 98% of the year available). The problem of this kind of warranty is, that the periods of non availability can fall into periods with strong winds and hence the loss of energy production can be much larger than expressed by the percentage of non availability. For instance a technical availability of 98 % can lead to a loss of energy production of 8 % if the 2 % periods of non availability always happen at wind speeds above rated wind speed. Therefore, a proper warranty of the WT availability should also incorporate the possible energy production during a certain period. A long term monitoring of the wind conditions at the wind farm site specially designed to the requirements of the performance verification can serve to prove the technical availability. It must be pointed out clearly, that the monitoring device usually offered by the WT manufacturers for supervision of the wind farm operation and fault detection is not suited for this purpose.

3. Methodology

Guarantees given by manufacturers and in some cases additionally by developers are related to either one or a combination of the following items:

- power curve
- technical availability
- wind farm efficiency and
- energy yield.

The warranty on energy production for a long time period is alternative to warranty on the first three items. Guarantees on power curve can be verified by measurements described in chapter 3.1; power curve and farm efficiency by the method in chapter 3.2 and 3.3 and the complete set of items by the procedure in chapter 3.4.

3.1. Power Curve Measurements at Single Wind Turbines via Met Mast

The existing standards for power performance tests at WT (Ref. [3], [4]) foresee power curve measurements with the help of a meteorological mast (met mast). The electrical power of a single WT is considered as function of the wind speed at hub height, which is measured at top of the met mast. From this relation the annual energy production of the single wind turbine can be calculated if the frequency distribution of wind speeds at the WT location is known. The uncertainty of such power curve measurements lies in the range of 5-10 % in respect to the resulting annual energy production, while the main uncertainty source is due to the wind speed determination. The distance between the met mast and the tested WT is chosen between 2-4 rotor diameters as compromise between good correlation of measured wind data and wind climate relevant for the wind turbine (short distance) and avoidance of wind blockage by the WT at the mast location (long distance). For the data evaluation only such wind directions can be considered in which the met mast as well as the WT are within undisturbed air flow, i. e. no flow disturbance by wind obstacles or other wind turbines. In complex terrain a so called site calibration with a second mast located at the WT foundation before the WT erection is necessary to account for terrain induced flow disturbances.

There are some practical drawbacks related to this standard power performance test:

- Due to the distances between WT usually realised in wind farms only up to two WT can be tested with one met mast.
- WT placed in the centre of wind farms can often not be measured because no appropriate locations for met masts exist due to the flow distortion caused by neighbouring WT.
- WT in complex terrain can only be measured if a site calibration was performed before the WT erection.
- The cost for met masts increases nearly exponentially with the hub height.

The standard power performance measurement is usually carried out at each wind turbine prototype and forms often the bases for predictions of the energy production and warrantees given by the WT manufacturer.

3.2. Power Curve Verification via Nacelle Anemometer

A WT power curve verification can be based on wind speed measurements at the WT nacelle. Because the nacelle anemometer is influenced by the flow distortion due to the nacelle body and the rotor blade roots a correction to the unperturbed wind conditions is required. This wind speed correction is dependent on the nacelle's and blade root's geometry as well as on the mounting arrangement of the anemometer on the nacelle and must be specified for each type of turbine by means of mast measurements in the unperturbed air flow, e. g. during the power curve measurement of the prototype turbine according to the IEC standard. Once the wind speed correction for the type of turbine to be tested is specified no met masts are needed for power curve verifications and the high cost for met masts can be avoided. This indeed makes this kind of power curve verification very attractive for wind farm operators and financiers to verify their WT power curves.
For a successful application of the nacelle anemometer for power curve verifications, a number of requirements must be fulfilled:

- The nacelle anemometer must be calibrated in a wind tunnel by a qualified institution according to the MEASNET guidelines [5] (also from the turbine from which the correction was derived). It must be pointed out that wind tunnel calibrations are a critical uncertainty source for all kinds of power curve measurements. This is expressed by the fact, that nowadays within the MEASNET group [4] only the anemometer calibrations from three out of seven measurement institutions are accepted mutually and that only the calibration of these three institutions passed the Round-Robin test described in [6]. The MEASNET guidelines for anemometer calibrations will also be taken over by a new IEA Recommendation „Wind Speed Measurement and Use of Cup Anemometry“ which will be published within the next months.

- The mounting arrangement and the type of the nacelle anemometer must be identical at the turbine to be measured and at the turbine which served for the determination of the correction to the ambient wind speed.
- The type of nacelle anemometer should be insensitive to inclined air flow and its positioning must be chosen properly.
- Wind directions in which the turbine to be measured is positioned in the wake centre of neighbouring wind turbines must be excluded from the power curve evaluation.

A shortcoming of this testing procedure is that the nacelle anemometer correction can be sensitive to the wind turbine settings (e. g. error in pitch angle) and also against inclined air flow in complex terrain. However, recent results show that differences in wind turbine settings can at least be identified by applying the nacelle anemometer even though a quantification of the effect of the different turbine settings on the power curve might be linked to additional uncertainties in single cases.

3.3. Wind Farm Efficiency

This method is used for the verification of the overall performance of a wind farm rather than the performance of individual machines. From the wind farm power output measured at the grid connection point and measurements of the ambient wind conditions with met masts around the wind farm power curves for different wind direction sectors are established (Fig. 2). These directional wind farm power curves are compared with the wind farm output predicted according to the guaranteed WT power curve and the modelling of site and wind farm effects also used in the planning phase of the wind farm. Alternatively, the energy production of the wind farm during a certain period can be compared with the predicted energy production based on the wind speed measurements and the guaranteed power curve.

The method for evaluating the theoretically achievable energy yield within the measuring period consist of a wind speed measurement and a suitable meteorological model and a wind farm model, see Fig 3. The wind speed measurement has to be performed analogous to the measurement described in Fig. 2. Additionally t measurement mast M1 in upwind direction of the wind farm, mast M2 is nacessary for those wind directions for which M1 is disturbed by the wind farm. To gain a well tested calculation model, measurements at additional sites located within the wind farm area should be performed some months ahead of the wind farm installation to make model adjustments possible. The meteorological model has to be suitable for the climatic situation at the wind farm site under consideration and it has to be capable of simulating three dimensional flow in case of complex terrain. As input to the flow model the wind speed over a certain time period, e.g. one month or a year, is used to calculate the wind speed distribution over the entire wind farm area. Based on this wind resource map the energy yield and in addition the losses due to mutual shading of WT is calculated. The result, corrected by losses in the electrical transmission system of the wind farm, is the energy yield that should be achieved by the wind farm for the considered time period. As the case of non available WT is usually not covered by the wind farm modelling, the periods of non availability should be eliminated from the verification process. Then differences between this predicted and the real achieved energy yield are due to deviations in power characteristics, errors during planning (e.g. wrong prediction of shading losses) and of course a certain error in the evaluation. As a consequence the developer can prove the modelling assumptions made for the site assessment and the manufacturer can prove the guaranteed WT power performance.

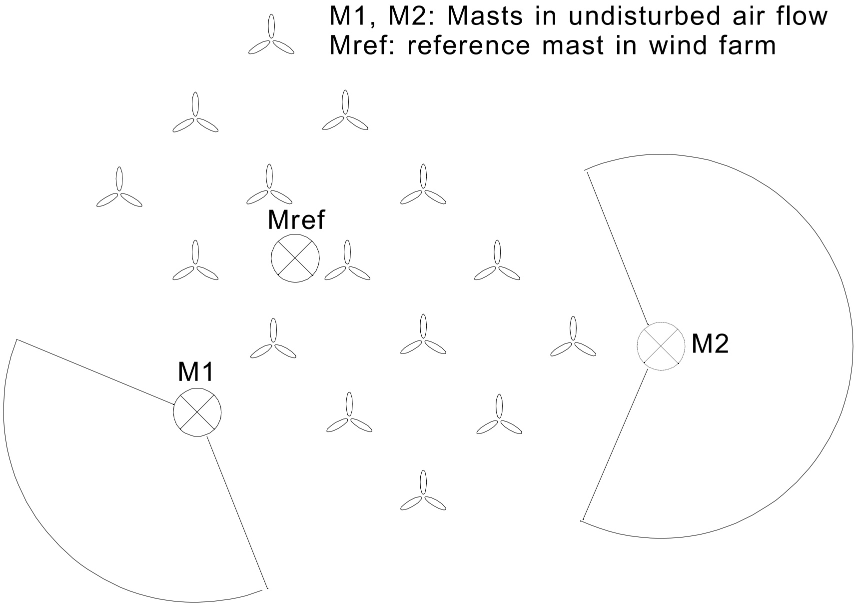

Fig. 2: Typical set-up for measurements of the wind farm efficiency. A reference mast can be installed before the erection of the WT to establish corrections for the wind measurements at the masts M1 and M2 to the centre of the wind farm.

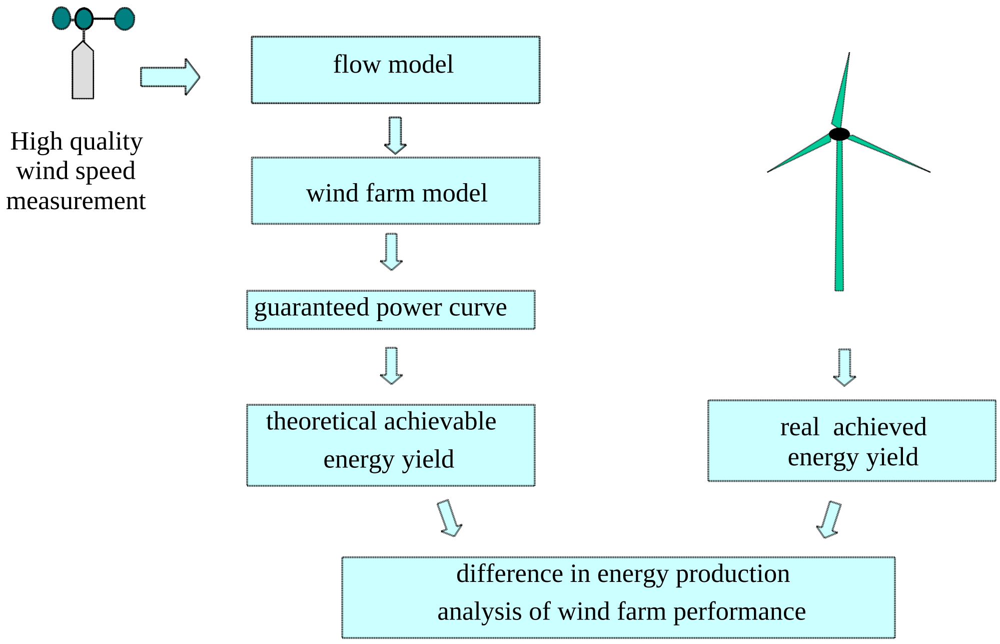

Fig. 3: Principle of wind farm efficiency verification. The energy yield determination based on actual wind speed measurement and the guaranteed WT power curve is compared with real achieved energy production for a certain time period.

Errors in the determination method are due to uncertainties in wind speed measurements, which can be diminished if performed according to IEC standards and with high quality, and in the models itself. In the regions of Northern Germany even boundary layer modells combined with on-site measurements give very good results. In complex terrain flow models have to be used, which are actually still in development.

Recently the IEC has drawn a draft recommendation for this type of performance verification (working group 6).

3.4. Monitoring of Wind Farm Performance and Energy Yield Verification

A different quality of performance verification is the monitoring of the wind farm operation and the verification of energy yield for a long period (e.g. 10 years). This means that the wind conditions and the WT power output will be evaluated during the whole lifetime of the wind farm to check the -possibly guaranteed- energy yield, wind farm power performance and technical availability. Principally, the long term performance monitoring allows to identify all possible origins for unsatisfactory energy production: insufficient WT performance or availability, failing wind resource assessment or seasonal variations of the wind potential. Furthermore, a decrease of the WT performance can be identified and a turbine optimisation can be initiated to avoid unnecessary financial.

The verification of energy yield of a complete wind farm has to be determined by the difference between real energy production and theoretically achievable production over a certain time period. The theoretically achievable energy production has to be evaluated by taking into account the guaranteed power curve plus technical availability and the predicted wind farm losses of the wind farm, as described in chapter 3.3. In case of directly guaranteed energy yield depending on wind conditions these items should also be stated in the contractual documents. Alternatively, the recording of power output and wind speeds measured by the corrected nacelle anemometer can be used to analyse the energy yield of every single turbine in the wind farm. Also a combination of the different methods for the determination of wind conditions can be applied, e. g. wind data from met mast corrected to a WT location can be cross-checked via the corrected nacelle anemometer or wind data derived from the electrical power of neighbouring turbines [7]. Energy losses can be clearly identified and can be used for periodical economic adjustment according to the contractual agreements.

The origin of energy losses has to be analysed in a separate procedure; e.g. the power curve verification via nacelle anemometer as described in chapter 3.2 is an appropriate method to determine the performance of single WT. Alternatively the analysis described in chapter 3.3, by comparing the real gained energy yield with the calculated results for each WT, can be used as the most simple way to gain information for improvement and optimisation of single WT. In addition the application of wind speed measurements during unavailability times gives losses in energy yield due to reduced technical performance.

A further step in the wind farm monitoring is to continuously measure different WT parameters apart from the electrical power, e. g. the yaw misalignment, rotor speed or the pitch angle. These measures can directly be used to find inaccurate WT settings and hence to optimise the turbines.

There are different reasons, why the monitoring performed by the WT control system (mainly for fault detection) is usually not appropriate for the long term performance monitoring. There are specific requirements for the type and quality of the measurements (e. g. the electrical WT power output, wind speed measurement, air density determination) and the data evaluation, which are in most cases not fulfilled by the data recorded by the WT controller. To guarantee a neutral evaluation of data for proofing warranties, the performance monitoring should be carried out by independent institutions.

4. Risk in Energy Production Contra Cost of Performance Verification

Fig. 4 compares the gain in safety in annual energy production with the cost of different kinds of wind farm performance verifications. A conservative estimate for the uncertainty in energy production if no measurements are performed at the wind farm site and no warranties are given by the WT manufacturer or the developer is shown in the left column of Fig. 4. Especially in complex terrain the uncertainty in the resource assessment can be up to 30 % of the predicted energy production, if no high quality wind data from the wind farm site are available. On site wind measurements over a period of at least one year in the planning phase of the wind farm cost usually less than 0.1 % of the total wind farm investment cost and reduce the financial risk attributed to a wind farm drastically (see Fig 4, second column from left).

The possible loss of energy production due to insufficient WT power curves can be reduced by a power curve warranty. A guaranteed WT power curve can be proven only by the measurements described above (chapter 3). The uncertainties associated to the different power performance verification techniques and cost estimates are shown in Fig. 4. Power curve measurements according to the IEC standard and MEASNET at each single machine based on met masts as described in chapter 3.1 offer the best accuracy of about 5 % with respect to the annual energy production. However, for WT in the middle of wind farms this technique is not available and also the cost are much higher than for power curve verifications based on nacelle anemometers (chapter 3.2) or wind farm efficiency measurements (chapter 3.3). Furthermore, instantaneous power curve measurements at each single machine based on the nacelle anemometer as well as measurements of the wind farm efficiency offer the possibility for the developer to proof the applied micro-siting and wind farm model and hence can contribute to shorten the risk for the financier.

From a financier's viewpoint a combination of wind measurements in the planning phase and a wind farm efficiency verification seems to be very attractive, as this reduces most of the uncertainties in energy production, and the cost for both can still be far below 1 % of the total investment cost (see Fig. 4, sixth column from left). The cost for this combination can be lowered by the fact that the met masts used for the resource assessment can also be used for the wind farm performance verification.

A WT manufacturer's warranty of the technical availability of the turbines with respect to the possible energy production can be proven only with a long term monitoring of the wind farm operation.

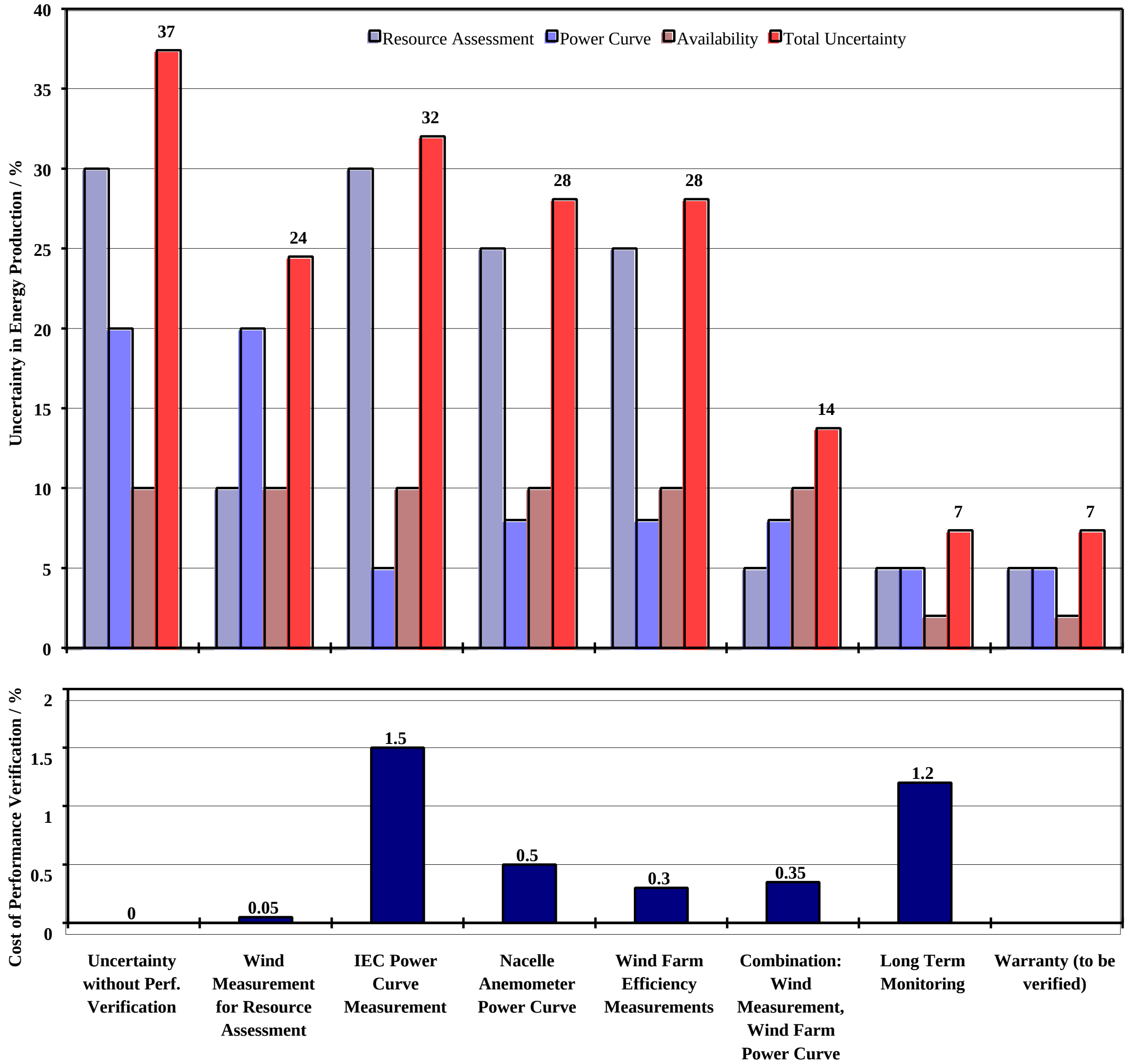

Fig. 4: Upper part: typical risk in energy production of a wind farm if different performance verifications are carried out: no on site measurements at all (left column), high quality wind measurements available for resource assessment (second column from left), all WT power curves measured with masts according to the IEC standard (third column from left), power performance verification based on nacelle anemometry (forth column from left), performance verification by means of wind farm efficiency measurements (fifth column from left), combination of wind measurements before WT erection and wind farm efficiency measurements (sixth column from left), long term performance monitoring (seventh column from left), warranties possibly offered by WT manufacturers and wind farm developers which have to be verified (right column). For each case the remaining uncertainty in energy production split by sources as well as the total uncertainty (square sum of single uncertainties) is displayed. An additional uncertainty in the annual energy production not shown in the graphic is due to annual variations of the wind potential.
Lower part: estimated cost for the verification techniques in percentage of the total wind farm investment cost.

Generally, the long term monitoring offers the possibility to verify all types of warranties (resource assessment, WT power curve and WT availability) and allows to identify changes of the WT performance with time (see Fig. 4, seventh column from left). For the wind farm operator still the risk of variations in the annual wind potential remains (not included in Fig. 4), but with a long term monitoring of the wind farm operation he at least can become aware of the origin for such variations in energy production. Overall the long term monitoring techniques have much to offer compared to its cost in the order of 1 % of the total wind farm investment cost. Moreover, the cost for a combination of wind measurements for resource assessment and a long term wind farm monitoring can be reduced by using part of the data acquisition system for both.

5. Manifestation of Performance Verification in Sales Contracts

Usually wind turbine manufacturers guarantee a certain WT power curve and technical availability to their clients. Unfortunately, in many sales contracts it is not stated clearly how the wind farm performance has to be verified and how the remaining risks resulting from the resource assessment and annual differences in the wind potential shall be handled. As a consequence many wind farm operators give up to verify the guaranteed wind farm performance to avoid differences with the manufacturer (and possible associated costs), even if indications for insufficient wind farm performance exist. On the other hand, often WT manufacturers and wind farm developers can not proof the performance of the sold wind turbines and the accuracy of the resource assessment for reasonable costs in a way accepted by the client. In order to avoid such conflicts between financier, manufacturer and developer it must be recommended to manifest the following matters in the sales contract:

- Who takes the risk for the different uncertainty sources in the wind farm's energy production? Usually the WT power curve and technical availability (in terms of energy production) are on the manufacturer's risk, while the responsibility for the modelling of the micro-siting and wind farm effects (mutual shadowing of turbines) will be taken over by the developer. The risk for the long term wind potential and annual fluctuations of the wind potential remains usually at the wind farm operator.

- Which method will be accepted between the contractors for a verification of the wind farm performance, a verification of the technical availability, and a verification of the resource assessment? It should be agreed on an independent institution, which is supposed to carry out the verification.

- Which tolerances to the guaranteed power curve and technical availability and which error in the resource assessment will be accepted? Which deviations of power curves within a wind farm are allowed?

- When will the performance verification take place?

- In case of insufficient power performance:

which period will be allowed for the manufacturer to optimise the WT? Will there be a verification of the optimised turbines by additional measurements?

- Who will take over the cost, who will order the wind farm performance verification and who will receive the results?
- In order to find practicable solutions for the performance verification it must be recommended to take independent advice from a specialist (DEWI offers such work) additional to legal advice.

6. Conclusions

There exists a large potential of uncertainty regarding the energy production of wind farms. A minimisation of financial risk involved in a wind farm already starts in the planning phase by performing high quality wind measurements at the wind farm location. Once the wind farm is in operation, the origin for a lower or higher than predicted energy production can be identified only by a wind farm performance verification based on measurements. The cost for such a performance verification is usually by order of magnitudes lower than the associated reduction of the financier's risk, at least if the financier, the manufacturer and the developer have agreed already in contract on the details of the performance verification. Furthermore, the wind farm performance verification pays for itself, as soon as the results lead to a small optimisation of the wind farm's efficiency.

Because part of the here presented methods for wind farm performance verifications are still under development and for some techniques only a limited amount of experiences exist, it is recommended to take advice from independent institutions when it comes to a detailed contractional manifestation of wind farm performance warranties.

7. References

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