Uncertainty Analysis of Energy Yield Predictions as Basis for Risk Evaluation of Wind Farm Projects (Unsicherheitsanalyse von Energieertragsprognosen als Basis für die Risikobewertung von Windparkprojekten)

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Zusammenfassung: Die Deutsche WindGuard hat Ansätze für die Unsicherheitsanalyse von Energieertragsprognosen entwickelt, die als Ausgangspunkt für ein Risikomanagement von Windparkplanungen dienen kann. Praktische Erfahrungen bestehen aus einer Vielzahl von Anwendungen dieses Analyseverfahrens für die Bewertung und Optimierung von Energieertragsprognosen. Eine Energieertragsprognose besteht aus verschiedenen, teilweise komplexen, Evaluierungen, angefangen bei Windmessungen oder dem Winddatenabgleich mit Betriebsergebnissen benachbarter WEA, dem Langzeitbezug der Winddatenbasis, der Übertragung der gemessenen Winddaten von den Messpunkten auf die Nabenhöhen und Positionen der WEA mit Hilfe von Strömungssimulationen, der Berechnung der Windparkverluste aufgrund der gegenseitigen Abschattung der WEA und der Beschreibung der Leistungsfähigkeit der Windenergieanlage. Für eine Unsicherheitsbewertung von Energieertragsprognosen muss jeder einzelne Berechnungsprozess und deren Zusammenspiel vorsichtig analysiert werden. Eine Konzentration auf einzelne Komponenten, z. B. der Windfeldsimulation, reicht hierbei keineswegs aus. Die Unsicherheitsanalyse von Energieertragsprognosen erfordert vielmehr detaillierte Spezialkenntnisse auf den Gebieten der Windessungen, der Strömungssimulation und der Messung und Beschreibung der WEA-Leistungsfähigkeit.
Windparkfinanzierer und Projektentwickler haben oftmals verschiedene Standortgutachten für denselben Standort vorliegen, die erhebliche Abweichungen aufweisen. Auf Basis einer detaillierten Unsicherheitsanalyse kann ein Gesamtergebnis aus verschiedenen Energieertragsprognosen eines Standortes abgeleitet werden, derart, dass die Gesamtunsicherheit der abgeleiteten Ergebnisse minimiert wird. Kosten für nicht sachgerechte Maßnahmen der Energieertragsermittlung können vermieden werden, indem bereits im Frühstadium der Projektentwicklung ein sinnvolles Verfahren für die Energieertragsprognose in Abhängigkeit von den Standortbedingungen auf Basis der zu erwartenden Unsicherheiten konzipiert wird.

1 INTRODUCTION

The financial situation of wind farm projects is strongly influenced by the expected energy yield. WindGuard has developed a methodology for the uncertainty analysis of energy yield predictions, which can be used as a starting point for a risk management of wind farm projects. Practical experience exist from a number of applications of this methodology for project due diligence and the optimisation of site assessments.

2 METHODOLOGY

In the past much emphasis had been put on the investigation and improvement of models for flow simulation. By this means it was often neglected that wind modelling is only a small part of the wind farm energy yield assessment. The energy yield assessment basically consists of the following parts:

- wind data input,
- terrain description,
- flow model to transfer the wind data input to the positions and hub heights of the planned wind turbines (WT) under consideration of the terrain description,
- long-term correlation of wind data,
- WT power curve,
- wake model to calculate energy losses due to mutual shadowing of wind turbines within the wind farm,
- thrust coefficient of WT as input for wake modelling,
- consideration of technical losses due to non-availability of the WT, grid and transformer losses, icing, special wind turbine operation (e.g. noise optimised operation).

All these steps of energy yield assessments are linked to uncertainties, which can have the same order of magnitude as the uncertainty of the flow model. Thus, it does not make sense to concentrate on one of the uncertainty factors, when assessing the uncertainty of energy yield predictions. WindGuard rather applies the following scheme for uncertainty assessment:

- detailed assessment of every uncertainty component by means of evaluation of measurement uncertainties, general methods of error propagation, statistical uncertainty analysis, and uncertainty estimates,
- careful cumulating of the different uncertainty components to the overall uncertainty of the energy yield assessment under detailed consideration of the correlation between the different uncertainty components.

3 TYPICAL UNCERTAINTIES

3.1 Energy Yield Assessment based on Wind Measurements

In the usual case energy yield predictions are based on wind measurements. In Fig. 1 typical uncertainties of the wind database are shown for the case of high quality wind measurements directly at the wind farm site and in the case of the use of data from nearby meteorological stations with low measurement heights.

In case of data from meteorological stations the intrinsic measurement uncertainties are often critical. This is due to the fact that often the wind tunnel calibration and mounting of cup anemometers does not follow the best practice as defined in ref. [1]. The low measurement height often present at meteorological stations (standard height 10 m above ground) has different negative aspects:

- The uncertainty of anemometer wind tunnel calibrations decreases with decreasing wind speed. As the wind speed decreases with decreasing height above ground the low measurement height is linked to a higher uncertainty of the wind tunnel calibration.
- The turbulence intensity increases with decreasing height above ground. Thus, higher effects of the ane-

mometer characteristics are present at low measuring heights [2].

- Wind measurements at low heights above ground are likely influenced by nearby wind obstacles (bushes, trees, buildings). The consideration of wind obstacles by means of flow modelling has large uncertainties. Also the influence of the terrain structure (roughness, orography) on the wind measurements is large at low measurement heights.

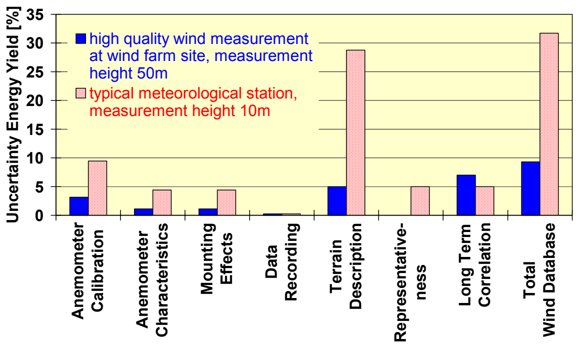

Fig. 1 Typical uncertainties of wind database in case of high quality on site wind measurements and wind measurements from meteorological stations.

As a general rule energy yield assessments based on data from typical meteorological stations are very uncertain as long as no further information about the wind regime in the direct vicinity of the wind farm project is available. Such further information can consist of wind data measured at the wind farm site or of energy production data of nearby wind farms (see next chapter). Typical uncertainties of energy yield assessments based on high quality on site measurements are shown in Fig. 2. Here, the most critical and also case sensitive aspects of site assessment are:

- the quality of measurements,
- the correlation of the on site measurements to a long term period,
- in complex terrain: the flow modelling (transfer of wind regime from measurement point to the hub heights and positions of the projected wind farms,
- the WT power curve.

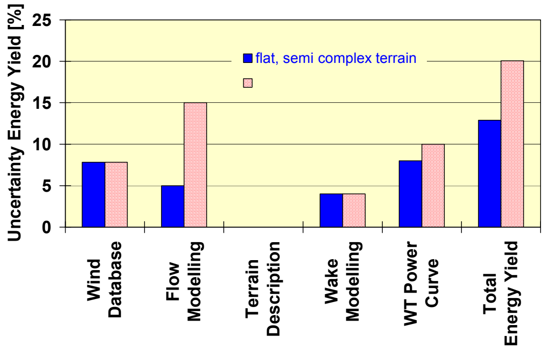

Fig. 2 Typical uncertainty of energy yield assessments in case of high quality wind measurements directly at the wind farm site.

3.2 Energy Yield Assessment based on Operational Data from nearby Wind Farms

In areas with a high wind farm population energy yield assessments can be adjusted to the operational data from existing wind farms in the near vicinity of the projected wind farm (common practice in Germany). The methodology is usually applied in a way that the wind input data or terrain description is adjusted to the long-term energy production of nearby wind farms. These adjustments of input data is however linked to a large number of uncertainty components as is presented in Fig. 3. The most critical aspects are:

- the correlation of the reference wind farm's energy production to a long-term period (especially in complex terrain),
- the power performance of the reference wind farm,
- the technical availability of the reference wind farm,
- in complex terrain: the flow modelling and the representativeness of the adjusted wind input data for the projected wind farm site.

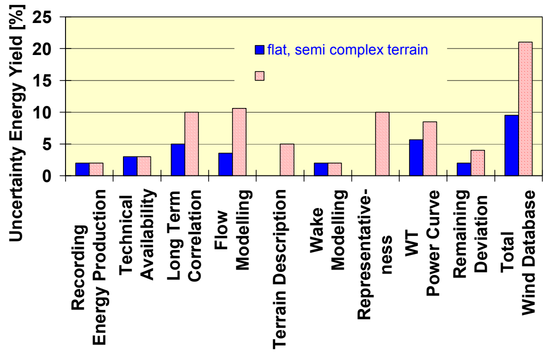

Fig. 3 Typical uncertainty of wind database in case of adjustment of input wind data to energy production of nearby wind farms following best practice.

In practice it has been often observed that the adjustment of the prognosis model or model input data to the production data of reference wind farms is not done with enough care. However, in flat terrain and semi complex terrain nearby reference wind farms can be applied successfully as good anemometers with an accuracy comparable to that of good quality wind measurements directly at the wind farm site if the following conditions are fulfilled:

- a detailed knowledge of the reference wind farm's performance in terms of technical availability and power performance,
- an advanced method for long-term correlation of the energy production data of the reference wind farms is followed,
- if the prediction model, which is to be adjusted, will be fed with a detailed terrain description of the reference wind farm site.

In general a reduction of uncertainty can be gained if different reference wind farms with more than one type of wind turbine and with hub heights close to the hub height of the projected wind farm are available. A new, very promising approach to assess the wind regime by operational data of nearby reference wind farms is to evaluate the time series data of the wind farm monitoring system (SCADA-data). By this means a detailed knowledge of the reference wind farm's technical availability in terms of energy losses and power performance can be gained [3].

Typical uncertainties of the complete energy yield assessment in case of the consideration of reference wind farms are shown in Fig. 4 (for a case of good practice).

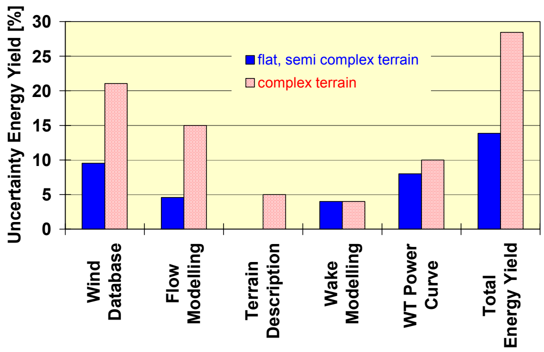

Fig. 4 Typical uncertainty of energy yield assessments in case of high quality adjustment of input data to the energy production of nearby wind farms.

Besides the above described uncertainties of the adjustment of the model input data uncertainties of the flow model (for the transfer of wind regime from the reference wind farms to the hub height and position of the projected wind farm), uncertainties of the wake modelling within the projected wind farm and uncertainties of the power curve of the projected wind turbines must be taken into account. In flat and semi complex terrain an accuracy comparable to that of high quality on site wind measurements (chapter 3.1) can be gained. In complex terrain the uncertainties are usually significantly higher than in the case of on site measurements.

4 SPECIAL ASPECTS OF ENERGY YIELD PREDICTION

4.1 WT Power Performance

WT type specific power curves assumed for energy yield predictions are linked to the following critical aspects:

- The uncertainty of WT power curves increases with decreasing annual average wind speed. This is an additional burden for low wind sites.
- Power curve measurements have found to be influenced significantly by the type of cup anemometer in use [2]. As a consequence the power curve of the projected turbine and the wind database for the energy yield prediction should be adjusted to each other [2].
- Measured power curves have high measurement uncertainties of typically 5-10% in flat terrain and 7-15% in complex terrain in terms of the annual energy production. WindGuard has recently developed a procedure to evaluate a power curve with reduced uncertainty from more than one power curve measurement at the same type of turbine. By repeating the measurements most intrinsic measurement uncertainties are reduced significantly. Also the evaluation of a resulting power curve from a measurement and a theoretical calculation is possible. Wind turbine manufacturers are called to ask for the evaluation of such resulting power curves.
- Theoretically calculated power curves have a high uncertainty of order 5-20% in respect to the annual energy production. This has lately been confirmed by blind tests of the latest WT simulation codes with controlled full-scale wind tunnel tests in the world's largest wind tunnel (NASA Ames wind tunnel) [4].
- At present the WT power performance is characterised only as function of the wind speed at hub height and the air density, even according to the latest revision of the IEC-standard 61400-121 [5]. For turbines currently in the prototype stage with rotor diameters in the order of 100 m significant influences of the vertical wind speed gradient and other flow field parameters on the power performance must be expected [6].

4.2 Long Term Correlation of Database

A large number of procedures exist for the long-term correlation of wind measurements performed at the projected wind farm site. The accuracy of the different methodologies is strongly site and case dependent. The methodology applied for long-term correlation and its uncertainty should be verified for every individual wind farm.

In Germany the so-called IWET-production index [7] is often used for long term correlating the energy production of wind farms (e.g. reference wind farms for site assessment). WindGuard has closely inspected the IWET-Index with the following results:

- In many regions of Germany the index shows a high correlation to the monthly energy production of a large number of wind farms. This is an important precondition for a successful application of the index.
- In the northern part of Germany a tendency of the index to underestimate the technical available wind potential at low wind periods and to overestimate the technical available wind potential at high wind periods has been observed at modern wind turbines. Further south in Germany the tendency is less pronounced to non-existing. This tendency has been found to be strongly dependent on the type (and hub height) of turbine under consideration and can to a large part be explained by the different design (ratio of generator size to rotor area) of the turbines contributing to the IWET-index compared to the design of more modern turbines.
- By definition, the IWET-Index is related to the reference period 1989-1999. Applying a longer reference period can reduce the statistical uncertainty of the index.

As a consequence WindGuard tests the applicability of the IWET-Index and applies self-developed adjustments of the IWET-Index for each individual wind farm under consideration [3]. The statistical uncertainty of the Index's application is significantly reduced by these adjustments, especially when the index is used for long term correlating periods below 6-12 months or periods with extreme wind potential. Overall the IWET-Index has been found to be a useful tool if the above-mentioned aspects are treated properly. At this point wind farm operators are called to deliver the production data to the initiators of the index.

5 UNCERTAINTIES OF ENERGY YIELD PREDICTIONS IN PRACTICE

Fig. 5 presents the deviations between energy yield predictions verified by WindGuard, to the expectation values evaluated by WindGuard for the last 20 wind farms for which WindGuard has been involved as the financier's auditor. At the present stage energy yield predictions for the same wind farm deviate up to 30 %, even for flat terrain sites. Fig. 5 illustrates that it does not make any sense to evaluate an energy yield from different prediction by simply averaging the results, neither does it make sense to use the lowest prediction.

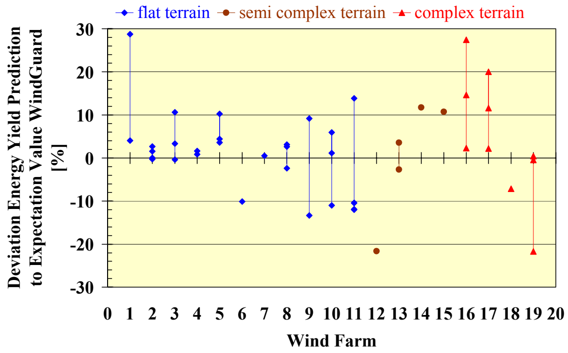

Fig. 5 Deviation of energy yield predictions verified by WindGuard to the expectation value evaluated by WindGuard. For many wind farms different predictions exist.

At this particular point even the best energy yield prediction is linked to significant uncertainties. As a consequence WindGuard has developed a scheme to evaluate a result from different energy yield assessment in a way that the uncertainty of the overall result is minimised.

6 RISK MANAGEMENT

From the predicted energy yield and its standard uncertainty the probability of exceeding certain energy yields can be calculated (Fig. 6). All uncertainties of the energy yield due to technical losses (e.g. technical non-availability of WT, grid and transformer losses, icing or soiled blades) can be incorporated in the probability distribution of the energy yield.

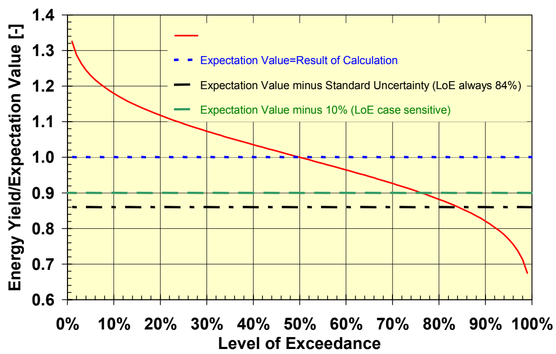

Fig. 6 Probability of exceeding different energy yields (example for 14% standard uncertainty of the energy yield prediction).

For a risk management of the wind farm planning it is recommended to define an acceptable risk for the energy yield (a level of exceedance to be covered) and to select the energy production assumed for the financing of the wind farm according to the corresponding level of exceedance. The remaining risk, that the energy yield falls below this value, can be covered by:

- a proper choice of capital resources for the financing,
- increased reserve capital until the realised wind farm project proofs to produce the assumed energy yield (has to be verified by an independent expert),
- splitting of risk between different wind farm projects.

7 RECOMMENDATIONS

- Uncertainties of energy yield predictions are reality and should not be ignored.
- Uncertainties of energy yield predictions are very case sensitive and should not be treated as a flat rate (what is often seen in Germany).
- The evaluation of the level of exceedance for the energy production can be used as a starting point for a risk management of the wind farm project.
- Site dependent conception of the energy yield assessment by experts is recommended in the early stage of wind farm planning in order to avoid cost for inappropriate surveys and to ease later negotiations with financiers.

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