LONG TERM VARIATION OF WIND POTENTIAL: HOW LONG IS LONG ENOUGH?

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Summary
Energy yield predictions for wind farms rely on the assumption, that the wind potential of the past represents the wind potential of the future operating period of the wind farm. It has been investigated on the basis of historic wind data, how accurate this assumption is. Based on this uncertainty analysis it is recommended that the considered past time period for the wind potential evaluation should cover a duration of at least 30 years. In the German wind energy branch the wind potential expectations are at present strongly oriented towards the wind potential of the 1990's. Different studies by Deutscher Wetterdienst in the filed of climate variations [1], [2] as well as reanalysis wind data [3] indicate that the wind potential of the 1990's was above average conditions. Thus the present expectations in the German wind energy branch might be biased to too high values.

1 Introduction

Energy yield predictions for wind farms are nowadays evaluated on the basis of the long term wind potential of the past. In northern Europe however the wind potential shows large long term variations, even if it is averaged over decades. Hence, the question arises, how uncertain the assumption is that the wind potential of a period in the past repeats over the future operating or financing period of the wind farm of typically 10 to 20 years. The presented investigations are so far concentrated to Germany.

2 Considered Relevant Available Studies

There are two recent studies available from Deutscher Wetterdienst that give good indications about long term wind variations over the past 100 to 150 years. A study by Schmidt [1] investigates the frequency of high wind conditions. Basis for the analysis is data from the geostrophic wind dating back to 1879 at the German North Sea coast, that has been calculated on the basis of air pressure measurements. Relevant results from this study are:

- Since 1879 no real long term trend regarding the wind potential can be observed.
- The long term wind conditions show large variations with the tendency to predominant cycles of about 35 years. The periodicity of the wind conditions is not distinct enough be used for predictions.
- The extreme values of long term wind conditions have a tendency to increase with time.
- The long term variations of wind speed are accompanied by variations of the frequency distribution of wind directions.
- In the first half of the 1990's the wind speeds were at a maximum.

A study by Tinz [2] investigates the relationship between air temperature over northern Europe and the so-called North Atlantic Oscillation (NAO) since 1824. The NAO can be defined as air pressure difference between Iceland and the Azores and is a simple measure for the zonal circulation in the Atlantic European sector. In tendency a high zonal circulation is linked to mild winters and higher wind potential ("high NAO-index" situation, in the winters e.g. 1900-1930 as well as around 1990). The opposite situations are attributed to the "low NAO-index" situation (more frequent in the winters of the 1960's). During the summer, the coupling between the NAO and air temperatures is much weaker than during the winter. Relevant results from the investigation of Tinz [2] are:

- Large variations of the long term NAO-Index have been observed with a minimum (regarding the winter half year) in the 1960's and a maximum (regarding the winter half year) in the 1990's.
- The NAO-Index for the winter half year shows in tendency predominant cycles of about 2 years and about 6-8 years in accordance with other climatological measurements. The NAO-Index for the summer half year shows in tendency predominant cycles of about 3 years, 5 years and 10-20 years. The periodicity of the NAO-Index since 1824 is hardly stable enough in order to be used for prediction purposes.

Both investigations of Schmidt [1] and Tinz [2] indicate a lower than average wind potential in the 1960's, a higher than average wind potential in the 1990's, an increase of the amplitudes of wind potential variations with the time spread over the last century and the absence of a real long term trend regarding the wind conditions.

3 Comparison of Different Long Term Data Sources

3.1 Production Index based on Reanalysis Data
The investigation of Deutsche WindGuard is based mainly on the data from the World Wind Atlas (WWA) as released by Sander+Partner for the period 1950-2003 [4]. The WWA-data consists of wind speeds and wind direction at the height of 50m and 500m above ground as calculated from the NCEP/NCAR reanalysis data [3]. Basis for the WWA-data is the NCEP/NCAR reanalysis wind data on the air pressure levels that correspond to the height levels above

ground surrounding the heights of 50 m and 500 m. The wind speed and wind direction data are available in the form of a sample for every six hours in a worldwide grid with a resolution of 2.5 degrees longitude and latitude.

In order to find one measure that is relevant for the use of wind energy, a wind energy production index has been calculated on the basis of the WWA-data. Basically the power output of a wind turbine has been simulated with the WWA-sample data for the period of 1950-2003. The production index is defined as the monthly average of the simulated power output divided by the average power output over a long term period (called base period). The base period is by definition the period with 100% technical applicable wind potential. The so defined production index is in the following called WWW-index. A production index is fundamentally dependent on the type of turbine, hub height and site-specific wind potential. Consequently, the adjustments explained in reference [5] have been used to make the WWW-index representative for an average modern wind turbine.

A high correlation of the WWW-index with the energy production of wind farms has been observed over large parts of Germany with correlation coefficients between the monthly production data and the WWW-Index usually in the order of R^2=0.90 to R^2=0.98. This high correlation ensures that the WWW-index is a good representative for the relative technical applicable wind potential.

3.2 Comparison of Reanalysis Data and Historic Wind Data

A comparison between the reanalysis data, wind data measured at different meteorological stations and the geostrophic wind as simulated by Deutscher Wetterdienst back to 1879 on the bases of air pressure measurements at the German North Sea coast [1] has been done.

For this purpose wind energy production indices have been calculated on the bases of wind measurement data from seven selected meteorological stations in the German North Sea coast area. The problems with this source of data are inconsistencies due to changes of the measurement equipment, the position of measurements or the surrounding of the met masts. However, if the production indices calculated from the 7 stations are averaged, a qualitatively good agreement to the WWW-index (based on reanalysis data) has been found (Figure 1).

Furthermore a relation between the annual mean values of the geostrophic wind speed as calculated by Deutscher Wetterdient on the bases of air pressure measurements [1] and the annual mean values of WWW-index at the grid point 7.5°E, 52.5°N has been developed for the overlapping period 1950-2003. Care has been taken to the fact that the used data of the geostrophic wind do not refer to calendar years. Deutscher Wetterdienst has averaged the data from 1st of September to 31st of August [1] for each year, i.e. the WWW-index has also been averaged over the same 12-months periods. The relation between the WWW-index and the geostrophic wind has been used to reproduce the WWW-index at the grid point 7.5°E, 52.5°N for the period 1879-2003. In the following this index is called GEO-index. The GEO-Index shows for most years between 1950 and 2003 a good agreement to the WWW-index (Figure 2), however in the period 1964-1968 the WWW-Index is much higher than the GEO-Index.

The following conclusions can be drawn:

- Even 5-year averages of the technical applicable wind potential in Germany show large variations between 80% and 120% of a long term average.
- At sites with lower wind potential, represented by Figure 2, the variations of the energy production indices are higher than for high wind sites, represented by Figure 1. This is mainly due to the fact that at high wind sites in tendency wind turbines operate more often at rated power.
- The 1990's in Germany had a higher than average wind potential. This corresponds with the above mentioned investigations of the Deutscher Wetterdienst [1], [2].

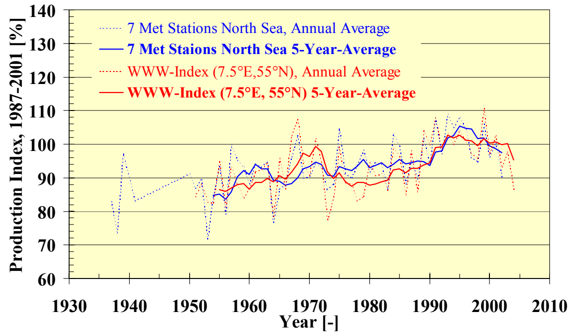

Figure 1: Wind energy production index as calculated from 7 met stations around the German North Sea coast compared to the WWW-index for a grid point in the German Bight.

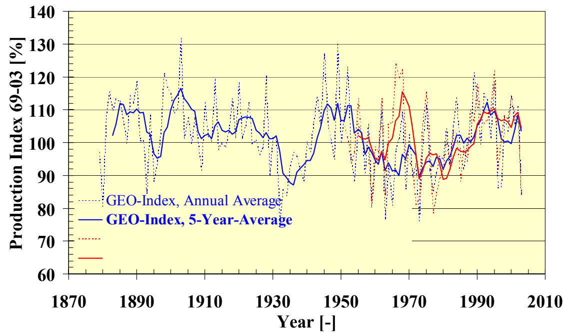

Figure 2: Annual averages of the GEO-index as calculated from data of the geostrohic wind and the WWW-Index at the grid point 7.5°E, 52.5°N (northern Germany). The base period for both indices is 1969-2003.

4 Influence of Lengths of Base Period on Accuracy of Energy Yield Predictions

4.1 Observation

The uncertainty of the assumption that the wind potential of the past will repeat in the future has been analysed in dependence on the choice of lengths of the considered past time period (base period for definition of a period with 100% wind potential). The 125-year time series of GEO-index has finally been used for this investigation, because the 56-year period with available reanalysis data has found to be not long enough. The basic evaluation technique followed was to analyse the differences of mean values of the GEO-index for successive inter annual time periods. The length of the first time period (denoted as past time period) has been varied between 1 year and 100 years. The length of the second time period (denoted as future time period) has been fixed to twenty years as typical operation period of a wind farm project. The considered past periods have been varied as moving periods from 1879 to 1983 and consequently the successive future periods as moving periods from 1880 to 2003.

The standard deviation of deviations between the GEO-indices of successive inter annual periods decreases with increasing lengths of the past time period up to past time periods of about 35 years (Figure 3). This was expected due to the lower arbitrariness of the wind potential in the past time period with increasing lengths of the past time period. However for past time periods with a lengths between about 35 years and about 80 years no further decrease of the standard deviation of deviations with increasing lengths of the past time period is observed. This may be caused by variations of the wind potential with long periodicities. The observed further decrease of the standard deviation of deviations for past time periods above 80 years may be linked to the fact that for such long past time periods successive inter annual periods could be varied only over a range of 25 years or less (as data were available only for 125 years).

The maximum observed absolute deviation between the GEO-index of successive inter annual periods also shows a tendency to decrease with increasing lengths of the past time period up to past time periods of about 35 years (Figure 3). Again the maximum deviation tends to remain constant for past time periods between 35 and 80 years. The further decrease of maximum deviation with increasing past time periods for past time periods above 80 years may again originate from the limitation of data to 125 years for the analysis. The maximum deviation can be interpreted as maximum error in terms of energy production that is linked to the assumption of the wind potential of a past time period of the corresponding lengths to appear again in a successive future period (with a lengths of 20 years).

The common practice for uncertainty estimations is to estimate the so called standard uncertainty [6], i.e. the true energy yield falls in a range of the expectation value plus/minus one standard uncertainty with a probability of 68 %. A good measure for the standard uncertainty is the square root of the square sum of the standard deviation of deviations and the mean deviation between GEO-Indices from successive periods. This uncertainty is shown in Figure 3 as function of the lengths of the past time period (denoted as empirical uncertainty). The empirical uncertainty decreases with increasing lengths of the past time period up to past time periods of about 30-60 years. As a consequence it is recommended to use base periods with a lengths of at least 30 years as base periods for energy yield predictions in northern Europe. It should be pointed out that the magnitude of the uncertainties is strongly dependent on the site conditions (wind potential) and wind turbine [6].

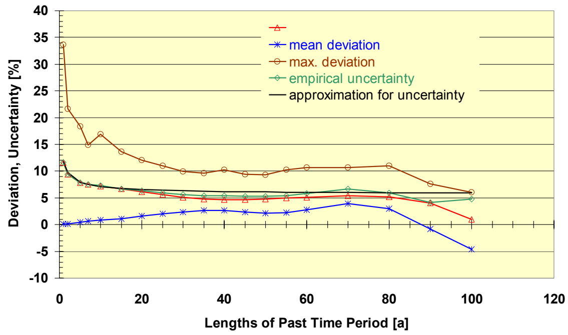

Figure 3: Deviation between the GEO-indices of successive inter annual periods as function of the lengths of the past time period. Shown are for each considered lengths of past time period: the mean deviation between the GEO-Index of the future periods (20 year period) and the past time periods, the standard deviation of deviations, the maximum deviation, the empirical uncertainty in terms of energy production linked to the assumption that the wind potential of the past time period is equal to the wind potential in the future period and an analytical approximation of this uncertainty.

4.2 Model for Uncertainty

In Figure 4 the correlation coefficients of GEO-indices of successive inter annual past time periods and future periods are shown. For past time periods up to 60 years the correlation between the GEO-indices of successive periods is small, indicating independence between the average wind potential in the past time periods and the future periods. For past time periods above 60 years a tendency to a strong anti-correlation between the GEO-indices of successive periods is observed (large negative correlation coefficients), what is assumed to originate from the limitation of the available data for this investigation to a total period of 125 years.

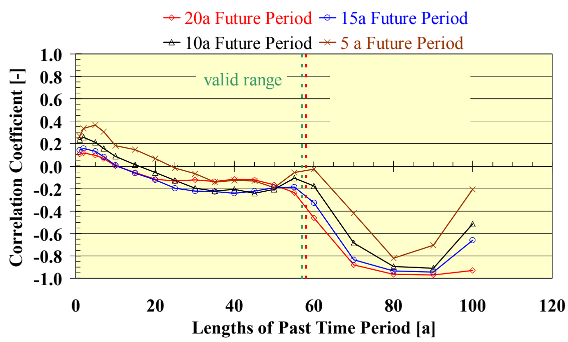

Figure 4: Correlation coefficient between the GEO-indices of successive inter annual periods as function of the lengths of the past time period.

Based on the assumption of independence between wind potential of past time and future periods the standard uncertainty of the approximation that the wind potential of the past time period repeats in the future period can be estimated as follows:

i) Calculation of the standard deviation of annual mean values of the wind potential std_{1a} from the long term data source.
ii) A good approximation for the standard deviation of mean values of the wind potential over n years is:

$$std_{na} = std_{1a} \cdot \left(\frac{3}{4\sqrt{n}} + \frac{1}{4} \right) \quad (1)$$

This formula can be applied for the calculation of the standard uncertainty of the wind potential of the considered past time period std_{Pa} and the future period std_{Fa}.
iii) The total standard uncertainty of the assumption of equal wind potential in the past time and the future period follows from the square root of the square sum of std_{Pa} and std_{Fa}.

The methodology has been tested with different data sources and different lengths of past time and future periods and generally a good agreement has been found (see e.g. Figure 3). Formula (1) has been derived by an empirical analysis of the GEO-Index (Figure 5).

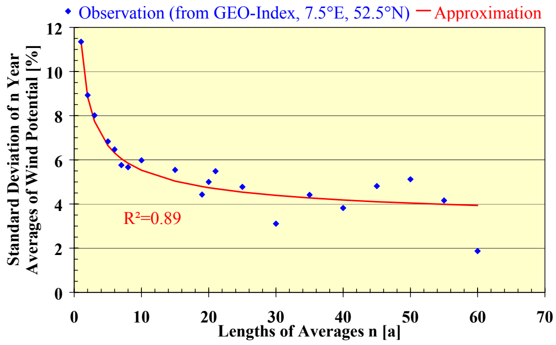

Figure 5: Standard deviation of n year averages of the technical applicable wind potential (GEO-Index) for the point (7.5°E, 52.5°N) compared to the analytical expression given in formula (1).

5 Long Term Variation of Wind Direction Frequency Distribution

Based on the analysis of the reanalysis data the long term variations of the wind potential have been found to be accompained by long term variations of the frequency distribution of the wind direction. In Figure 6 an example of shifts of the wind direction frequency distribution with time for a grid point at the North Sea is schown. In tendecy the frequency of wind directions shifts to oposite directions with the course of time, i.e. shift from northeast to southwest and from northwest to southeast. The long term variations of the wind direction frequency distribution is linked to an uncertainty of wind farm wake losses as predicted from past time wind data.

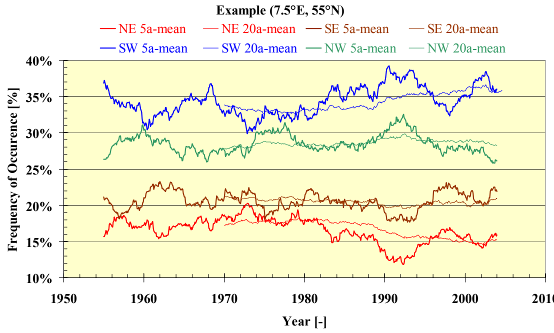

Figure 6: Frequency distribution of wind directions as evaluated form the reanylsis data (World Wind Atlas data at 50m above ground).

6 Situation of Wind Farm Planning and Wind Farm Control in Germany

6.1 General Situation

Energy yield prediction in Germany has often been adjusted to production data of wind farms from the 1990's. Also the IWET production index [7] widely in use by the German wind energy branch was until recently adjusted to the base period 1989-1999 and has been changed at the beginning of 2004 to the base period 1989-2002. However, the investigation of Schmidt [1] and Tinz [2] as well as the WWW-index indicate clearly a higher than average wind potential in the 1990's compared to longer periods.

Position	co-ordinates	1989-1999/ 1969-2003	1989-1999/ 1950-2003	1989-2002/ 1969-2003	1989-2002/ 1950-2003
North Sea	7.5E, 55.0N	1.07	1.09	1.06	1.08
North West	7.5E, 52.5N	1.08	1.07	1.08	1.05
Middle-South	7.5E, 50.0N	1.02	0.97	1.02	0.97
Far-South	10.0E, 47.5N	1.09	1.10	1.11	1.12
North East	12.5E, 52.5N	1.07	1.07	1.05	1.05

Table 1: WWW-index averaged over the periods 1989-1999 and 1989-2002 with base periods 1969-2003 and 1950-2003 for five different grid points within Germany

The WWW-indices for the periods 1989-1999 and 1989-2002 are for most regions within Germany about 5 % to 10 % higher than compared to the periods 1969-2003 or 1950-2003 (Table 1). Thus, present expectations of wind potential in the German wind energy branch are likely to be biased to optimistic values.

6.2 IWET-Index

Within the presented investigation a methodology has been derived for the extension of the base period of the IWET-Index [7] to the period before 1989 on the bases of reanalysis data. This methodology basically follows three steps:
i) Derivation of a relation between the WWW-Index and the IWET-index from the common covered period,
ii) Application of this relation in order calculate the IWET-Indices before 1989,

iii) Scaling of the IWET-Index since 1989 to the extended base period.

The relation between the WWW-Index and the IWET-Index gained from step i) can further be used for a check of the stability of the IWET-Index, what has been done for a large number of wind farms nearly all over Germany. In many regions inconsistencies of the IWET-Index in single months caused by a too low and inconsistent number of contributing wind turbines became evident, especially in the early years of the IWET-Index. Furthermore, in many regions a decrease of the IWET-Index with time in certain levels has been found (Figure 7).

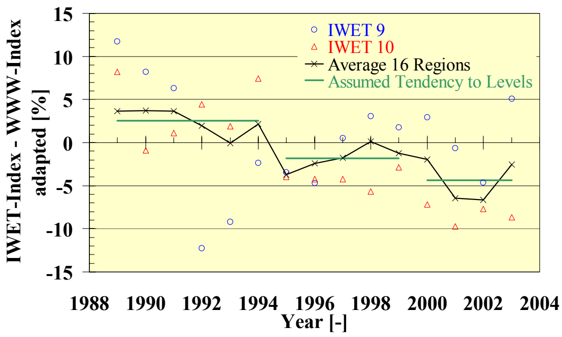

Figure 7: Difference between annual averages of the IWET-Index and the WWW-Index after application of the transformation between the WWW-Index and the IWET-Index.

The borders of these levels are 1994/1995 and 1999/2000. At these times the IWET-Index has been subject to changes of the calculation procedure. Thus, a connection between the tendency to levels of the IWET-Index and the changes of the calculation process of the IWET-index is assumed. Furthermore, the comparison between the WWW-index and the IWET-index has shown, that some IWET-regions (e.g. region 17 and 20) are too large to be well covered by a single index. Consequently, a complete reprocessing of the IWET database and recalculation of the IWET-index is recommended.

7 Conclusions

The following conclusions can be drawn from the presented investigations:

- Long term wind potential variations are linked to significant risks for wind farm projects in the northern part of Europe, mainly because the longest known cycles of the wind potential exceed the expected lifetime of wind farm projects.
- The considered base period for energy yield predictions should cover a period of at least 30 years.
- The wind potential of the 1990's cannot be expected to be representative for the next twenty years, what may lower expectation values of wind farm energy yields in and around Germany.
- A reliable cliamte prediction for the next 20-50 years would be extremly usefull for the planning of wind farm projects.

8 References

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