

On Predictability and Grid Integration of 25 GW German Offshore Wind Power: Simulating the production for the years 2001-2005 with actual NWP data

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The integration of large shares of wind power from large-scale offshore wind farms is very challenging and economically important. In particular, the German 25 GW offshore wind power scenario is very ambitious in this respect. In our study we address the aspect of wind power predictability using state-of-the-art meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF). Weather analysis and forecasted wind speeds in high resolution are analyzed for the years 2001-2005 to show anticipated forecast performance. The aggregation of wind power from regional distributed offshore wind farms is the key factor to reduce the anticipated forecast error significantly. The overall RMSE forecast error is 15% for day-ahead and 21 % for the two-day-ahead.

Error smoothing is particularly strong in high wind situations and helps to reduce the regional forecast error. This is related to the nominal speed of the turbines power curve that can uncorrelate the wind power forecast error from the wind forecast error.

Low wind power production can be forecasted with a higher skill than intermediate production, as these weather situations are linked to stable high pressure systems, which have in general a better predictability.

The variability of load factors for the planned German offshore wind farms are given for the 5 years that had been analyzed. The average is 48.7 % which corresponds to 106 TWh per year. The aggregation of on&offshore wind power increase the availability of wind power in Germany considerably.

1) INTRODUCTION

Reliable and save grid integration of large-scale offshore wind power is of primary importance to push the ambitious German offshore plans forward. The challenge of the goal of 25GW wind power capacity in the German Bight by 2030 [1] is, that it can hardly be solved by experience, but by simulation. That means that the problems with stable grid integration will rather increase than decrease while more and more wind power will be connected. Therefore wise decisions on grid infrastructure and planning of new conventional power plants are needed in the near future.

However, there is no doubt that the integration of high shares of fluctuating wind power will be doable while ensuring stable grid operation. But care must be taken that the costs for required reserve power and regulative power do not render offshore wind power uneconomic for individual stakeholders or the entire domestic economy.

In particular, the *capacity credit* and *predictability* of offshore wind power need to be addressed by research energy meteorologists. The work with weather (wind) data is essential to study the variability and coherence of the fluctuating Renewable Energy Sources (RES) like solar and wind on a pan-European level. The combination of these results with load profiles and conventional power generation will give insight into crossborder flows, required market rules and the capacity credit of RES.

The *predictability* of offshore wind power using Numerical Weather Predictions (NWP) is in the focus of this paper. The predictability determines the amount and respond time of regulative power that is maximal required to balance deviations between actual wind power production, forecasted wind power and deviations in the load forecast.

Spatial forecast error smoothing is known to reduce forecast errors significantly for onshore wind power [2]. As the local concentration of offshore wind power capacity will be much higher than onshore, this new topic is discussed in this paper to show achievable wind power forecasting skills.

The skill of offshore wind power predictions reflects mainly the skill of wind forecasts that are provided by various meteorological services worldwide. The downscaling of forecasted wind speeds from large scale wind fields to single wind farm sites is less problematic offshore than onshore, provided no coastal influences are present, since offshore local conditions are more homogenous. Local effects like locally generated turbulence and distorted air flow due to orographie, obstacles, spatial changes in surface roughness or induced heat fluxes can be disregarded. However, the accurate modeling of the vertical wind profile gains importance as in general much higher wind speeds prevail over sea (typically 10 m/s at 100m height) than over land (7-8 m/s).

Tambke et al. [3] started to investigate the anticipated offshore forecast error in the German Bight for 25 GW offshore wind power. The analysis was done for the year 2004 and a smoothing factor of 0.73 was calculated. The smoothing factor is the ratio between the regional forecast error and the forecast error assuming the whole capacity is concentrated in one point, i.e. all turbines are at the same site.

In this paper the study period of offshore wind power predictability in the German Bight is extended to the years 2001 to 2005 and emphasize is given to the anticipated predictability in extreme situations, i.e. situations with very low and very high wind power penetration. In a first step the probability distribution of anticipated wind power is analyzed to discriminate wind power penetration (Section III). The predictability up to 72h ahead is shown in Section IV and spatial smoothing factors are presented. Section V concludes results and points to future work how to improve current achievable forecast skills. Section II starts to describe the methodology and the used data.

2) METHODOLOGY

The predictability of wind power in the German Bight is simulated using wind forecast data of the European Centre for Medium-Range Weather Forecasts (ECMWF). Wind speeds from vertical high resolved model fields are interpolated to a unified height of 100m. 00UTC and 12 UTC model runs are used up to forecast step 72h.

The simulation of wind power is carried out for 22 planned wind farm projects in the German Bight (Fig. 1) and wind speeds are horizontally interpolated to these sites. The original resolution is $1 \times 1^\circ$ which corresponds to 44km in meridional and 27km in zonal direction at 53°N . The study period is Jan 2001 to July 2005 unless otherwise stated.

For the transformation of wind speeds to wind power a typical multi megawatt power curve is used. The cut-in speed is set to 2.5 m/s, nominal power is reached at 14 m/s and the cut-off wind speed is 25 m/s. It should be mentioned here that in the entire study wind power (production) is used as a dimensionless number that refers to the rated capacity.

The validation of predicted wind power is done with ECMWF analysis data that is available every 6 hours on a $39 \times 39 \text{ km}$ grid. The same interpolations as for the forecast data are applied to these model fields. Wind analysis from operational NWP is a good representation of the true state of the atmosphere according to Tambke et al. [3] who showed the good agreement between FINO1 wind observations in 100m height and wind analyses from the German Weather Service (DWD). The successful use of ECMWF wind speed analyses in the development of statistical wind power algorithms was shown by von Bremen et al. [4].

3) HISTORIC WIND POWER IN THE GERMAN BIGHT

In this section the wind power production for the 22 wind park projects in the German Bight is discussed.

Fig. 1 shows the cumulative distribution of anticipated (normalized) offshore wind power production (green, dashed line). More than 10% of the time nominal power is produced. And about 20% of the time 95% of nominal power is reached. Another 20% of the time the power yield is less than 10.2%. The 20% and 80% percentile are chosen to separate the data set into low, intermediate and high offshore wind power production cases.

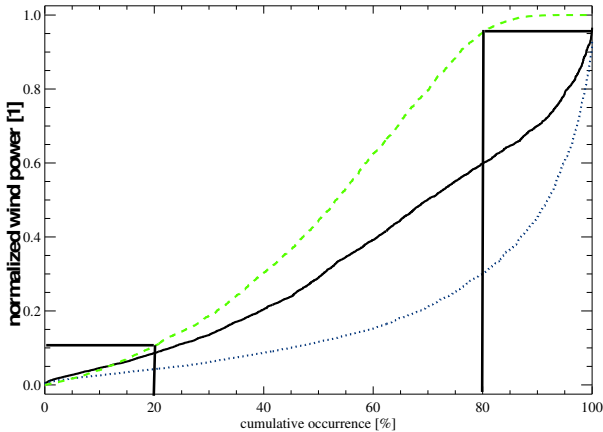


Fig. 1. Cumulative occurrence of anticipated offshore wind power production in the German Bight for Jan 2003-July 2005 (green, dashed line), produced onshore wind power (blue, dotted line) and aggregated on/offshore (black, solid line).

Fig. 1 shows also the (real) onshore wind power production in Germany (blue, dotted line), which availability is much poorer than offshore. The aggregation of on/offshore makes wind power steadier than onshore alone. In that case half of the time about 28% of the installed capacity is available, while 12% are available from onshore wind power.

Fig. 2 shows the intra-annual and inter-annual variability of the load factor. Seasonal differences dominate the variability. The highest power yield is expected in March while the weakest season is the end of the summer (August, September). The strongest seasonal signal occurred in 2001, where the beginning of the year started with high yields of almost 54% of rated capacity. However, in August 2001 the lowest load factor in the whole study period occurred (43.5%). The wind year 2003 was very poor. In all months of 2003 the load factor is lower than the $4\frac{1}{2}$ year average.

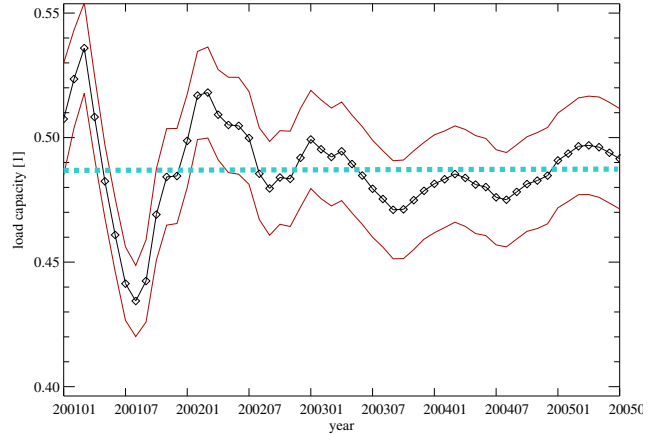


Fig. 2. Monthly load factor for the 25 GW German Wind Power scenario from 2001 to mid 2005 as anticipated from ECMWF wind speed analyses. The enveloping lines represent the standard deviation among the 22 wind farms. The straight line marks the average load factor of 48.7%. The enveloping red lines show the standard deviation that exists between the individual wind farms.

The average load factor for the planned wind projects in the German Bight is calculated with ECMWF wind analyses and is 48.7% of the rated capacity. This leads to an anticipated average annual wind power yield of 106 TWh for the 25 GW scenario. The equivalent full-load hours are 4350h.

4) PREDICTABILITY

In this section the anticipated skill for wind power forecasts for the planned wind parks in the German Bight is studied. The validation is focused on the normalized RMSE error, which is depicted every six hours against the forecast step (Fig. 3). The forecast error is shown for all 22 wind parks individually. The average forecast error is the bold solid line (yellow with \bullet). The skill of an aggregated forecast (green line with \times) is considerably higher as forecast errors are balancing each other (spatial error smoothing). The RMSE ranges from only 7% at forecast step +6h to 23.5% at forecast step +72h.

The beneficial effect of spatial error smoothing is expressed by the smoothing factor that is defined and discussed in more detail at the end of this section.

4.1 Low and high wind power production

It is of interest for the integration of wind power to know the skill of wind power forecast in the lower and upper limits of possible wind power penetration. Therefore it may give confidence to a transmission system operator (TSO) to know that the occurrence of low wind power penetration is better predictable than other situations. In this case he will calculate

with lower uncertainties when buying the (large) shares of conventional power to substitute the (missing) wind power. The same is true when wind power penetration is high. The TSO would react more conservative when knowing that the expected forecast error is high compared to less conservative when he believes that the forecast error will be small.

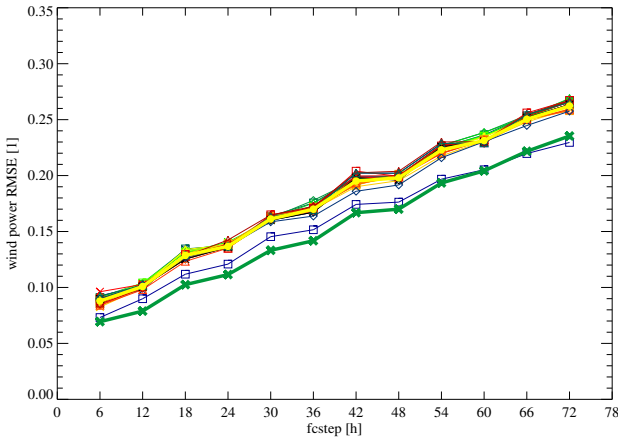


Fig. 3. Root mean square wind power forecast error (RMSE) for the German offshore wind park scenario calculated for the period April 2001-July 2005 with ECMWF data. All thin lines represent the performance for the individual parks and the yellow (solid with ●) the average performance. The lower green line (solid with ×) is the spatially smoothed forecast.

The complete data set is divided into classes of expected (forecasted) wind power production (low, intermediate and high). The intervals of the classes are defined by the occurrence of wind power production (Fig. 1). For each class the forecast performance (RMSE) of the aggregated (regional) forecast is shown (Fig. 4).

In fact, it can be seen that the forecast error is much smaller for low expected wind power production than for the complete data set (Fig. 4, black line). The RMSE is 3% at forecast step 6 and increases to 19.5% at forecast step 72h. The forecast error for all data is 7% and 23.5%, respectively.

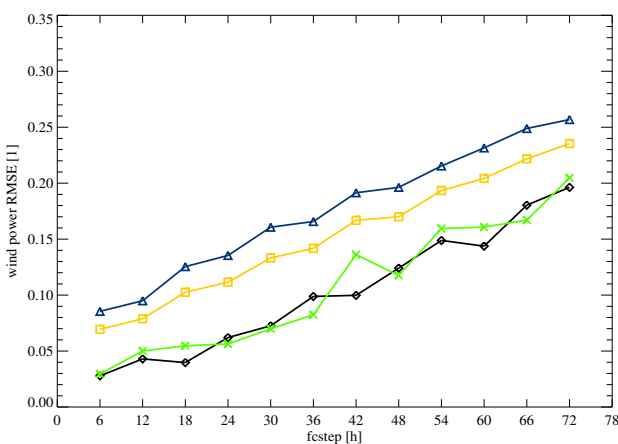


Fig. 4. Root mean square wind power forecast error (RMSE) for the German offshore wind park scenario (April 2001-July 2005). The regional forecast errors are divided into forecasted wind power production classes <10.2% (20% percentile, black, ◇), 10.2-95% (20-80% percentile, blue, △), >95% (>80% percentile, green, ×) and all classes (orange, □).

The forecast error is larger for intermediate wind power production (Fig. 4, blue line) and increases from 8.5 to 26 %. For very high wind power productions (green line) the forecast error is about the same as for low wind power production. The later means full power production can be better forecasted than half power production. This is understandable as wind forecasts in the range of 14 to 25 m/s (dependant on the power curve) correspond to the same wind power forecast, i.e. nominal power. Obviously, the wind power generation and wind forecast error are in this range uncorrelated.

4.2 Spatial forecast error smoothing

The beneficial effect of spatial error smoothing is expressed with the smoothing factor. It is defined as the ratio between the regional forecast error and the forecast error assuming the whole capacity is concentrated in one point, i.e. all turbines are at the same site.

The regional smoothing factor (ratio between the lower green line (solid with ×) and the thick yellow (solid with ●) in Fig. 3 is calculated for each of the three defined power production classes and is depicted in Fig. 5.

Regional error smoothing has the most positive effect in high wind power conditions (green line with ×) up to forecast step +36h. The regional forecast error is only 72% (at day 1) of the error if all wind power is installed in one place, which is given by the average forecast error of all individual wind parks.

Error smoothing is smallest for low wind power production from forecast step +36h onwards. The smoothing effect is considerably lower (the factor is higher) than for the other two classes with higher wind power production.

The overall smoothing factor (orange, □) ranges from 0.82 at day 1 and 2 to 0.88 at the end of day 3.

The reason behind the forecast error smoothing is that forecast errors at individual sites are to a certain extent correlated. The higher the correlation, the smaller is the positive (balancing) effect of regional error smoothing. Or in other words, the more individual forecast errors are uncorrelated, the stronger is the effect of regional smoothing.

For the case of very high wind power production the nominal wind speed of the turbines power curve plays again an important role to understand the high error smoothing up to forecast step +36h. Whenever the nominal wind speed is reached, the correlation of wind power forecast errors drops automatically to zero. This explains the very strong error smoothing in case of high wind power production. Apparently the prediction of wind speeds that exceeds 14 m/s has a good forecast skill up to +36h ahead.

To explain why the error smoothing effect is weaker for low wind power production (black line, ◇ in Fig. 5) the nature of synoptic systems must be analyzed. The correlation between individual forecast errors gets higher the less the whole synoptic situation is characterized by advection. If forecast errors are more dependent on local conditions or developments, then forecast errors of individual adjacent sites are higher correlated, i.e. once the forecast for a region is wrong and the flow is non-advective, future forecasts will also be wrong (with the same sign).

Synoptic systems with low advection are characterized by low pressure gradients and are often more stable than other situations, e.g. persistent high pressure systems. The low pressure gradient gives the link to low wind power.

The benefit of spatial forecast error smoothing is therefore from forecast step +42h onwards highest in advective westerly

weather conditions with intermediate wind speeds and wind power production (blue line, Δ in Fig. 5).

Analysis errors explain why the smoothing factor depends on the forecast step, i.e. the effect of error smoothing declines with the look-ahead time. The relative importance of analysis errors compared to model errors increases with the integration of the forecast model [5]. Thus regional forecasts are affected as a whole and forecast errors are more correlated between single sites. Conclusively, the error smoothing is reduced.

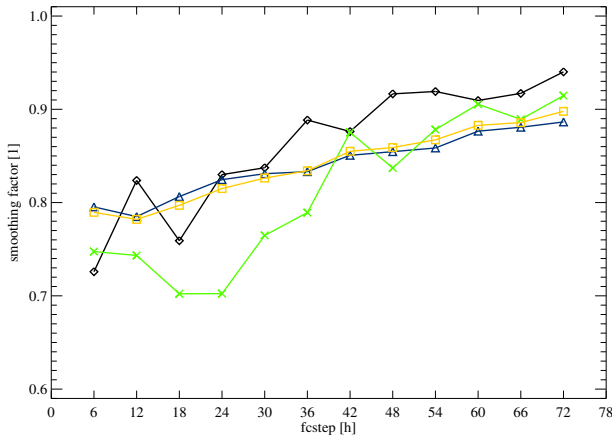


Fig. 5. Spatial smoothing factor for different wind (forecasted) production classes <20% (black, \diamond), 20-80% (blue, Δ), >80% (green, \times) and all classes (orange, \square) in the German Bight, as calculated with ECMWF forecast and analysis data for April 2001-July 2005.

5) CONCLUSIONS

High resolution weather analysis and forecasted wind speeds from the European Centre for Medium-Range Weather Forecasts (ECMWF) are analyzed for the years 2001-2005 to calculate the anticipated forecast performance on a 6 hourly basis. A standard multi-megawatt power curve was used. Preparatory work shows that the load factor of the 22 planned German offshore projects is 48.7%. The aggregation of offshore and onshore wind power ensures that half of the time 28% of the installed wind power capacity is available. Without offshore wind power only 12% are available.

The root mean square forecast error (RMSE) increases from 7% at forecast step +6h to 23.5% at forecast step +72h for the regional aggregated wind power forecast. The average RMSE for day-ahead is 15% of the installed capacity.

It was found that the predictability of either low or high wind power production is considerably higher than for all situations. The nominal wind speed of the turbines power curve makes the wind power forecast independent of the wind forecast error and helps to reduce the wind power forecast error.

On average, the spatial forecast error smoothing reduces the regional forecast error to 82% of the error for a single site for the day-ahead. The error smoothing effect is highest for strong wind situations as the wind power forecast error correlation is minimal when some wind parks reach nominal power.

On the other hand error smoothing is minimal for low wind power production for forecast steps larger than 36 hours. This is due to non-advective weather situations, where local weather developments (as well as errors) are more correlated.

The error smoothing effect declines with increasing look-ahead time as the regional forecast error growth is more and more determined by analysis errors.

When comparing the obtained offshore results with state-of-the-art onshore predictions for Germany, one has to bear in mind that i) the load factor is more than twice as high than over land and that ii) the effect of regional smoothing is considerably smaller. The effective size of the German offshore wind farms is only 180km in diameter, whereas the effective size of the German onshore wind power is larger by a factor of about 3.

Future work will show if the usage of an independent analysis will increase the effect of error smoothing that can be anticipated. The quality of offshore forecasts will improve with increased horizontal and vertical resolution of NWP models, better parameterizations and better initial conditions. In the field of wind power forecasting the combination of output of different NWP models [6] or the use of single-model ensembles [7] has great potential.

ACKNOWLEDGMENTS

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