Advanced Forecast Systems for the Grid Integration of 25 GW Offshore Wind Power in Germany

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Abstract

The economic success of offshore wind farms in liberalised electricity markets strongly depends on reliable short-term (48 hours) predictions of their power output. In the EU-project ANEMOS for wind power forecasts, we investigate the short-term predictability of marine wind speeds and wind power. We found that the accuracies of wind speed predictions provided by the European Centre for Medium-Range Weather Forecasts, ECMWF and the German weather service DWD for the offshore sites Horns Rev and FiNO1 are similar or better than for single onshore sites considering that the mean producible power is twice as high as onshore. A weighted combination of the two forecast sources leads to reduced errors: This combined power prediction for a single site in the North Sea with a hub height of 103m shows a relative root mean square error of 16% of the rated power for a look-ahead time of 36h, while the mean producible power amounts to 51% of the rated power. A regional forecast of the aggregated power output of all projected sites in the German Bight with a total capacity of 25 GW benefits from spatial smoothing effects by an error reduction factor of 0.73, showing an RMSE of 3GW.

1. Introduction

Due to the large dimensions of offshore wind farms, their electricity production must be known well in advance to allow an efficient integration of wind energy into the European electricity grid. In a liberalised electricity market, where balancing power is expensive, the economic value of wind energy strongly depends on reliable information on its availability at least two days ahead. For this purpose short-term wind power prediction systems which are already in operation for onshore sites have to be adapted to offshore conditions. This study aims to estimate the future performance of wind power forecasts for offshore sites. We evaluate the accuracy of numerical wind speed forecasts for potential offshore sites in the North and Baltic Sea.

As predicted wind speed is typically the main input into power prediction systems, its accuracy is vitally important. The predictions were produced by the Lokal-Modell (LM) which is the numerical prediction model of the German weather service (DWD) and by the ECMWF model. For the investigated offshore sites the special meteorological characteristics of the marine boundary layer must be considered to predict the correct wind speed at the hub height of the wind turbines. Compared to the situation over land the situation offshore is different in three ways: the non-linear wind-wave interaction causes a variable, but low surface roughness, the large heat capacity of the water changes the spatio-temporal characteristics of thermal stratification, and internal boundary layers due to the land-sea discontinuity modify the atmospheric flow.

2. Wind power prediction systems

For onshore sites several wind power prediction systems with a time horizon up to 96 hours have been in operational use for many years, e.g. in Germany [1,2]. The physical prediction systems explicitly simulate the phenomena in the boundary layer that influence the power output of a wind farm. The system Previento [3], which has been developed at the University of Oldenburg, follows this physical approach (Figure 1). It is now in operational use for German energy companies (EWE, EnBW, RWE, Vattenfall, E.ON) to forecast the output of 17GW installed wind power.
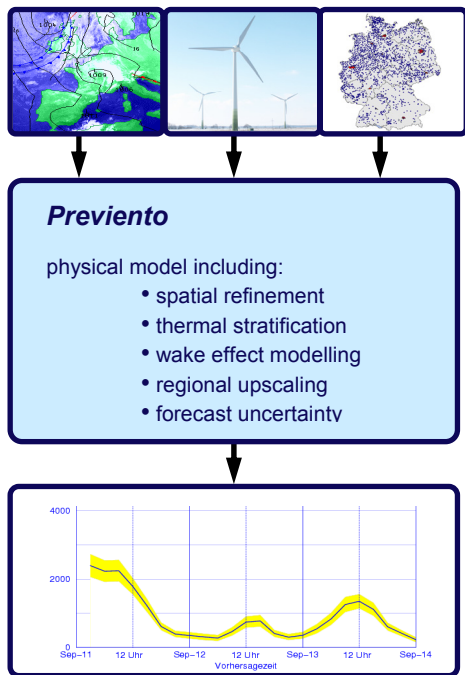
Fig. 1: Previento is a wind power prediction system that is based on physical parameterisations of the atmosphere.

Numerical weather prediction (NWP) systems have a typical horizontal resolution between 7km (DWD) and 40km (ECMWF). They have to be refined considering the local conditions of the specific site, e.g. orography and surface roughness. To calculate the wind speed at hub height, the thermal stratification of the atmosphere has to be taken into account [3]. The wind speed prediction is transformed to power output by the power curve of the wind turbine considering the shadowing effects within wind farms. As a result Previento gives the predicted power output of a specific wind farm. The advantages of ensemble predictions are utilised with an adaptive scheme for the combination of different forecast sources that depends on the current weather situation. In the very short forecast range of 6 hours, the accuracy is increased by a continuous forecast

adaptation with a neural network. Algorithms for the prediction of weather specific forecast uncertainties and an early warning system for erroneous forecasts allow for a sound risk management by the end user.

An independent evaluation by EnBW [11] for the time period Nov. 2004 until June 2005 revealed a root mean square error of 4% of the installed capacity of 17GW for the intra-day trading time range (< 24 hours) and of 6% for the day-ahead interval (24-48 hours). These values are far below those for single sites owing to spatial smoothing of local prediction errors and owing to the use of a large number of different NWP sources from various European weather services.

Previous investigations for onshore sites [2,3,4] showed that the two most important factors determining the accuracy of a single site power prediction are the quality of the numerical wind speed forecast provided by the weather services and an adequate description of the vertical wind profile in different meteorological conditions. We investigate these two aspects for offshore sites.

Fig. 2 shows the positions of investigated sites in the North and Baltic Sea

3. Evaluation of offshore wind speed predictions at 10m height

We evaluated the accuracy of the wind speed forecast of the NWP system "Lokal-Modell" (LM) of the German weather service DWD (www.dwd.de) using measurements of the wind speed at 10m height at several coastal sites in the German Bight and the Baltic Sea and two offshore sites in the North Sea that are far away from the coast, i.e. the lightships "Ems" (denoted as emsx) and "Deutsche Bucht" (deut). Several coastal sites are represented by measurements at the island Norderney (nord), Cuxhaven (cuxh) and List (list) and in the Baltic Sea at the island Fehmarn (west), Boltenhagen (bolt), Warnemuende (rost), Cape Arkona (arko) and the small island Greifswalder Oie (grei).
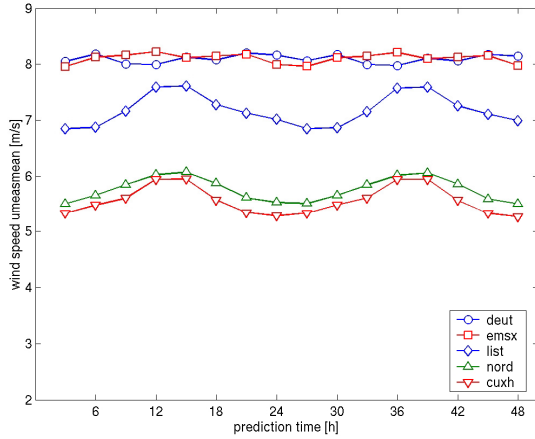
Fig. 3: Annual mean measured 10m-speeds versus look-ahead time of the forecast, North Sea, 2002
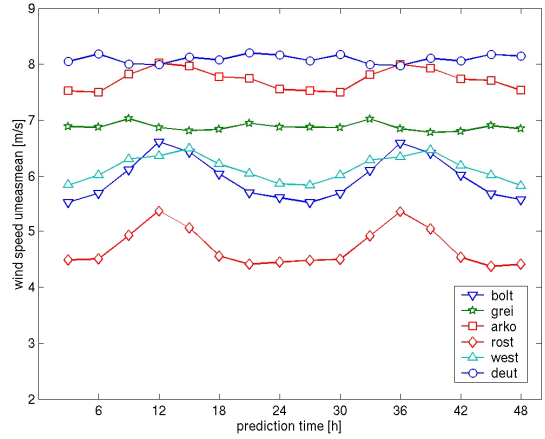

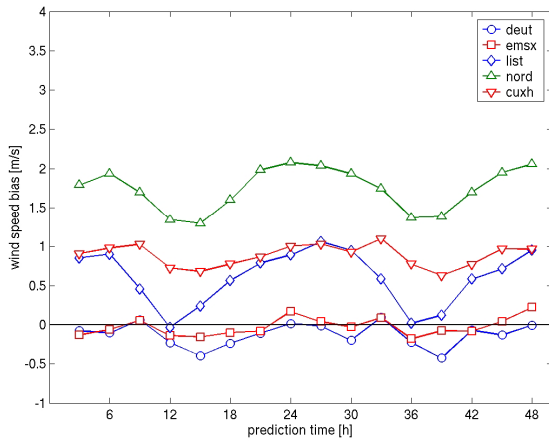*Fig. 6: Annual mean measured 10m-speeds versus look-ahead time of the forecast, Baltic Sea, 2002*

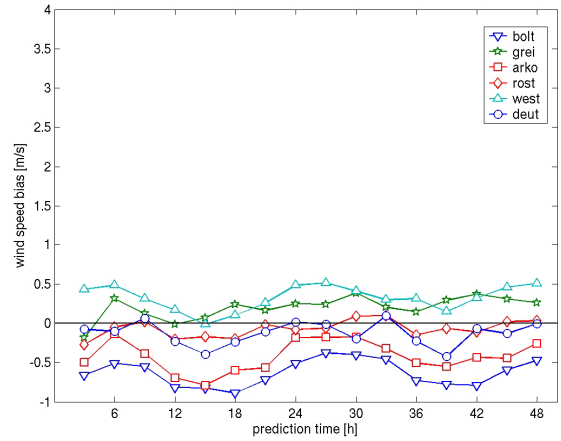*Fig. 4: Annual BIAS = mean[u(pred) - u(meas)], North Sea, 2002*
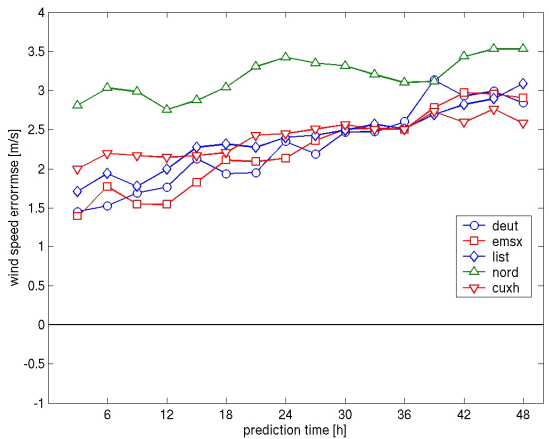

Fig. 7: Annual BIAS = mean[u(pred) - (umeas)], Baltic Sea, 2002

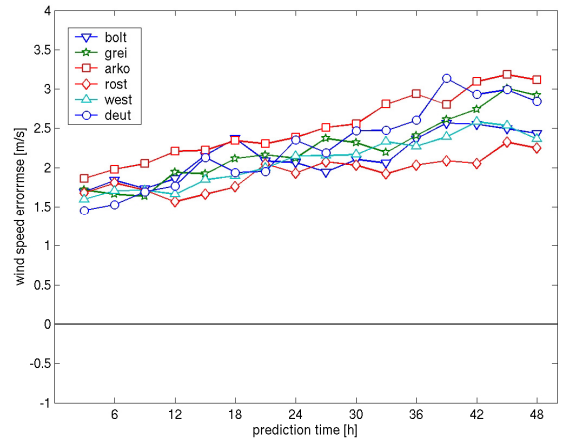*Fig. 5: RMSE of DWD wind speed predictions in 2002, North Sea*

Fig. 8: RMSE of DWD wind speed predictions in 2002, Baltic Sea

The locations are shown in Figure 2. The offshore measurements are affected by flow distortion above the lightships, but are sufficiently accurate for the purpose of forecast verification.

3.1 Error measures

Prior to discussing the results we briefly introduce the error measures that are used in order to improve the comparability to other publications. Let *u(pred)*

be the predicted and *u(meas)* the measured wind speed then the deviation between the two is given by *e := u(pred) – u(meas)*. The root mean square error between the two time series is defined as RMSE := *sqrt[$\underline{e^2}$]* where the underscore denotes the temporal mean of *e^2* and *sqrt* the square root. Using simple algebraic manipulations the RMSE can be decomposed into three different parts which illustrate the origin of the forecast errors. This decomposition has been beneficially used in previous investigations, e.g. [5]. Hence, with the notation from [5] the RMSE is given by

$$RMSE^2 = BIAS^2 + SDE^2$$
(1) $$RMSE^2 = BIAS^2 + STDBIAS^2 + DISP^2$$

where   BIAS := $\underline{e}$, SDE := $\sigma(e)$,
STDBIAS := $\sigma(upred)$ - $\sigma(umeas)$ and
DISP := sqrt[$2\sigma(upred)\sigma(umeas)(1 - r_{p,m})$]

with $r_{p,m}$ denoting the cross-correlation coefficient between the two time series and $\sigma(upred)$ and $\sigma(umeas)$ their standard deviations, respectively. The BIAS accounts the systematic difference between the prediction and the measurement. The SDE measures the fluctuations of the error around its mean (the BIAS) and has two contributors:

i) The STDBIAS is the difference between the standard deviations of *u(pred)* and *u(meas)* evaluating errors due to wrong predicted variability. The STDBIAS together with the BIAS indicate amplitude errors which are typically related to site specific effects.

ii) The dispersion, DISP, involves the cross-correlation coefficient weighted with both standard deviations. Hence DISP accounts for the contribution of correlation ("phase") errors to the RMSE, reflecting global properties of the prediction system.

3.2 German Bight and Baltic Sea

The investigated time period comprises one year (2002) with a temporal resolution of 1h and a forecast horizon of 48h. The 00 UTC forecast run of the LM has been used. Hence, the prediction times directly correspond to times of the day. The predicted and the measured wind speeds are both given at 10m height (annual mean in Figures 3 and 6). In Figures 4 and 7 the BIAS of the forecasted to the measured wind speeds at the investigated sites are shown. For offshore sites (emsx and deut), which are far away from the coast, the BIAS is rather small for all prediction times, with a weak diurnal variation. In contrast to this, for North Sea sites located directly at the coast (cuxh) or islands close to the coast (list, nord) the BIAS has a large positive offset and strong diurnal variations with maxima at approximately midnight (24h and 48h) and minima at noon (12h and 36h).
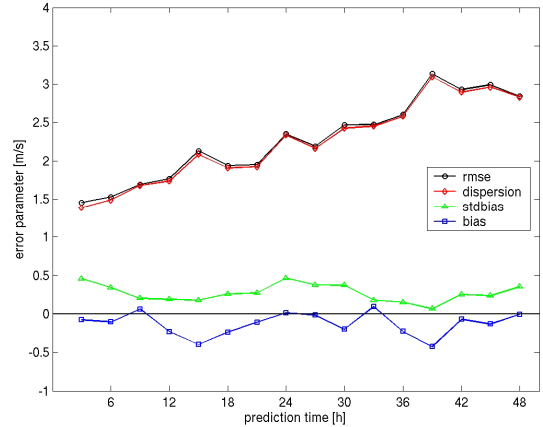

Fig. 9: Decomposition of RMSE at lightship "deut"

In general, the actual wind speeds at the coastal sites are overestimated by the DWD-forecast. In particular, the change in the BIAS over the day indicates that the thermal stratification of the atmosphere is not accurately resolved by the numerical model. There are two thermal effects that can explain the diurnal cycle of the coastal surface wind speeds: Owing to convective mixing with higher atmospheric layers, surface wind speeds are on average stronger at daytime compared to the night where a stable atmosphere leads to lower surface wind speeds. Second, onshore convection during the day also drives the sea breeze, i.e. it causes additional surface air flow from sea to land.

The LM contains algorithms for variable sea surface roughness and thermal stratification of the atmosphere. But apparently, the model considers the three exposed coastal sites at the North Sea as being already far offshore. Luckily, the discrepancies between forecast and measurement are limited to the coastal sites and do not affect the offshore forecast. Considering the BIAS (Fig 7), the Baltic coastline seems to be represented more accurately in the NWP-map. Nevertheless, the RMSE is similar for all sites (Figures 5 and 8).

Figure 9 summarises the forecast error according to the decomposition in equation (1) for the lightship deut. Here and for emsx which are both far away from the coast, BIAS and STDBIAS are negligible and the dispersion dominates the RMSE.

The systematic prediction errors can be corrected by subtracting the BIAS and by inflating or deflating the standard deviation of the prediction [5]. But the dispersion error (DISP) is proportional to $(1-r_{p,m})$. Hence these correlation errors, in contrast to amplitude errors, cannot be removed by linear corrections of the time series as the correlation is invariant under this transformation. Therefore additional linear post-processing is not expected to lead to major improvements for the offshore sites that are far away from the coast. If the RMSE at the offshore sites is normalised to the

annual mean measured wind speed of about 8 m/s, the relative error is about 20% to 30% in the first 24 hours. This is significantly better than for a typical onshore site which has a relative RMSE of about 30% to 45%. In terms of the relative error, the numerical wind speed forecast for offshore sites looks quite good but the absolute errors of about 3 m/s for 48h are higher than onshore.

4 Speed and Power Predictions at Hub Height

4.1 Horns Rev, 62m height

The meteorological mast at Horns Rev is located approximately 18 km west of the Danish North Sea coast near Esbjerg and is operated by Elsam Engineering A/S [6].

The mast provides wind speeds at various heights, in particular at 62m. We investigate the period from 10/2001 till 04/2002 for which the raw measurement data was provided by the "Database on Wind Characteristics" www.winddata.com.

The numerical weather predictions of the LM are available in three relevant heights (10m, 34m, 110m). In order to predict the wind speed at 62m height, the forecasted wind speeds at 33m and 110m were interpolated under consideration of the neutral logarithmic wind profile, like indicated by the red line in Figure 10.
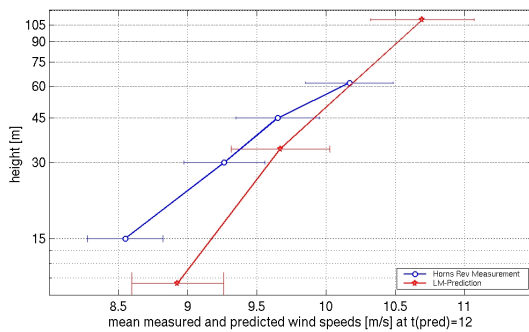
Fig. 10: Mean measured and predicted wind profiles at Horns Rev at 12h; average of the winter period

This interpolation scheme does not require to make extra assumptions regarding the roughness length or the friction velocity as these values are implicitly given by the LM. However, this simple approach is an approximation as profiles corrected for thermal stratification should be used.

In terms of the statistical error measures (Fig 11) the accuracy of the interpolated 62m-prediction is similar to the lightship "deut" (Fig 9). Normalised to the mean wind speed of 10.3 m/s at 62m (winter period), the relative RMSE error increases from 17%
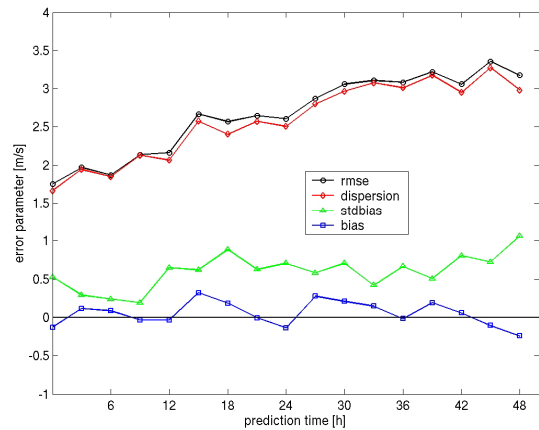
Fig. 11: Decomposition of RMSE of DWD forecasts at Horns Rev, 62m height, winter period 2001/02

to 32% during the forecast range of 48h. As said before, the corresponding values for single sites onshore increase from 30% to 45%. The sharp scatter plot of predicted versus measured wind speeds at 62m in Fig. 12 reflects the relatively good prediction quality for Horns Rev. The cross correlations between forecast and observation range between 0.95 for 0h and 0.75 for 48h.

Although the logarithmic interpolation to hub height is not ideal, in this case the relative accuracy is fair and outperforming onshore predictions for single sites. However, the absolute error of 1.6 to 3.3 m/s is still quite large.
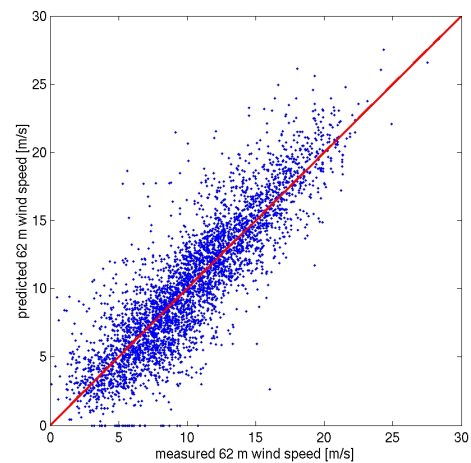
Fig. 12: Scatter plot of predicted (DWD) versus measured wind speeds at 62m at Horns Rev (0-48h)

What is the resulting accuracy for *power* predictions? To answer this question, we calculated time series of potential power output by multiplying measured and forecasted wind speeds with the power curve of a typical Multi-Mega-Watt turbine in the 3 to 5 MW class. This machine is constructed for offshore conditions and cuts in at 3 m/s. The nominal power is reached at approx. 14 m/s, the cut out wind speed is 25.1 m/s.
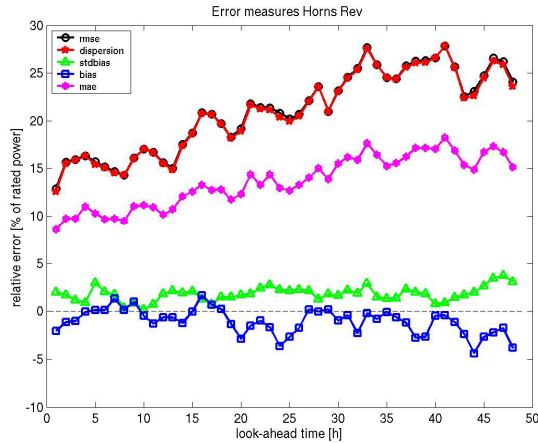
Fig.13: Decomposition of RMSE and MAE of DWD-Power at Horns Rev, at 62m height, winter 2001/02

The variations of the mean wind speed for different times of the day (from 10 m/s to 11 m/s) lead to similar variations in power: The mean producible power output varies between 51% and 57%.

The amplifying effect of the non-linear transformation from speed to power is more pronounced for the error measures (Fig. 13): Normalised to the rated power, the RMSE starts with 13% for the 3h-forecast time and increases up to 28% for the 48h range. In other words, the prediction error of 17 - 32% in wind speed leads to power errors of 24 - 52% relative to the mean producible output, and this mean output is 54% of the rated power.

In Figure 13 and in the following plots, we added the mean absolute error MAE to support comparability to other investigations. Nevertheless, the RMSE is a more relevant parameter for the energy industry since it reflects better the cost function of regulative power.

Fig. 10 illustrates that measured wind shears deviate from forecasted wind profiles. This effect can be detected for all different weather situations and indicates the need for a more detailed description of the marine boundary layer, see [7].
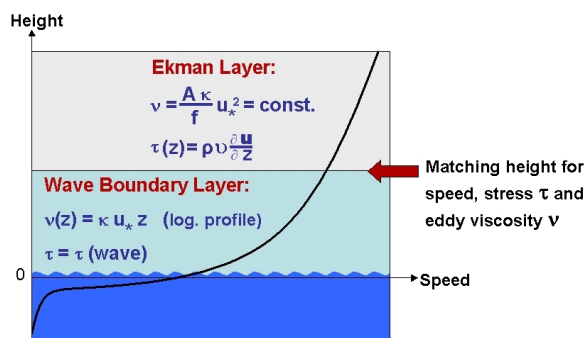

Fig. 14: Scheme of the vertical wind profile used in the ICWP model.

In our new air-sea-interaction model called ICWP (Inertially Coupled Wind Profiles, Fig. 14), we couple the Ekman layer profile of the atmosphere to the wave field via a Monin-Obukhov corrected logarithmic wind profile in between [8]. With this approach, it is possible to refine the vertical resolution of NWP profiles in a better way.

4.2 FINO1, 103m height

The met mast FINO1 is located 40 km off the German coastline, see Figure 1. The scientific program is described at [9]. In this study we used the wind speeds measured in 2004 at 103m height.

The mean wind speed in 2004 is 9.8 m/s, with a diurnal cycle between 9.5 m/s at noon and 10 m/s at midnight. The resulting power varies between 48% and 54% of the rated power. This effect indicates that on an average, also the marine atmospheric boundary layer is more stable at night, resulting in lower turbulence and thus, less transport of momentum downwards to the surface. Therefore, the flow at 103m height looses less energy and remains faster than during the day. In the first three months of the year, the mean wind speeds varied even between 10 and 11 m/s during the diurnal cycle.

In addition to DWD, we analysed forecasts from ECMWF that are available for 2004. The ECMWF model has a horizontal resolution of 40 km and three levels below 103m height. Using the ICWP scheme for vertical interpolation, we derived predictions for 100m height from the ECMWF and DWD forecast fields.

Figure 15 shows the same quality of DWD forecasts as in 2002 (Fig 11). But a comparison between Figures 15-17 with Figures 18-20 reveals a considerably higher accuracy of ECMWF forecasts: Starting from 1.5 m/s, the ECMWF-speed RMSE does not reach 3m/s like for DWD, but only 2.5 m/s after 48h. Normalised to the mean wind speed of 9.8 m/s, this gives a relative RMSE of 15% to 25%.

The resulting errors of the power prediction (derived in the same way as for Horns Rev, but for a hub height of 100m) are shown in Figures 16 and 19.

Especially the direct comparison in Figures 21 to 24 shows a new quality of power predictions for single sites: ECMWF clearly outperforms DWD in the day-ahead range of 24 to 48 hours. Instead of RMSEs between 15% and 27%, ECMWF's wind power prediction error ranges only from 13% to 22% of the rated power. Figure 21 and 22 reveal that the ECMWF forecasts are correlated far better to the measured wind speeds. This is true despite the fact that the horizontal resolution of the ECMWF model is about six times coarser than the DWD resolution (7km). The higher quality is presumably credited to a better global weather analysis as much more data is assimilated into the system.
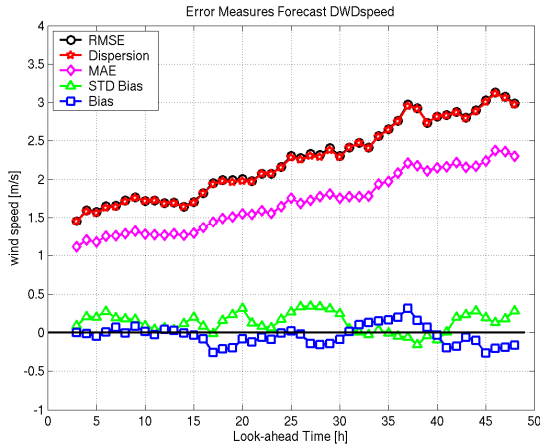
*Fig. 15: Decomposition of **DWD Wind Speed** RMSE and MAE at FiNO1, 103m height, complete 2004.*
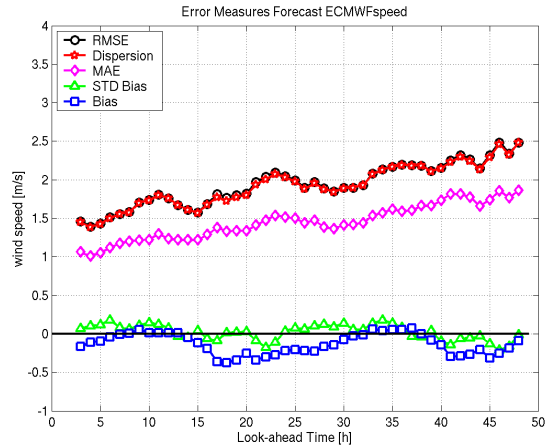

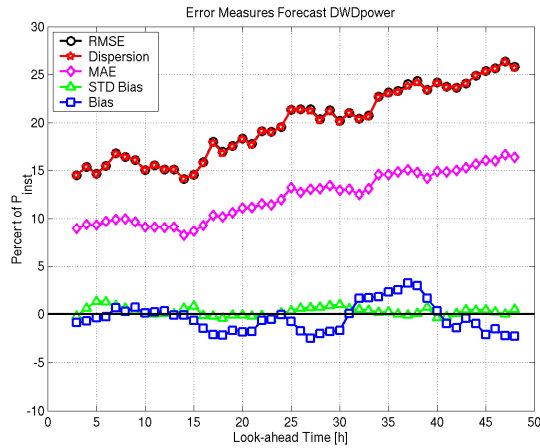*Fig. 18: Decomposition of **ECMWF Wind Speed** RMSE and MAE at FiNO1, 103m height, full 2004.*

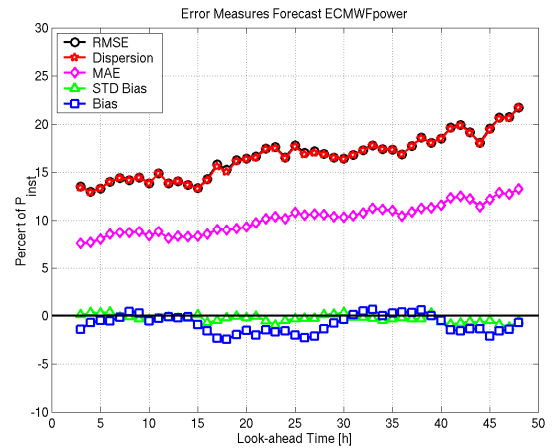*Fig. 16: Decomposition of **DWD Power** RMSE and MAE at FiNO1, 103m height, complete 2004.*

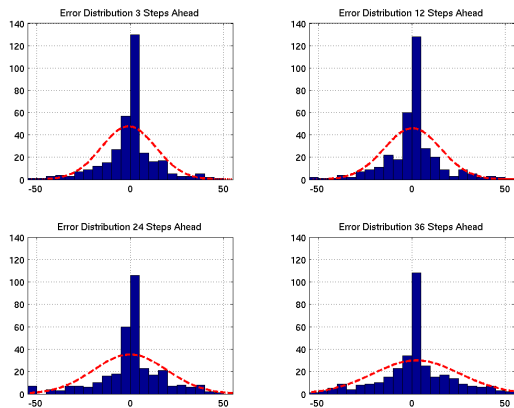*Fig. 19: Decomposition of **ECMWF Power** RMSE and MAE at FiNO1, 103m height, complete 2004.*

*Fig. 17: **DWD power forecasts:** Frequency [days, sum:350] of errors [percent of rated power] for the Look-ahead times 3h, 12h, 24h and 36h. Red curve: Gaussian distribution with same standard deviation.*
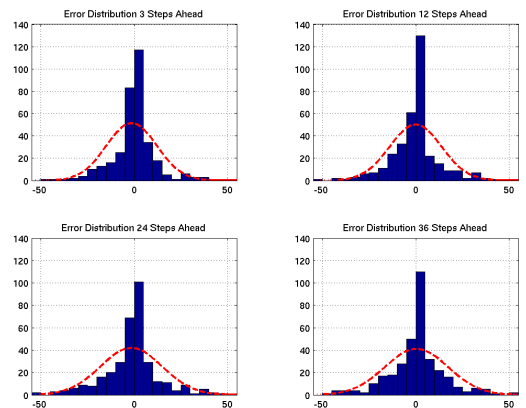
It is a general result that wind *speed* forecast errors have a Gaussian distribution, a fact we could reproduce for our cases. Owing to the non-linear

*Fig. 20: Like Fig 17, but **ECMWF power forecasts***

power curve this not the case for *power* forecast errors, which is clearly visible in Figs 17 and 20. For the forecast range up to 36h, 3/4 of all ECMWF forecast runs have an error that is smaller than 15% of the rated power (262 of 350 forecast runs). The respective DWD frequency is only 230 of 350 runs.
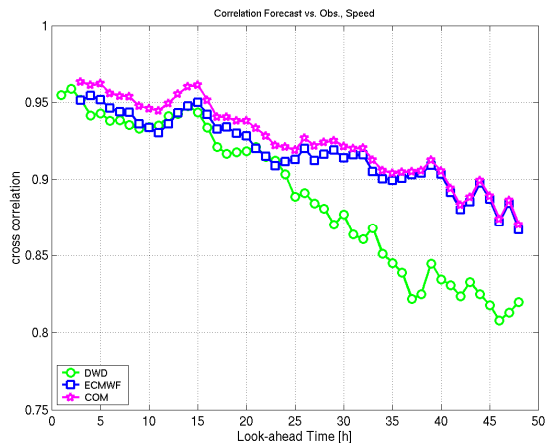
*Fig. 21: Cross-correlation of **speed** forecasts from DWD, ECMWF and their combination against **Obs.** at FiNO1, at 103m height, complete year2004.*
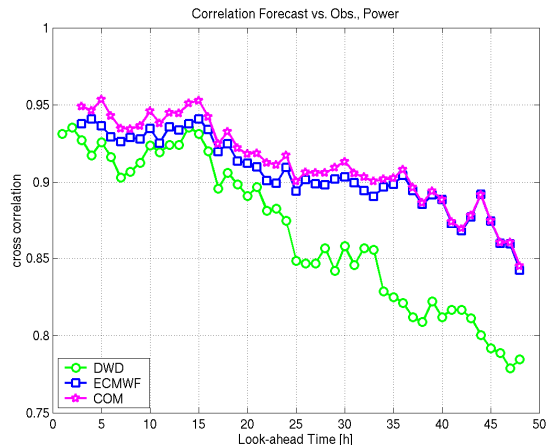

*Fig. 23: Cross-correlation of **power** forecasts based on DWD, ECMWF and their combination against **Obs.** at FiNO1, at 103m height, complete year2004.*
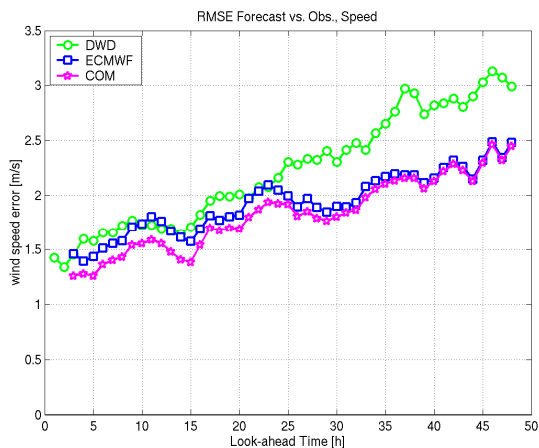

*Fig. 22: RMSE of **speed** forecasts from DWD, ECMWF and their combination against **Obs.** at FiNO1, at 103m height, complete year 2004.*
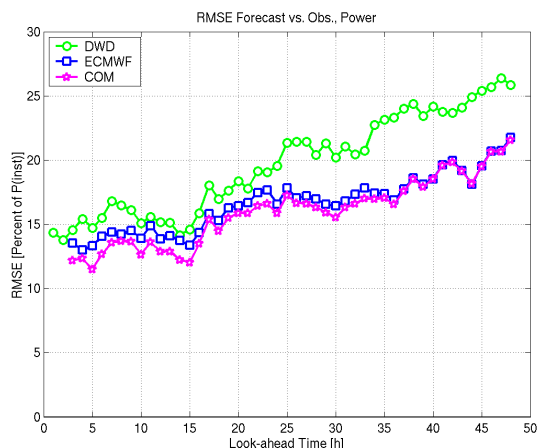

*Fig. 24: RMSE of **power** forecasts based on DWD, ECMWF and their combination against **Obs.** at FiNO1, at 103m height, complete year 2004.*

4.3 Combination of DWD and ECMWF at FiNO1

The advantage of ensembles of forecasts is to counterbalance erroneous forecasts since insufficient initial conditions of the forecast model let forecast errors grow rapidly. The advantage of using different models in the ensemble is that NWP deficiencies, e.g. erroneous initialisations of model runs that may cause dips in the forecast, are less pronounced. This effect even holds for our case, where one of the forecasts is clearly better than the other. As a first approach, we combined ECMWF and DWD forecasts for FiNO1 with an exponential weighting, starting with a weight of 60% for DWD at a look-ahead step of 3h and ending with a weight of 10% for DWD at 48h.

Figure 21 shows that in the forecast range up to 30 hours the correlation of the combined forecast is considerably better than the ECMWF forecast alone.

The benefit for the RMSE of speed is also strongest in the first 30 hours (Fig 22). The RMSE is reduced by about 0.2 m/s. When multiplying the combined forecast with a Multi-Mega-Watt power curve, the benefit of the combined forecast prevails for the mentioned forecast range (Figs 23, 24).

The reduction of the RMSE is about 2% of the rated power, i.e. from 14% to 12% in the first 15 hours. For 24h, the reduction factor is still 0.95, but even for 36h, a slight improvement can be detected.

Further studies and longer time series should be used to investigate the combination of DWD and ECMWF forecasts in more detail. It can be speculated that a more elaborated combination has to depend on a classification of the specific meteorological situation. More forecast parameters, e.g. thermal stratification, are beneficial to improve the wind speed and power output forecast.

5. Forecasts of 25GW Wind Power in the North Sea

Previous investigations for onshore wind power have shown that a regional forecast has lower errors than a forecast for a single site, see especially [3, 10]. The relative prediction error for the aggregated power output of many wind farms in a region decreases for increasing region size (Fig 25) as single errors are less correlated, a general effect in NWP. This reduction occurs even when the number of wind farms in the regions stays constant. How strong is the effect for offshore predictions?
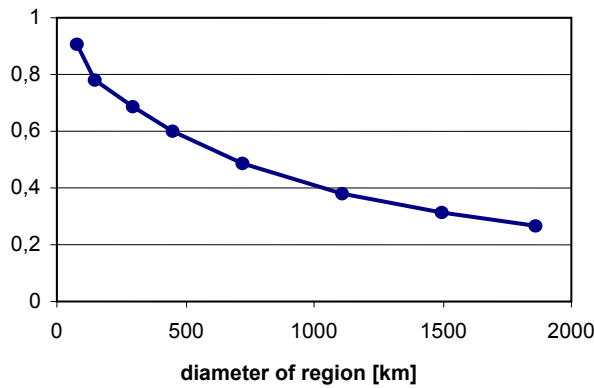

Fig. 25: Error ratio (regional forecast error divided by an average single site error) depending on the size of the region, forecast time: 36h, from [10].

For this investigation, we consider the projected wind farms in the German Bight, covering a region with a diameter of 180 km. Because simultaneous offshore measurements are so scarce, we used hourly weather Analysis data from the German weather service as a reference for the forecasts. The first question for using this method is if the forecast
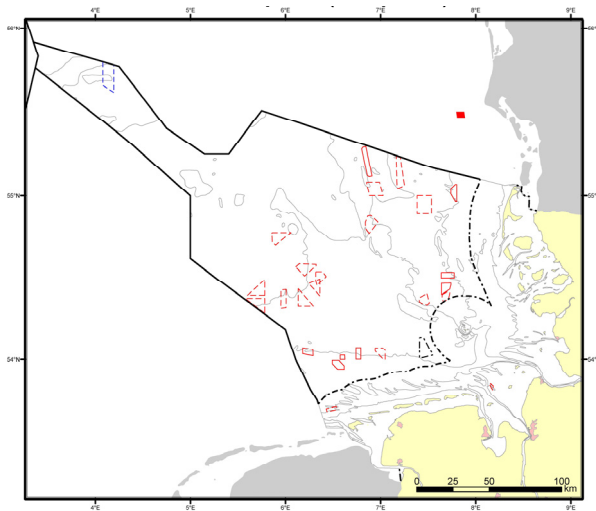

Fig. 26: Red lines mark the sites for all offshore projects in the German Bight with official applications. Source: BSH.
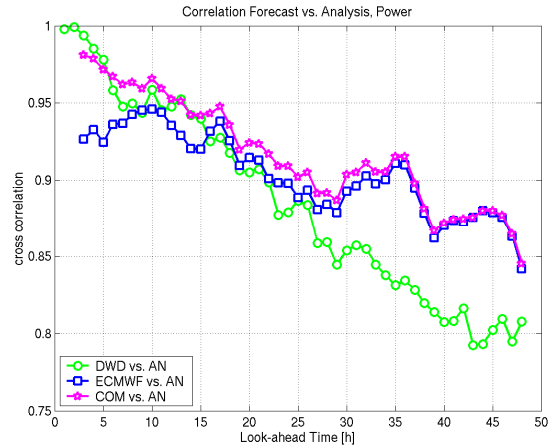

Fig. 27: Cross-correlation of **power** forecasts based on DWD, ECMWF and their combination vs. **Analysis** at FINO1, at 100m height, complete year2004.
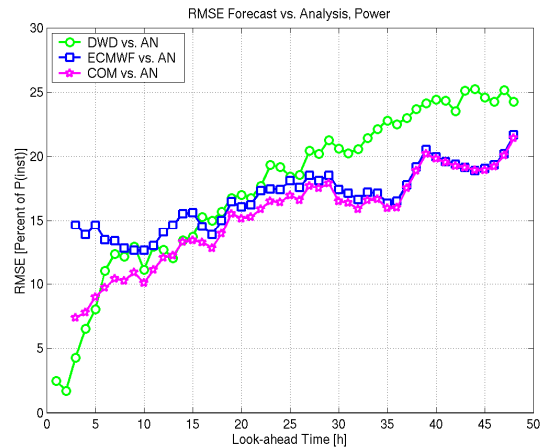

Fig. 28: RMSE of **power** forecasts based on DWD, ECMWF and their combination vs. **Analysis** at FINO1, at 103m height, complete year2004.

error for a single site like FiNO1 is the same when we use weather Analysis data instead of the real measurements. Indeed, Figs 27 and 28 show the same range of correlation and RMSE for the ECMWF power forecast like in Figs 23 and 24. Also Fig 31 exhibits very similar error distributions like Fig 20 (here, 261 of 350 forecast runs have an error below 15% at 36h). In contrast, the DWD forecast is highly correlated to the DWD Analysis in the first 12 hours, basically because it is the same model starting with the same input. But in the range beyond 24h, even for the DWD forecast the Analysis seems to be a realistic substitute for the measurement.

The next step is the calculation of time series of power based on the forecasts and Analysis data for all 22 identified offshore sites in Fig 26, which can than be equally summed up to 25 GW max. power. Fig 29 shows that the forecast errors at two specific sites are maximal correlated for site distances <20km while the error correlation decreases rapidly
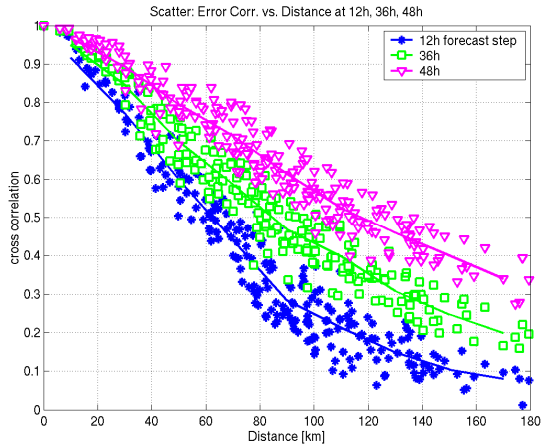
Fig. 29: Scatter dots: Correlation between the forecast errors at two out of 22 offshore sites vs. their distance in km. Lines: Binned values. Blue: forecast time 12h, Green: 36h, Pink: 48h.
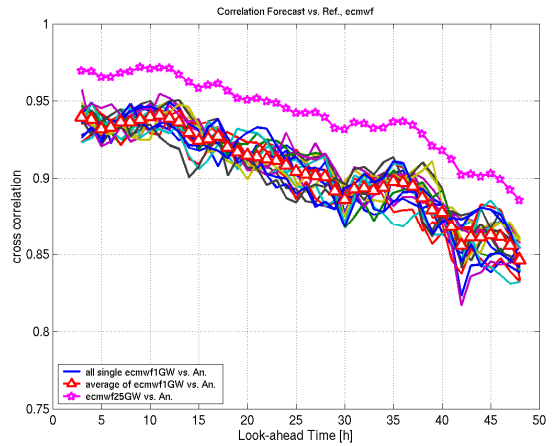

Fig. 32: Cross correlation of ECMWF wind power forecasts to DWD Analysis. Thin lines: all single 22 sites. Red triangles: Average correlation. Pink stars: Sum of forecasts vs. sum of Analysis (max. 25GW)
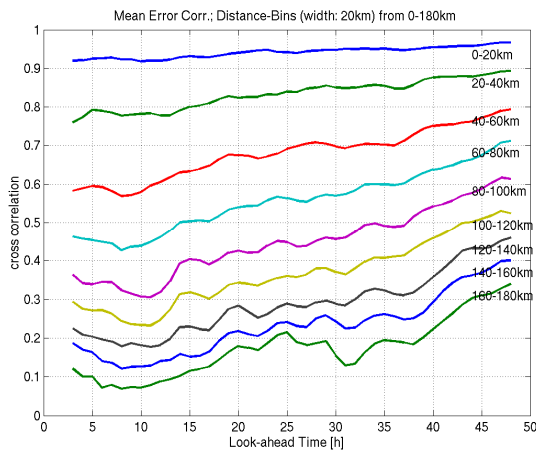

Fig. 30: Mean correlation of errors vs. forecast time. Line at the top for sites with distances 0-20km, bottom line for distances of 160-180km between sites
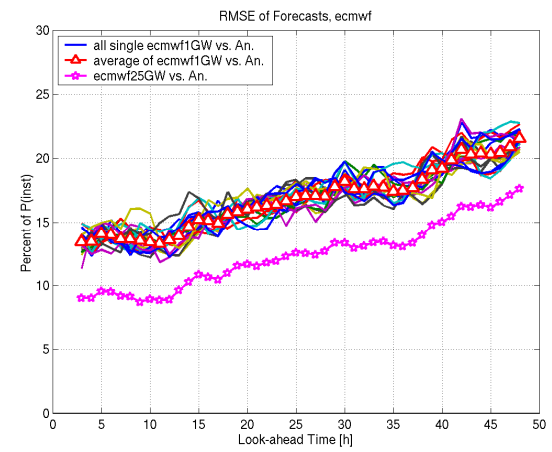

Fig. 33: Like Fig 32, but normalised RMSE, at 103m height, complete year 2004.

with distance. The values in Figure 29 fully resemble the results for onshore sites in [10]. During the forecast time range, the correlation increases as

global upstream forecast errors are amplifying common errors at the sites of interest (Fig 30). Site distances of max. 180km are not large enough that upstream errors could have a more distinct influence
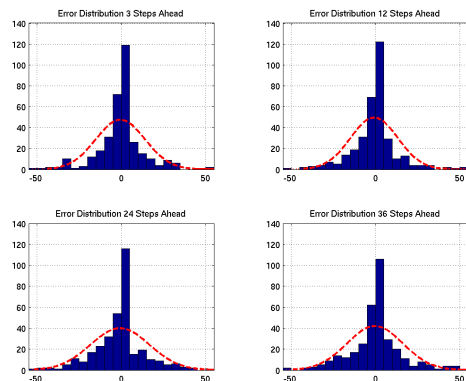

Fig. 31: Like Figure 20, but for errors of ECMWF-forecasts vs. DWD-Analysis at FiNO1.
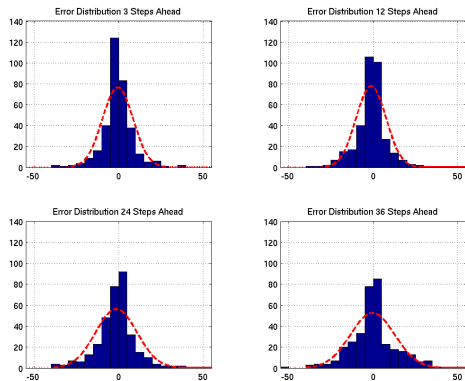

Fig. 34: Like Fig 31, but regional ECMWF-25GW forecasts vs. DWD-Analysis for the German Bight.

on each of the 22 investigated sites. However, the fact that the single errors have quite a small average correlation of 0.5 has the consequence that they, to some degree, smooth out each other. Due to this error smoothing, the sum of all single power forecasts (max. 25GW) has a significantly higher cross correlation to the sum of all power outputs derived from Analysis (Fig 32). Accordingly, the regional 25GW forecast has a strongly reduced RSME ranging from 9-17% during the forecast time span of 48h (Fig 33). The reduction compared to the average normalised RMSE of all single sites in the German Bight ranges from a factor of 0.65 for the 9h-forecast up to 0.82 for the 48h-forecast. The smoothing effect decreases with increasing forecast time because the single site errors get more correlated (see Fig 30). The value for 24h is 0.73, for 36h it is 0.75, while the mean value of all forecast times is again 0.73. This error reduction due to spatial smoothing fits perfectly to the onshore value in Figure 25 for a diameter of the region of 180 km.

The error distribution of the regional forecast (Fig 34) shows that at 24h forecast time, 84% of the errors are smaller than 15%, but at 36h, this share is 77% which is very near to the value of 75% for the single site forecasts in Fig 20 and 31. This reflects the feature that the error distribution of the regional 25GW forecast comes closer to a Gaussian than the sharper single site distributions.

6. Conclusion

Our evaluations of wind speed forecasts against measurements at lightships, coastal sites and the met masts Horns Rev and FiNO1 have shown that offshore power predictions based on DWD have a normalised RMSE of 15-27% of the rated power for 3-48h. This is comparable or better than onshore accuracy, especially with regard to the mean *producible* power, which is twice as high as onshore. It is important to note that comparisons with onshore forecasts have to consider this different power *output*, not only the rated power: the higher the mean power output, the larger the absolute errors.

A comparison at FiNO1 shows that ECMWF outperforms DWD with an RMSE of 13-22%. A weighted combination reduces the error by a factor of 0.94. Further studies have to show how statistical tools perform in the first 6 forecast hours and how more elaborated forecast combinations can increase the general accuracy.

The regional forecast for a total capacity of 25GW in the German Bight shows an RMSE of 9-17%, credited to spatial smoothing effects that reduce the error by a factor of 0.73 compared to a single site. Hence, a combined regional forecast for all offshore sites would show an RMSE of 12% at 36h forecast time, i.e. an absolute RMSE of 3GW. Since our offshore results fit to the previous onshore

investigations, it can be speculated that the respective spatial error smoothing also holds for the ensemble of onshore and offshore wind farms in Germany. The area size of 800km gives an error reduction factor of 0.45. With a single site error of 16% at 36h forecast time, this would result in an absolute RMSE of 3.6 GW for a total installed capacity of 50GW in 2030.

8. References

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