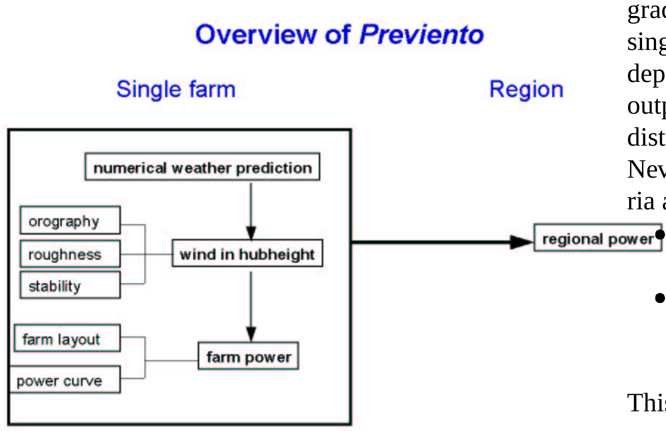
1 Introduction

The development of wind energy use has led to a noticeable contribution to the energy supply in Germany. At the moment, for some regional utilities the installed capacity of wind turbines is of the order of magnitude of the minimal load (approx. 30 % of max. load). The feed in of electricity by wind energy acts as a negative load leading to an increase in fluctuations of net load patterns. The insecurity of the temporal development of wind speed may have consequences for the operation of conventional power plants or load management, respectively. For a time scale from some hours to two days additional conventional reserves have to be kept ready to replace the wind energy share in case of decreasing wind speeds.



Previento is an operational wind power prediction system for a time horizon up to 48 hours which is based on an physical approach. Input is the forecast of any weather prediction model e.g the *Lokalmodell* of the German Weather Service. *Previento* models the boundary layer with regard to roughness, orography and wake effects. Important for the calculation of the windspeed at hubheight is the daily variation of the thermal stratification of the atmosphere which is used to change the logarithmic profile. Using the specific power characteristic of the turbine the expected power output for single sites is calculated. The method and principle we use is described in detail in [1,2]. Due to a needed aggregated power output of wind farms of a region we developed an innovative upscaling method to forecast the expected power output of a whole region. *Previento* runs operational at Oldenburg and can be used everywhere with small adaption effort.

In this paper we concentrate on a method of generating a regional forecast. The problem occurs that it is not possible to forecast the power output of each single turbine. We divide the region in sub-regions. For each sub-region one representative sites is determined. Afterwards the forecast for this site is upscaled to the summarized power of the sub-region. Two aspects have to be considered in this process. Due to spatial smoothing effects the prediction error for the combined power output will decrease compared to a single site. The dependency of the prediction error on the regionsize and the number of turbines is described in [3]. Not only the error of the prediction but also the statistical characteristic, for example the fluctuation of the expected power output is a measure for the quality of the prediction. With linear upscaling the fast fluctuations of the expected power output of a single site are shifted to the regional forecast. But due to spatial correlation of the power output of single sites smoothing effects can be expected. The power gradients for the regional forecast are lower than for single sites [4]. The extent of the smoothing effects depends mainly on the spatial correlation of the power output of single sites, the number of sites itself and the distribution of the sites over the area.
Nevertheless linear upscaling is possible if two criteria are granted:

- The fluctuations of the regional measured and predicted power have the same magnitude.
- The magnitude of the fluctuations of the regional power (measured as predicted) converge with increasing number of turbines.

This will be shown in the following.

2 Regional forecast

All calculations are based on measurements and predictions for 30 sites distributed over the northern part of Germany (figure 1). The measured data is provided by the 250 MW programm of the German government. We used data for the year 2000. More details are described in [4]. The respective wind power forecast is calculated by *Previento* .

In the beginning we take a closer look at the desciption of the fluctuations of the expected power output. To receive general information we use randomly distributed wind farms. This allows us to vary the size of region and the number of turbines in a wide range to see how the fluctuations depend on these parameters. To quantify the fluctuations we use the variance of the power. For an ensemble of sites it is calculated by

$$\sigma^2_{ensemble} = \frac{1}{N^2} \sum_x \sum_y \sigma_x \sigma_y r_{xy} \qquad (1)$$

where σ_x is the standard deviation of the prediction error of single site an N is the number of sites.

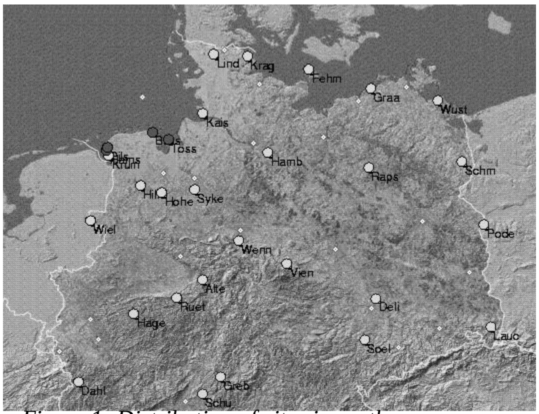


Figure 1: Distribution of sites in northern germany.

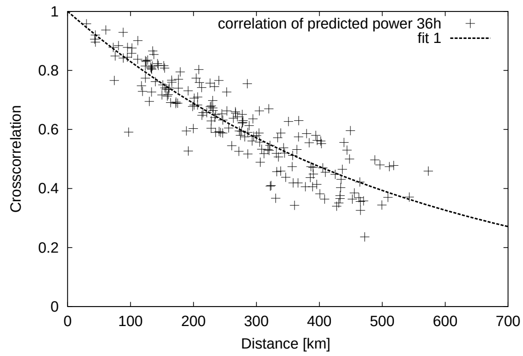


Figure 3: Crosscorrelation of 36 hour prediction of power for each pair of sites.

2.1 Crosscorrelation

In a first step we calculate the crosscorrelation r_{xy} for the measured and predicted power which we want to compare. The pairwise crosscorrelation for each of the 30 sites for the measured power versus the distance is shown in figure 2. Up to 100 km the crosscorrelation decreases fast to a value of $r_{xy} = 0.7$. Afterwards the behaviour is changes to slower decrease.

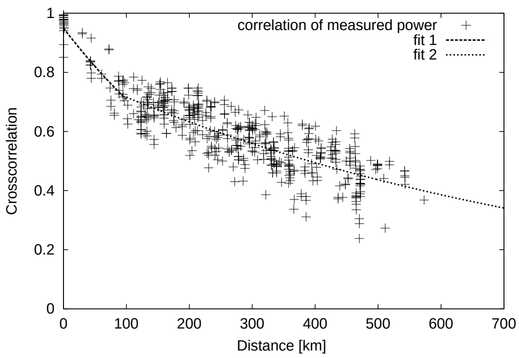


Figure 2: Crosscorrelation of measured power for each pair of sites.

The crosscorrelation of the predicted power decreases slower than for the measured power (figure 3). This is expected due to the resolution of the weather prediction model of 7 x 7 km^2. Interesting is that the crosscorrelation of the predicted power is lower for distances more than aprox. 400 km.

2.2 Ensemble of Sites

To calculate the variance for random ensembles of wind turbines with equation 1 we have to fit the crosscorrelation. We obtain a suitable function which we can use in equation 1 by fitting the data with functions of the form $r_{xy} = a \cdot e^{-x/d}$. Due to changing behaviour of the crosscorrelation for measured power a piecewise fit is made. We use equation 1 to calculate the standard deviation for a region of 500 x 500 km^2 with variing number of turbines. Each calculation is done for 10 different random distributions of wind farms. Figure 4 shows the ratio of the standard deviation for the regional power and a single site versus the number of turbines for measured and predicted power.

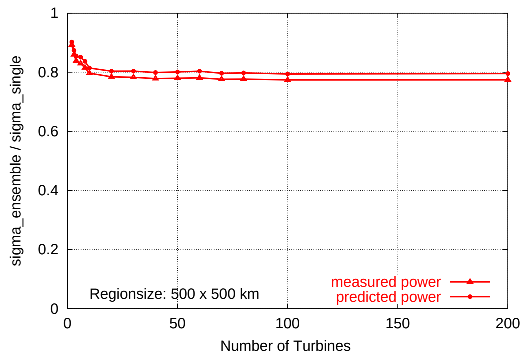


Figure 4: Ratio between standard deviation of regional power and single power versus number of sites for a region of 500 x 500 km^2

As expected the reduction of the standard deviation is higher for measured power than for predicted power. But the absolute difference is small. The saturation values are of the same order with 0.77 and 0.79. For measured as for predicted power the ratio of $\sigma_{ensemble}/\sigma_{single}$ stay constant with increase of turbines.

2.3 Behaviour of Saturation

The distribution of distances has a big influence on the moment of saturation. Figure 5 shows a random distribution for a region of 500 x 500 km^2 for 20, 50, 200 and 1000 sites. It is clearly recognisible that the form of the distributions is relative similar. This is besides the number of turbines the decisive factor for the saturation of the ratio $\sigma_{ensemble}/\sigma_{single}$.

3 Upscaling

Now we discuss the consequences of the statistical analysis on the upscaling from single turbines to an ensemble of sites. The first important fact is that the

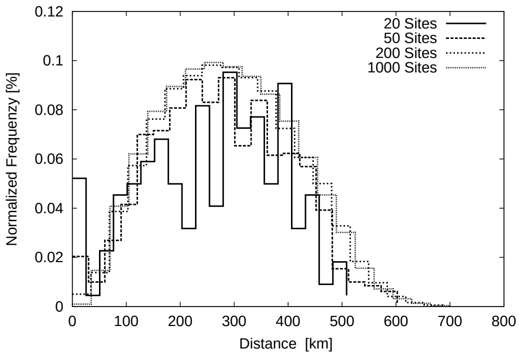


Figure 5: Random distribution of distances for 20, 50, 200 and 1000 sites.

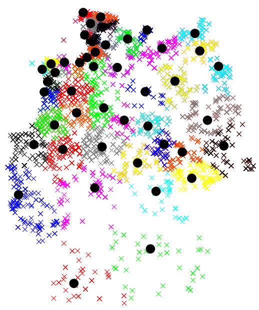


Figure 6: Sub-regions and assignment of representative wind farms in Germany

predicted power shows the same characteristics as the measured power due to reduction of fluctuations for ensemble of sites. That means the forecast of the expected power output of regions has the same fluctuations as in reality (compared with measurements). Furthermore the ratio $\sigma_{ensemble}/\sigma_{single}$ converges. For our example, 500 x 500 km^2, for more than 20 sites the fluctuations of the expected power output do not decrease anymore. An detailed power forecast for 20 sites and linear upscaling for each sub-region reaches sufficient smoothing of the expected power output. This forecast will have the same magnitude of fluctuations as the real power output of all turbines (e.g. 3000) in this region.

4 Regional forecast for Germany

For this calculation the coordinates, hubheight and turbine type (that means power curve) of each installed wind turbine are needed. In a first step we have to determine the number of turbines which will satisfy the smoothing effects described before. The saturation value of 0.64 is reached for 30 turbines for a regionsize covering whole Germany (1000 x 1000 km^2). In [3] we calculated the effect of regional smoothing on the prediction error. It reaches the minimum for Germany nearly for 50 sites.

We divide Germany in 45 sub-regions with almost the same installed wind power capacity. The sub-regions are shown in figure 6. For each sub-region a representative site has to be determined. The main selection criteria for the representative wind farm of each sub-region is the size of the windfarm and the site evaluation (roughness, orography, etc.).

In general it is not possible to give by measurements validated results for the aggregated power, because measured data is not availiable for all installed turbines in Germany (aprox. 10.000 turbines). But in [3] the reduction of the error from a single site to a region for the forecast system *Previento* is calculated. The root mean square error normalized to the installed power capacity for an hour mean value is between 4% and 7% depending on the forecast time.

prediction time [h]	6	12	18	24	36	48
error [% $P_{installed}$]	4.7	6	5.6	5.6	6.9	6.5

Table 1: Prediction error for power prediction of hour mean values for whole Germany. The prediction error is given in power output normalized to installed power.

5 Resume

Previento is an operational wind power prediction system for single sites as well as for whole regions. It can be adapted in other countries with small effort. For a regional forecast we have to consider the reduction of the prediction error [3] and the magnitude of the fluctuations. The fluctuations of the predicted regional power from *Previento* are of the same order as in reality (compared with measurements). Moreover the variance stays constant for increase of predicted sites in the region. Therefore, the power prediction, e.g. for Germany is possible with a detailed forecast for 45 sites. Neither the prediction error decreases nor a better description of the real fluctuations is reached if more sites are used.
The prediction error for Germany is between 4% and 7%.

6 Acknowledgements

We like to thank ISET, DWD and *Ingenieurwerkstatt Energietechnik* for providing the data. Parts of this work have been funded by the EU with project JOR3CT980272 and the Deutsche Bundesstiftung Umwelt.

7 References

[1] H.G. Beyer, D. Heinemann, H. Mellinghoff, K. Mönnich, H.-P. Waldl: *Forecast of regional power*

output of wind turbines. EWEC 1999, Nice.

[2] K. Mönnich: *Vorhersage der Leistungsabgabe netz -einspeisender Windkraftanlagen zur Unterstützung der Kraftwerkseinsatzplanung.* Dissertation, Oldenburg, 2000

[3] U.Focken, M.Lange, H.-P. Waldl : *Reduction of Wind Power Prediction Errors by Spatial Smoothing effects.* EWEC 2001, Kopenhagen.

[4] ISET: *Wind Energy Report Germany 1999/2000 - Annual Evaluation of WMEP*, Kassel, 2000

[5] U. Focken, M. Lange, K. Mönnich, H.P. Waldl: *Reduction of Wind Power Prediction Errors by Spatial Smoothing Effects.* Proceedings of the EWEC 2001, Kopenhagen.