SHORT-TERM POWER FLUCTUATION OF WIND TURBINES: LOOKING AT DATA FROM THE GERMAN 250 MW MEASUREMENT PROGRAM FROM THE ANCILLARY SERVICES VIEWPOINT

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ABSTRACT

Short-term power fluctuations from wind farms have the potential to negatively affect interconnected grid operational costs and stability. With wind power growing at a rapid pace worldwide, this has become an increasing concern. In the context of electric industry restructuring in the U.S., these fluctuations are evaluated by examining costs and provisions for ancillary services. However, the magnitude of the impact has is not well quantified and the affect of aggregation of multiple turbines is not well established, due to a lack of actual wind farm power fluctuation data. This paper analyzes individual turbine and aggregate power output data from the German "250 MegaWatt" data project. Electric system load following and regulation impacts are examined as a function of the number of turbines and turbine spacing in order to quantify the impacts of aggregation. These data show a significant decrease in the relative system regulation burden with increasing number of turbines, even if the turbines are in close proximity.

INTRODUCTION

The application of wind energy has grown rapidly within the past 15 years. This resulted in 1500 MW of capacity built in the late 1980s in California. The trend continued in Europe since the early 1990s to the present. In Denmark, Germany and recently in Spain, the growth of wind energy has been encouraged by different kinds of support. In the USA a recent tax credit program helped to develop substantial new wind capacity. In Minnesota the Department of Public Service has mandated that Northern States Power purchase 450 MW of wind capacity, with another 400 MW to be evaluated. Iowa is developing 240 MW, and is evaluating a total installation of about 1,600 MW by the year 2015. New capacity is or has recently been under development in Texas, California, Wyoming, and other states in the U.S. Over 10,000 MW installed capacity world-wide was reached in April 1999. Driven by the CO_2 reduction plans and due to the decreasing costs of big turbines as well as the development of new resources on shore and off shore, the installed capacity will continue to grow over the next years.

Against this background, the ability of integrating the operation of significant levels of wind power in the existing grid becomes more important. Where wind power has to compete with other kinds of generation plants, the quality of electricity is an important issue. With wind power, this is mostly related to power fluctuations for both short time frame like seconds or minutes, and longer time frames, such as over a couple of hours. With the restructuring of the electricity market, there is the possibility of unbundling ancillary services. These services can be defined as “those services that are necessary to support the transmission of capacity, and energy from resources to loads while maintaining reliable operation of the Transmission Provider's Transmission System in accordance with Good Utility Practice.”

The magnitude of the burden to the grid caused by large-scale wind power plants has not yet been well quantified. In the present work I used power output data from the German "250 MW Wind" data project to analyse the Ancillary Services for individual turbines up to the aggregated power output from all turbines within the monitoring program. Furthermore, I analysed the effects of turbine spacing from the ancillary services viewpoint, and examined how the operators can benefit from a large number of turbine and their spatial spread.

DATA SOURCE

Data Base and Data Processing

The German Federal Ministry of Economics and Technology is promoting the use of wind energy with the 250 MW Wind-Programme. The Institut für Solare Energieversorgungstechnik (ISET - Institute for Solar Energy Supply Technology) in Kassel has been commissioned with the accompanying Wissenschaftliches Meß- und Evaluierungsprogramm (WMEP - Scientific Measurement and Evaluation Program). This program acquires statistically relevant data on the practical use of wind energy converters (WEC).

WMEP Remote Data Acquisition Network

At 230 selected sites, data loggers and wind measurement equipment are installed. Data loggers are connected to the central data base system at ISET via modem and the public telephone network. Electrical power, wind speed and wind direction are measured at a 10 Hz sample rate. Five minute mean values and 22 additional statistical measures are derived from this raw data. In addition, 10 Hz raw data can be transmitted on-line for any period without disturbing the statistical long-term measurement.

ANCILLARY SERVICES

The term “ancillary services” refers to power system services other than the pure provision of energy and real power. These services may include services such as scheduling and dispatch, load following, regulation, reliability reserve, voltage control, etc. In the past, these services were provided by the local utility. But with the restructuring of the electricity market, they have been separated from generation and transmission. However, up to now as the restructuring continues to develop, ancillary services are mostly still provided by the local utility. In the future, it is likely that generation providers, transmission providers, and even the customers will trade these services.

In terms of wind energy, the following five ancillary services are mostly of interest:

- **Regulation:** Maintenance of the minute-to-minute generation/load balance
- **Load Following:** Maintenance of the hour-to-hour generation/load balance
- **Reactive Supply and Voltage Control from Generation:** Injection and absorption of reactive power from generators to control transmission voltages
- **Frequency Responding Spinning Reserve:** Immediate response to contingencies and frequency deviation
- **Supplemental Reserve:** Response to restore generation/load balance within 10 minutes of a generation or transmission contingency

The wind turbine’s operator must either buy regulation or provide it with a controllable generation device like a fuel-powered generator or a hydro plant. He or she can sell load following services if the wind turbine output follows the load’s power demand. Otherwise he or she must also buy this service. As more new turbines are equipped with electronic power converters, it may be possible for a wind plant operator to sell the voltage control service by injection or absorption of reactive power. Of course, it would then be necessary for the utility to provide a signal for the demand for reactive power.

Variable speed controlled machines could use the momentum of the rotor and the generator to respond to frequency deviation and provide spinning reserve in this way. The kinetic energy stored in the rotor is about one second at rated power. These turbines could provide stability by adjusting the power a little higher or lower for a few seconds.

The output of a single turbine can fail abruptly due to broken components or cut-out caused by high wind speed. Unlike a single turbine, a wind plant won’t show this behavior. The wind never dies or increases substantially within seconds over the whole area of a wind plant. It takes at least a few minutes for the total power to come down. Thus, a wind plant operator does not need to buy supplemental reserve like other generation devices.

LOAD FOLLOWING

Load following is the tracking of the hourly trends in power output. It catches the hourly changes in power demand over a day within a control area. I extended the time frame and looked at the trend from one to four hours. I wanted to know how the wind power correlates with the power demand. Therefore I used the five-minute average data of the aggregated power of two groups of turbines. The first contains 176 turbines placed all over Germany. This is to simulate a European wind plant. The second group has 17 turbines in three spots 200 km (120 mi) to 300 km (180 mi) apart. This constellation is more like U.S. style wind plants. I performed linear regressions for data sets with a time frame of one hours. The linear regression finds a linear graph, which fits the best in the given data set. Only the slope of the linear regression is of interest. Using different time frames helps determine if the short trends continue over a longer time. (Short time frames like one hour catch the momentary changes while longer regressions like 2 to 4 hours show longer trends.)

I divided the value of the slope in classes of 0.1% of rated power per five minute or 0.02% per minute. E.g. for the one-hour regression at 12 p.m. in the summer, like shown in Figure 1, I went through all the days in the summer and looked at the slope of the regression from 12 p.m. to 1 p.m. I then counted how often each class occurred.

I performed this calculation for every half an hour of the day to see if there was a significant behavior at specific times of the day.

I chose several ways to display the results of this calculation graphically. Figure 1 shows the distribution of the slope at 8 a.m., 12 p.m. and 5 p.m. for the summer and the winter seasons together for group one. This graph is useful for identifying how often each slope occurs. However, this graph permits visualization of only a few time periods. The difference between the morning and the afternoon is evident in this graph. In the morning, the graph shows more positive slopes. In the afternoon, it shows more negative slopes.

To display the whole day I made a graph I call weighted slope (Figure 2). In this graph I multiplied the square of the slope with the number of occurrences for each half an hour of the day, e.g. one event of 0.1 %/min counts as much as four events of 0.05%/min. This intensifies large changes, because they may have a bigger impact on the utility.

The lines in the graph need more explanation:

Positive + negative Change

This line shows the resulting weighted slope of positive and negative slope. A positive slope nullifies a negative one and vice-versa. A slope of 0%/min does not count no matter how often it occurs.

Positive Change and negative Change

This shows the weighted slope for positive and negative slopes separately. This is more informative than the sum because it determines if the sum shows a clear trend or just a difference in positive and negative slopes.

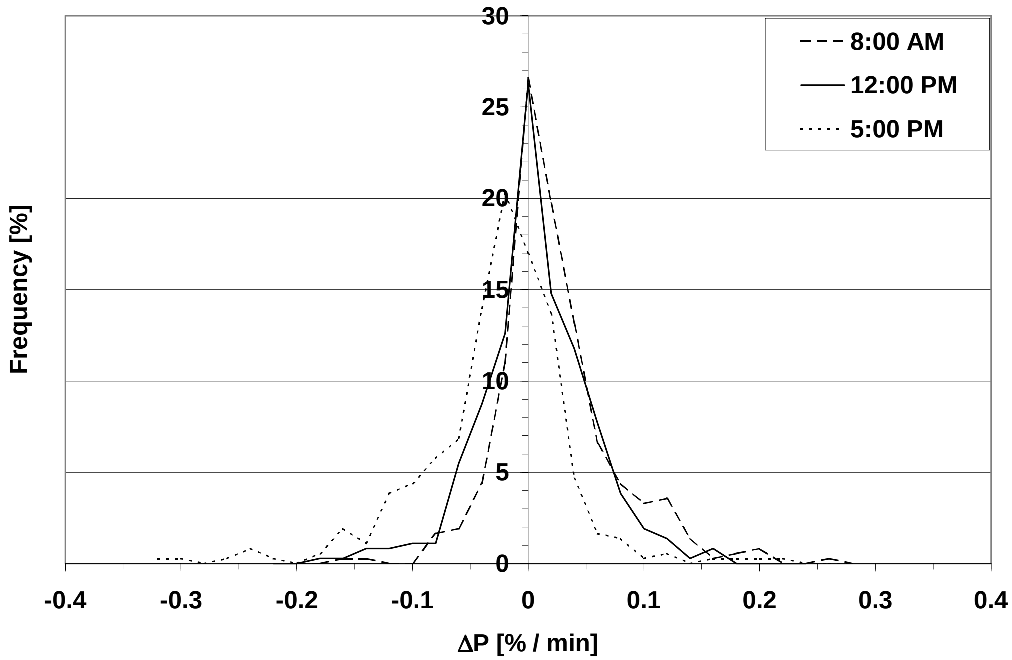


FIGURE 1. DISTRIBUTION OF THE SLOPE OF A ONE-HOUR REGRESSION FOR THE TOTAL OUTPUT OF 176 TURBINES (GROUP 1)

The analysis shows that between 15 % and 50 % of the time there is essentially no change (the slope is in a band between –0.01%/min and 0.01%/min which is interpreted as zero). If there are changes, they will be very small. The biggest change that occurs at group 1 is 0.24%/min or 14.4 %/h and occurs only once. For group 2 changes are more likely and bigger in value because of the fewer number of turbines.

Although the wind in Germany is mostly driven by weather fronts, a daily pattern caused by the sun is evident. That is why I divided the year in two parts, the first one from October to March when you have fast winds and little sunshine and the second one from April to September when the average wind speed is slower and sunshine is more likely.

In the winter a daily pattern is also evident. The changes that occur most likely follow the daily load pattern, which actually helps the utility. Not only the resulting change but also the positive and negative changes show this behavior. Especially in the summer there are almost no days with a decrease in the morning and with an increase in the afternoon. This behavior is most distinctive for the group 1 because of the many turbines and the large area they are placed on. However, group 2 still shows a similar pattern as group 1 (Figure 3) .

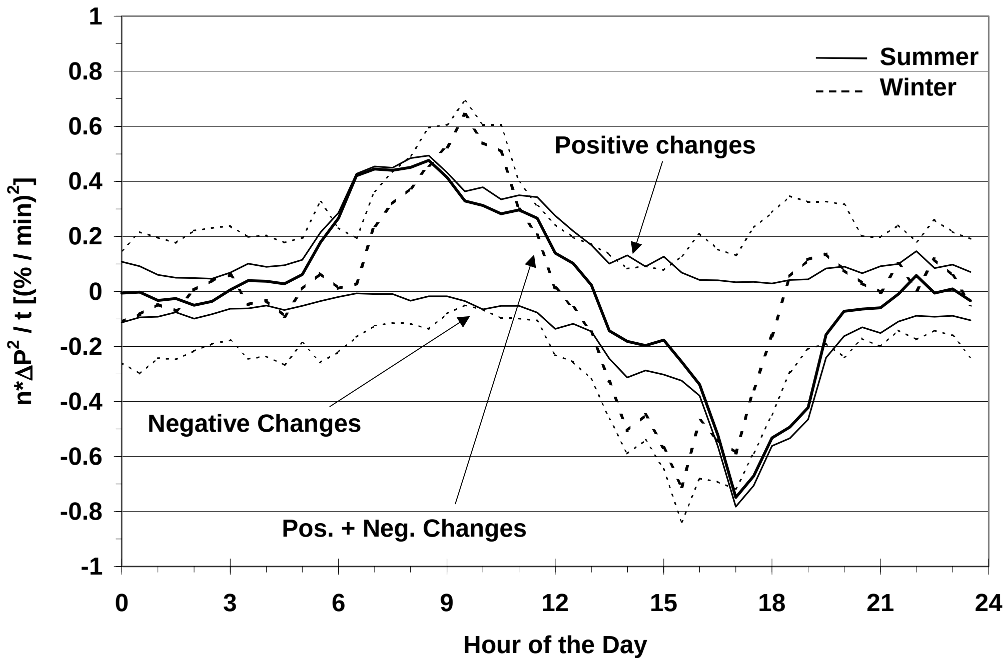


FIGURE 2. NUMBER OF OCCURRENCES WEIGHTED WITH THE SQUARE OF THE SLOPE OF THE ONE-HOUR REGRESSION FOR THE TOTAL OUTPUT OF 176 TURBINES (GROUP 1)

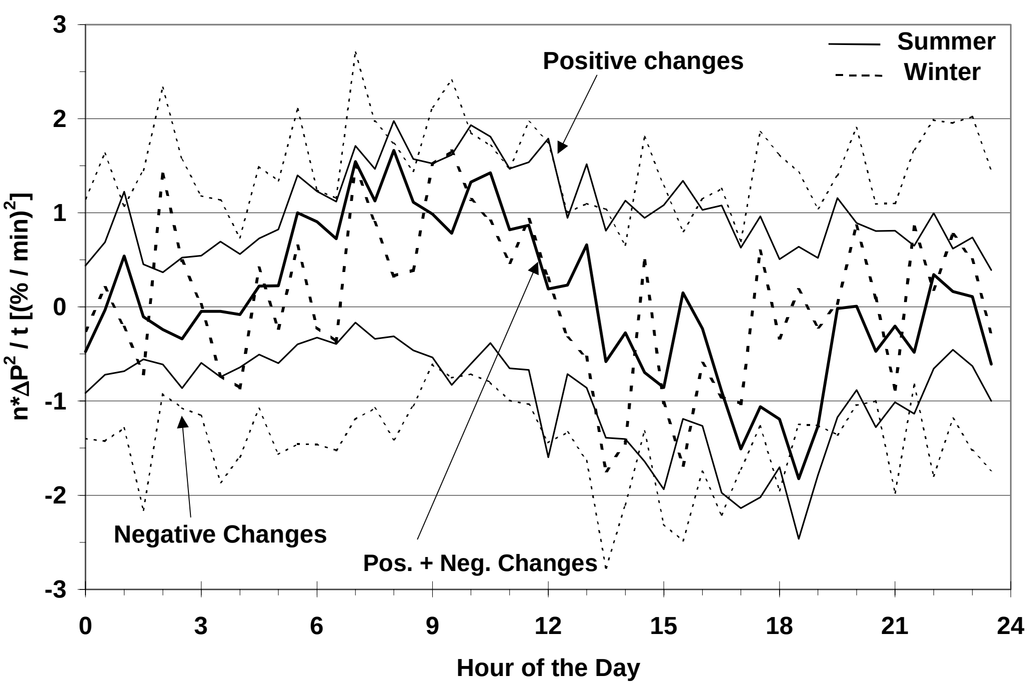


FIGURE 3. NUMBER OF OCCURRENCES WEIGHTED WITH THE SQUARE OF THE SLOPE OF ONE-HOUR REGRESSION FOR THE TOTAL OUTPUT OF 17 TURBINES PLACED AT THREE SPOTS (GROUP 2)

REGULATION

There are several ways to separate regulation from load following. A convenient method for after-the-fact analysis is to use a 60-minute rolling average (30 minutes before and 30 minutes after). Regulation is the difference between the actual signal and the rolling average. The standard deviation of the regulation is a good measurement for the regulation burden. This technique has the advantage of providing a smooth transition between measurement periods. The technique has the disadvantage that data must be available for 30 minutes before and 30 minutes after the analysis period. Hence an hour of analysis is lost. This is a serious disadvantage if you have only a short data set available.
Up to now the utilities look for minute-to-minute fluctuations but they may look at 30 second average data in the future to catch even faster fluctuations. That is why I used 30-second data for these calculations. Only 5 minute data is usually stored in the database within the “250 MW Wind” Program, but it is possible to obtain 10 Hz data online via modem.

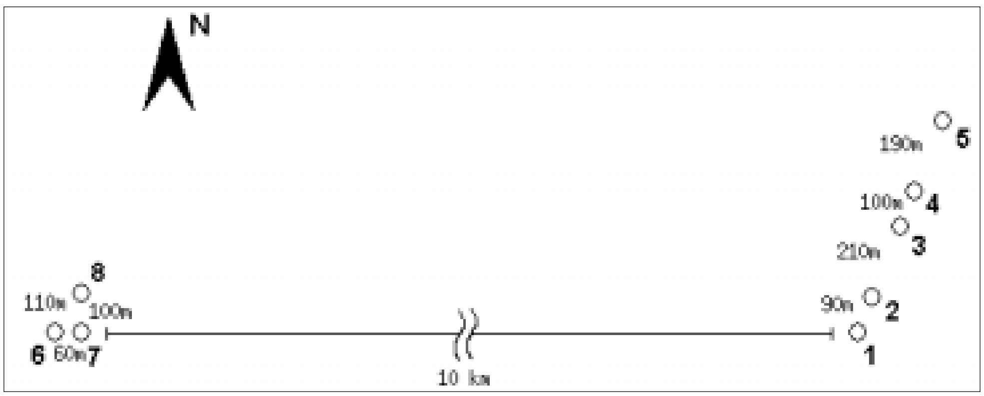


FIGURE 4. MAP OF TURBINES FOR THE REGULATION ANALYSIS

The 30-second data sets are typically only one to two hours long. I used the corresponding 5 minute-data to calculate the rolling averages at the start and end of each data set because the data sets were already so short. This procedure allowed me to use the whole 30-second data set for the regulation analysis.

On the analyzed site (Figure 4), the turbines are different in type and size so I normalized the power output to the average power of the data set to make them equal in size.

I did the analysis for different numbers of turbine and constellations to see the affects of the regulation burden. For each constellation I performed the calculation with all data sets and took the average. Because of different lengths of data sets, I used a weighted average depending on the length of each data set.

Figure 5 shows an example of the regulation. It shows actual power output, rolling average, and their difference for both a single turbine and a grouping of 6 turbines. The smoothing effect of the wind plant is easy to see. The regulation is relatively smaller for the wind plant than for the single turbine. To measure the smoothing effect I calculated the ratio between the standard deviation of the regulation for the total output, and the sum of the standard deviation of the regulation for the single turbines. The ratio shows the reduction in regulation burden that results from a constellation of turbines. A lower ratio means a lower relative regulation burden. The ratio for this data set is 50.2%. Following statistical rules the ratio should be equal to the square root of n divided by n where n is the number of turbines. In this case, the ratio should be 40.8%. However, the rule only applies if the signals are uncorrelated and have the same distribution. Turbines that are closely spread, as in a wind plant are of course not uncorrelated (see Correlation) and their power signals do not have exactly the same distribution. This explains why the ratio is indeed higher than the theoretical value.

Table 1 displays different constellations and the ratios I analyzed. The solid dots, in the icon, show which turbines were respectively considered for the constellation. At the constellations one to three, you can see that the ratio increases with the decrease in the number of turbines. The constellations four to seven all have three turbines but with different distances increasing from constellations four to seven. With increasing distance there is a decrease in the ratio value.

For constellation seven, the turbines are spaced 200 m (660 ft) and 400 m (1320 ft) apart which is quite typical for wind plants with large modern turbines. The ratio is 60%, and the theoretical value is 57%. This trend indicates that closely spaced turbines (like at a wind farm) does not decrease the benefit of having a large number of turbines. This trend also demonstrates that the correlation of the 30-second average data within a wind plant is not as high as one might expect. Even if longer average times are analyzed (like five minutes) the ratio is still close to the theoretical value.

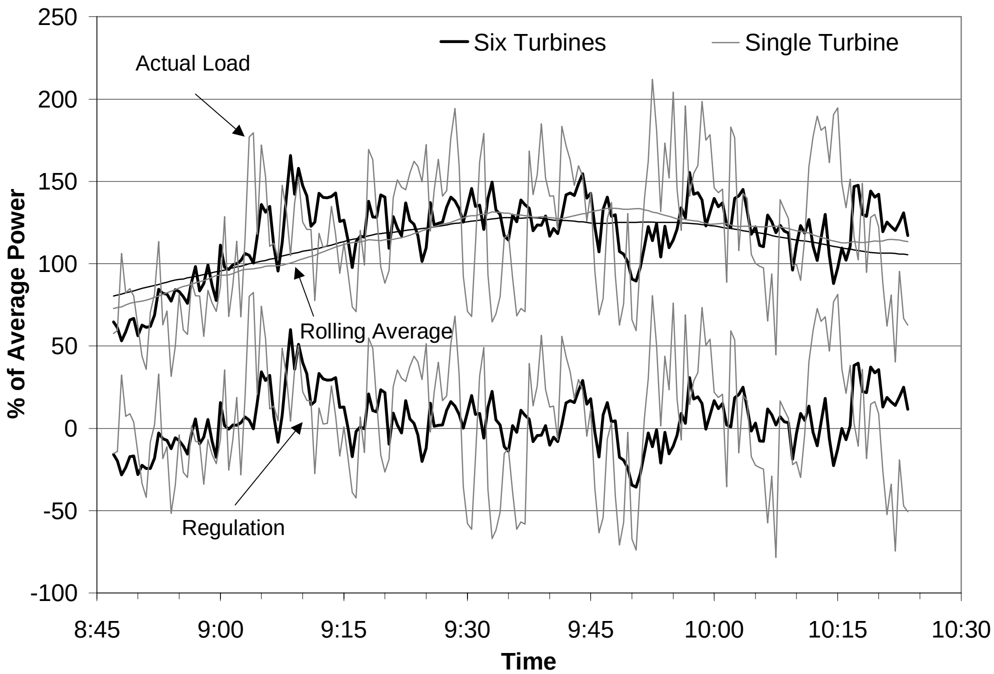
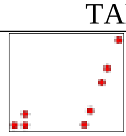
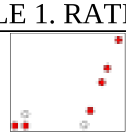
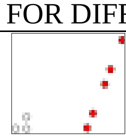
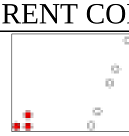
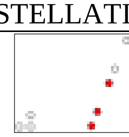
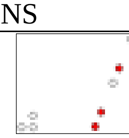
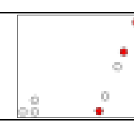


FIGURE 5. ACTUAL POWER, ROLLING AVERAGE AND REGULATION FOR A WIND PLANT AND A SINGLE TURBINE

TABLE 1. RATIO FOR DIFFERENT CONSTELLATIONS

Icon							
Constellation	1	2	3	4	5	6	7
Ratio, 30s data	0.449	0.523	0.534	0.853	0.669	0.642	0.603
Ratio, 5min data	0.501	0.533	0.572	0.904	0.712	0.672	0.623
Theoretical Ratio	0.354	0.408	0.447	0.577	0.577	0.577	0.577

The absolute value of the standard deviation of the regulation is a quantum for the regulation burden. Unfortunately it is yet not quantified how much it will cost to regulate the fluctuations because this depends primarily on the system where the wind plant is located.
I also did the calculation for all of the constellations with the five-minute data to see if I could also quantify the ratio with five-minute data also. This quantification is important because I have five-minute data of the last few years available from over 200 German turbines.

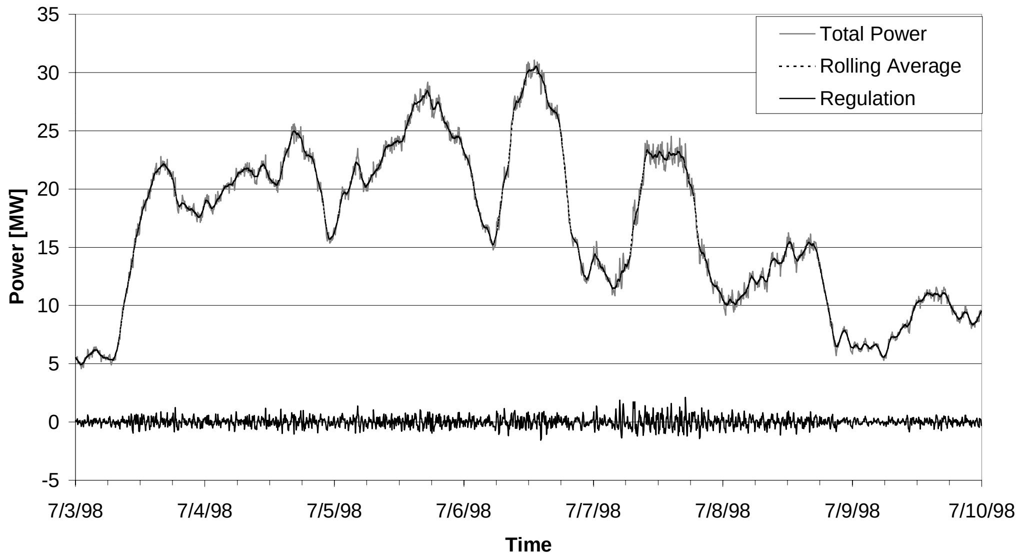


FIGURE 6. ACTUAL POWER, ROLLING AVERAGE AND REGULATION FOR GROUP 1

This method doesn't work to find out about the absolute regulation burden, but the ratio came out about the same value. This finding encouraged me to do more calculations with five-minute data to learn more about the effects of number of turbines. Figure 6 shows the regulation for group 1 over a period of one week in June. I did this calculation twice. The first time I did it with the absolute power and the second time I normalized the power output of each turbine to it's rated power. The turbines were all treated as if they were all the same size. The size of the turbines of group one varies from 30 kW to 1.5 MW. When using absolute power, large turbines appear to have more influence. Thus, there appears to be fewer turbines than there actually are. Obviously, this is actually occurring but with the normalization you can see the pure effects of increasing the number of turbines. This trend may be interesting for transferring the results to other areas. The ratio I calculated was 12.4% with absolute power data and 9.5% with relative power data while the theoretical value is 7.5%.

CORRELATION

As seen before, more distance between turbines necessitates fewer ancillary services. This trend is due to the correlation between the turbines. The farther the turbines are apart the less they are correlated. To see how correlated they are, I calculated the correlation coefficient for different distances. I used the change in power ΔP from one step to the next instead of the absolute power. From the ancillary services viewpoint, this is more interesting than the absolute power. I took five-minute data from two sites with a high availability and looked at the correlation with all the other turbines.
Figure 7 shows the results not only for five-minute average times but also for up to twelve hours as well. I classified the distance between the turbines that I compared. The displayed lines are the averages of these classes. Because of the long times these calculations needed, I did it not for the whole year but only

for three months in the summer and three months in the winter. There is not a significant difference between the two seasons so I displayed only the average over both seasons.

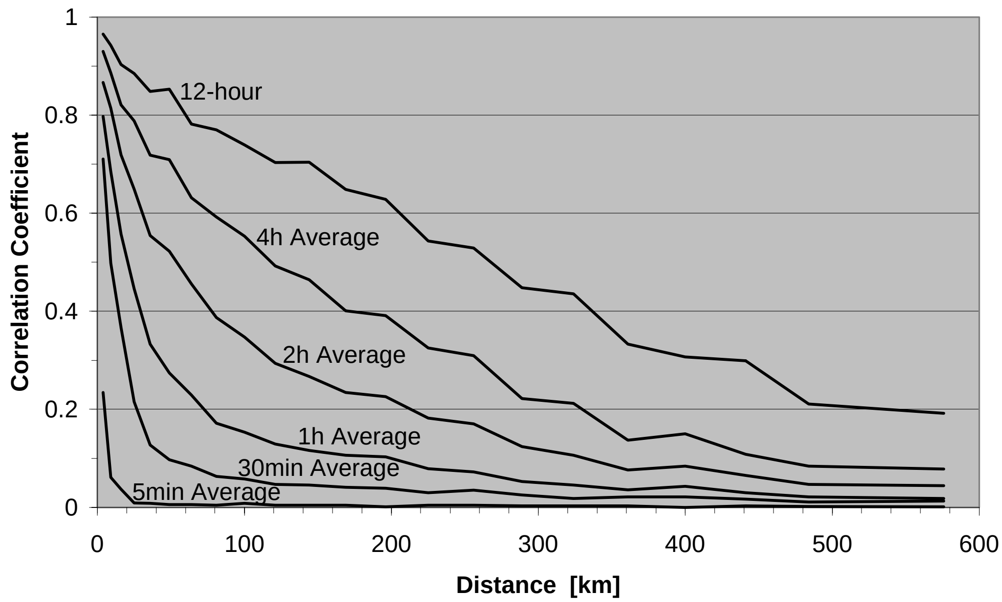


FIGURE 7. CORRELATION COEFFICIENT OF ΔP FOR DIFFERENT AVERAGE TIMES OVER THE DISTANCE

The correlation coefficient for five-minute data already drops down to almost zero after a few kilometer. According to the regulation where you look at 30s or 1 minute averages turbines standing even closer would be uncorrelated.

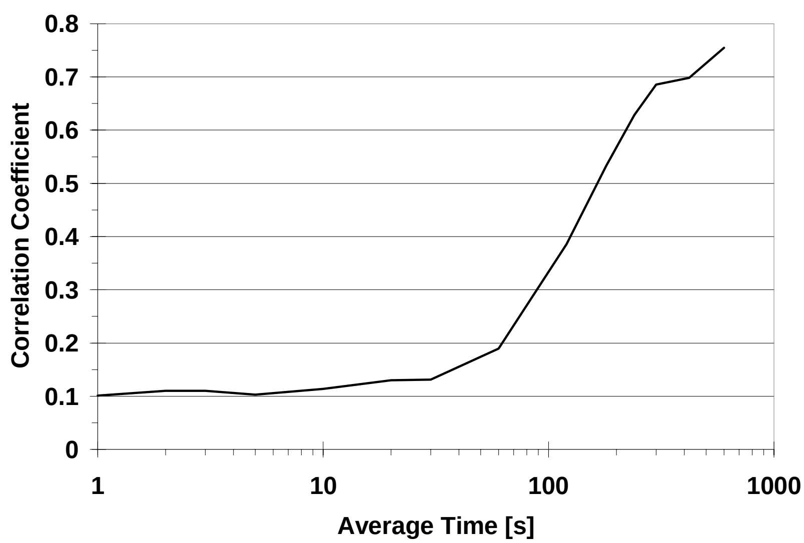


FIGURE 8. CORRELATION COEFFICIENT OF *ΔP* OVER THE AVERAGE TIME FOR TWO TURBINES WITH A DISTANCE OF 170 M

After doing the calculations with five-minute data, I used the 10 Hz data sets to look at turbines standing closer together at even shorter average times. Figure 8 shows the correlation coefficient of two turbines at a distances of 170m for different average times. At an average time of 10 minutes, they are very highly correlated which was expected. Up to one minute, the correlation coefficient is under 0.2, which means they are mostly uncorrelated. That explains why closely spaced turbines can obtain high benefits in terms of regulation burden. Fluctuations up to a few seconds are caused by the wind and by the control mechanism such as those regulated for variable-speed machines.

CONCLUSIONS

This paper has analyzed wind power data in the context of ancillary services. A large number of turbines and spatial spread may decrease the ancillary service requirements substantially. The results for load following are probably unique to the German weather conditions, and it is not clear that wind plants elsewhere would show the same behavior. However, the results of the regulation and the correlation analysis are transferable to other sites.

Correlation analysis of the data shows clear spacing diversity of wind turbine outputs. Wind turbines that are only a couple of kilometers apart are almost totally independent during a short average time like five minutes. The data also confirm that during a shorter time period, wind turbine output within a wind farm is mostly independent. Turbulence within the local wind field accounts for this phenomenon.

Load following analysis suggests that during a longer time frame, wind generation in Germany have a regular pattern. Based on the available data, the power level of wind generation is generally increasing in the morning and decreasing in the afternoon. In addition there is a chance between 15% and 50% of that the power output does not show a trend over an hour. For wind power plants that have similar behavior to those studied here, a wind turbine operator in an ancillary service market would generally expect to be paid for the load following provided by the wind plant. The operator would be billed for the hours that the power output does not follow the system requirements.

Spatial diversity of wind resources helps to reduce regulation burdens of wind power. However, the regulation analysis in this report suggests that the number of turbines have more influence on the regulation burden than the physical separation of wind farms.

Finally, further measurements are necessary to analyze big wind farms in the US. NREL has begun a collaborative data collection project. Analysis of this data, when it becomes available, will provide important insights to wind farm behavior in the US.

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