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Short-Term Power Fluctuation of Wind Turbines: Analyzing Data from the German 250-MW Measurement Program from the Ancillary Services Viewpoint

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SHORT-TERM POWER FLUCTUATION OF WIND TURBINES: ANALYZING 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 may affect interconnected-grid operating costs and stability. With the increasing availability of wind power worldwide, this has become a concern for some utilities. Under electric industry restructuring in the United States, the impact of these fluctuations will be evaluated by examining provisions and costs of ancillary services for wind power. However, the magnitude of the impact and the effect of aggregation of multiple turbines are not well quantified due to a lack of actual wind farm power data. This paper analyzes individual turbine and aggregate power output data from the German "250-MW Wind" 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. The results 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 during the past 15 years. This resulted in 1,500 megawatts of capacity installed in California in the late 1980s. 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 various forms of public support. In the United States the tax credit program has stimulated substantial new wind capacity. New capacity is or has recently been under development in Minnesota, Iowa, Texas, California, Wyoming, and other states. More than 10,000 MW of installed capacity worldwide was reached in April 1999; this capacity is expected to grow continuously during the next few years.

Against this background, the ability to integrate 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 frames such as seconds or minutes, and longer time frames, such as more than 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 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. For this report, we used power output data from the German "250-MW Wind" data project to analyze the ancillary services for individual turbines up to the aggregated power output from all turbines within the monitoring program. Furthermore, we analyzed the effects of turbine spacing from the ancillary services viewpoint, and examined how the operators can benefit from a large number of turbines and their spatial spread.

DATA SOURCE

Database 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 (Institute for Solar Energy Supply Technology [ISET]) 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.

WMEP Remote Data Acquisition Network

At 230 selected sites, data loggers and wind measurement equipment were installed. Data loggers were connected to the central database 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 were derived from this raw data. In addition, 10-Hz raw data could 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 functions such as scheduling and dispatch, load following, regulation, reliability reserve, and voltage control. In the past, these services had been provided by the local utility. But with the restructuring of the electricity market, they have been separated from generation and transmission. 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 of the most 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 operator must either buy regulation or provide it with a conventional dispatchable generator. He or she may also buy or sell load-following services depending on the match of wind turbine output and load demand. 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. Variable-speed turbines could use the momentum of the rotor and the generator to respond to frequency deviation and provide spinning reserve. 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 because of 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 stops 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 may require less supplemental reserve with wind turbines than with 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 within a control area. We extended the time frame and examined at the trend from one to four hours to determine if during the course of a day the wind power correlated with power demand. The five-minute average data of the aggregated power of two groups of turbines were used for this analysis. The first contains 176 turbines placed all over Germany. The second group has 17 turbines at three sites 200 km (120 mi) to 300 km (180 mi) apart. Linear regressions were performed on data sets with different time frames. 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 whereas longer regressions such as two to four hours show longer trends.) The resulting slope values for every hour were divided in classes of 0.1% of rated power per five minutes (or 0.02% per minute) and tabulated. The process was carried out everyday in the summer to see if there was a significant behavior at specific times of the day. Figure 1 shows the distribution of the slope for a one-hour regression at 8:00 a.m., 12 p.m., and 5:00 p.m. in the summer.

Several different graphs which were useful for identifying how often each slope occurs were chosen to display the results of this calculation for the summer and the winter seasons. 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. This suggests that in the morning the wind generation levels are more likely to increase than decrease, and in the afternoon, the opposite is true. However, this graph permits visualization of only a few time periods.

To display the whole day, a weighted slope graph is presented in Figure 2. In this graph the slope values were squared then multiplied by the number of occurrences for each half hour of the day. This operation has the effect of equating 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 following provides further explanation of the lines in Figure 2.

Positive and 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.

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; this 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 we divided the year into 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.

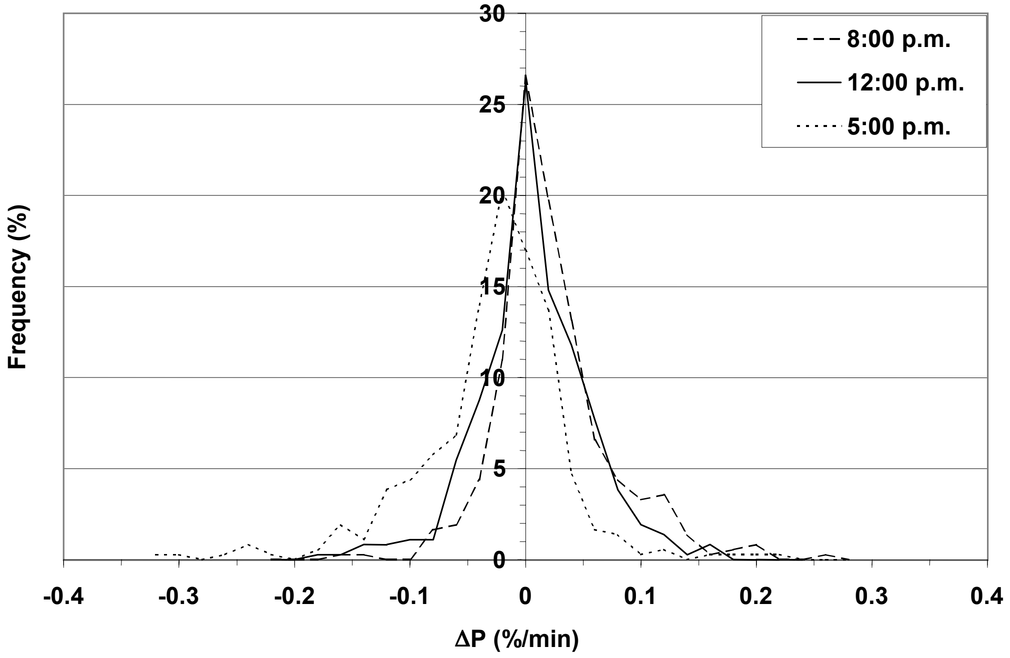


Figure 1. Distribution of the slope of a one-hour regression for the total output of 176 turbines (Group 1)

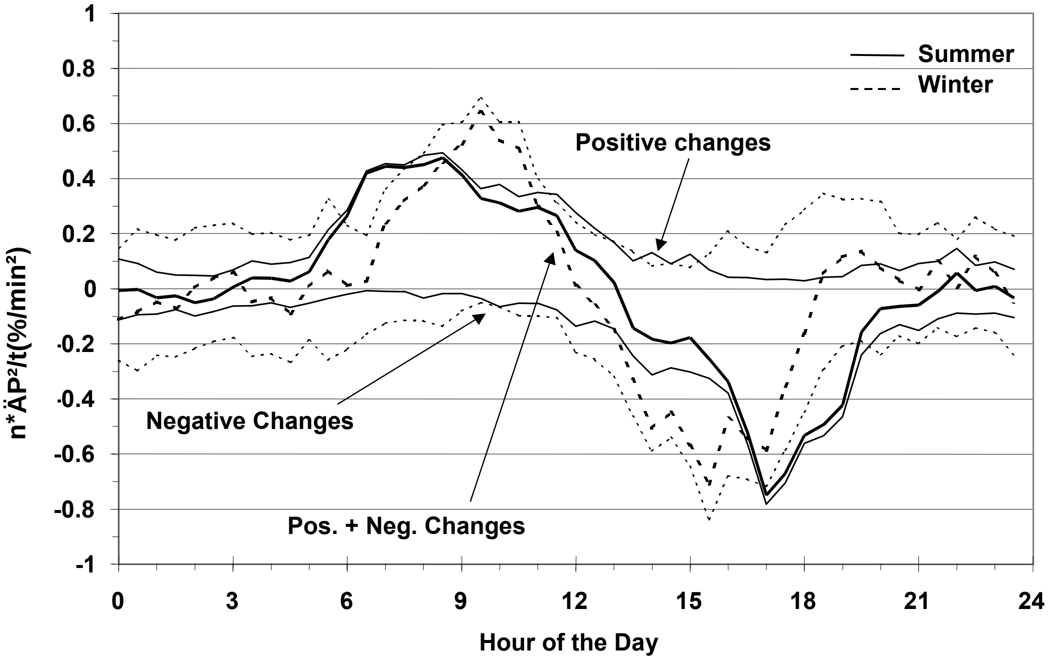


Figure 2. Number of occurrences weighted with the square of the slope of the one-hour regression for the total output of 176 turbines (Group 1)

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 Group 1 because of large number of the turbines and the large area they are placed on. However, Group 2 still shows a pattern similar to that of Group 1 (see Figure 3).

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. Currently, utilities look for minute-to-minute fluctuations; however, they may look at 30-second average data in the future to catch even faster fluctuations. That is why we used 30-second data for these calculations. Only 5-minute data is usually stored in the database within the "250-MW Wind" project, but it is possible to obtain 10-Hz data on-line via modem.

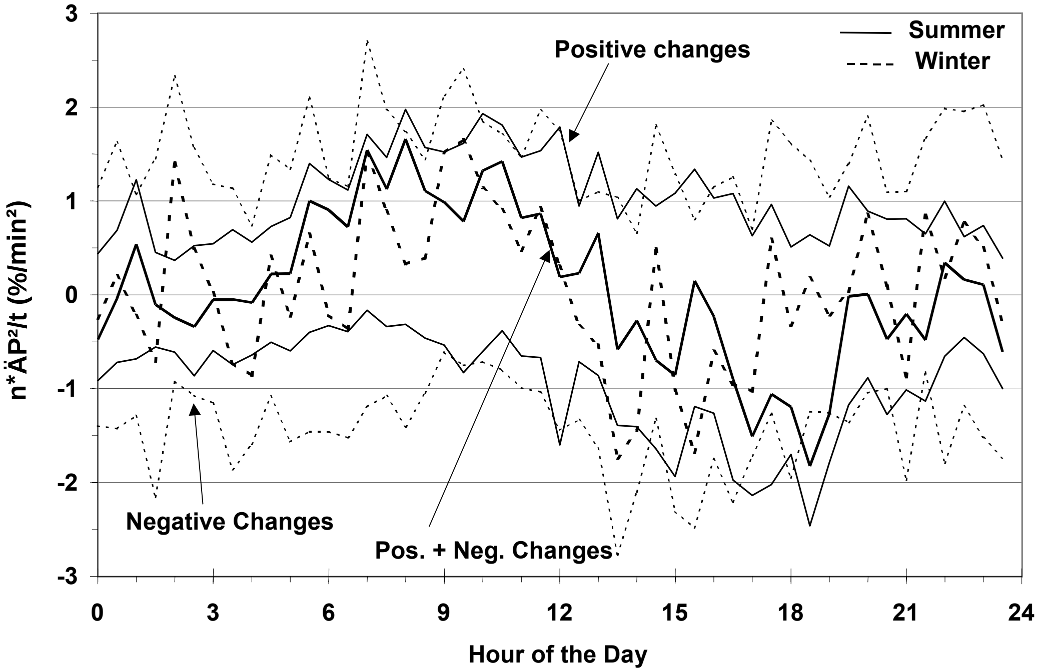


Figure 3. Number of occurrences weighted with the square of the slope of one-hour regression for the total output of 17 turbines placed at three spots (Group 2)

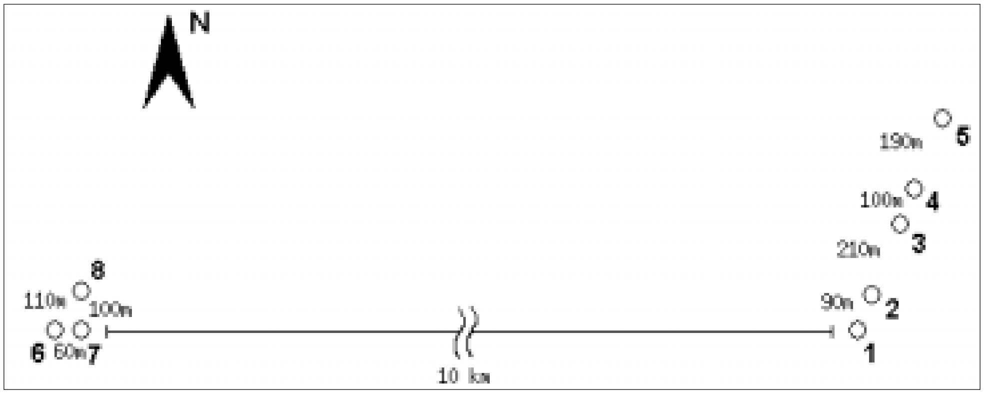


Figure 4. Map of turbines for the regulation analysis

The 30-second data sets are typically only one to two hours long. The corresponding 5-minute data were used 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 us to use the whole 30-second data set for the regulation analysis. On the analyzed site (see Figure 4), the turbines are different in type and size. The outputs were normalized with respect to each turbine's average power of the data set to eliminate the size discrepancies.

The analyses were carried out for different numbers of turbine and constellations to see the effects of the regulation burden. For each constellation the calculation was performed with all data sets and an average was taken. Because of different lengths of data sets, a weighted average is derived 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 six 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, the ratio between the standard deviation of the regulation for the plant output is calculated, as is 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%. If the turbine outputs were totally uncorrelated, theoretically 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 theoretical ratio should be 40.8%. However, these turbines are closely located in a wind plant, and 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 calculated ratios. The solid dots, in the icon, show which turbines were respectively included for the constellation. At the constellations one to three, 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 spacing turbines (similar to 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 (5 minutes in this case) the ratio is still close to the theoretical value.

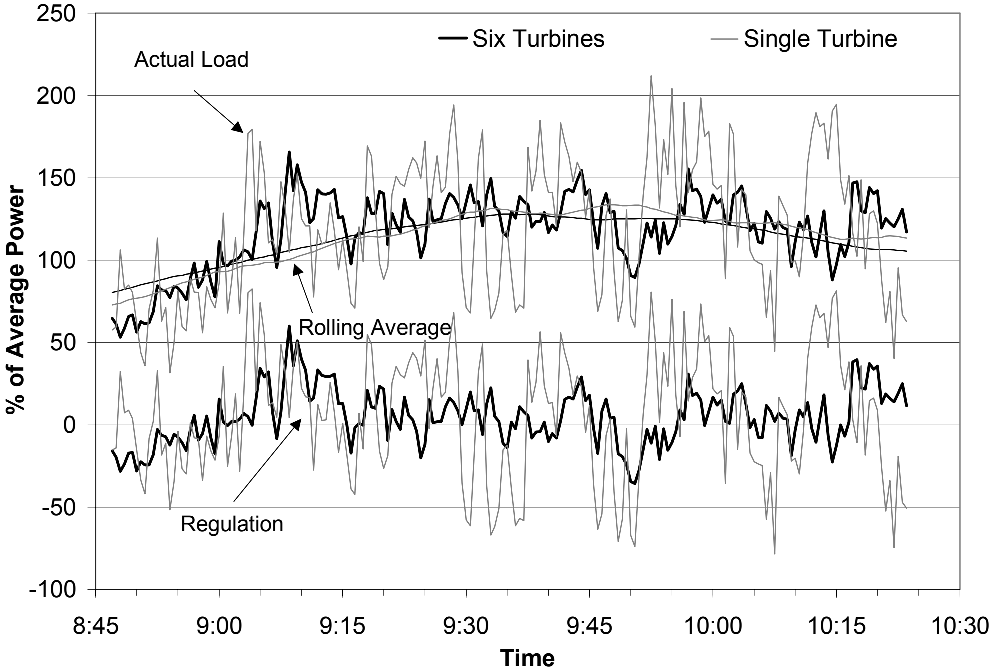
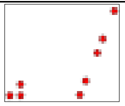
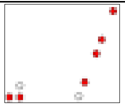
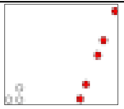
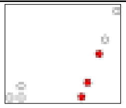
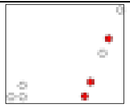
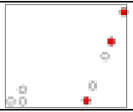


Figure 5. Actual power, rolling average and regulation for a wind plant and a single turbine

Table 1. Ratio for different constellations

Icon							
Constellation	1	2	3	4	5	6	7
Ratio, 30-s data	0.449	0.523	0.534	0.853	0.669	0.642	0.603
Ratio, 5-min 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. However, the cost of regulating the fluctuations has not yet been quantified, because this depends primarily on the system where the wind plant is located. The same calculations with all of the constellations were performed with the 5-minute data. This quantification is important because 5-minute data of the last few years are available from more than 200 German turbines.

Although the 5-minute data analyses cannot tell us the absolute regulation burden, the resulting ratios display a similar pattern. Figure 6 shows the regulation for Group 1 for a one-week period in June. This calculation was performed twice: the first time with the absolute power and the second time with the power normalized by each turbine's rated power. (The turbines all behaved as if they were all the same size.) The size of the turbines in Group 1 varied from 30 kilowatts to 1.5 MW. When using absolute power, large turbines have more influence. Thus, there appear to be fewer turbines than there actually are. Obviously, this is what actually occurred. However, with the normalization, the effect of increasing the number of turbines is clearly seen. This trend may prove interesting when the results are transferred to other areas. The ratio with absolute power was calculated at 12.4% and 9.5% with relative power data. Theoretically this value should be 7.5% if the turbine outputs are totally uncorrelated.

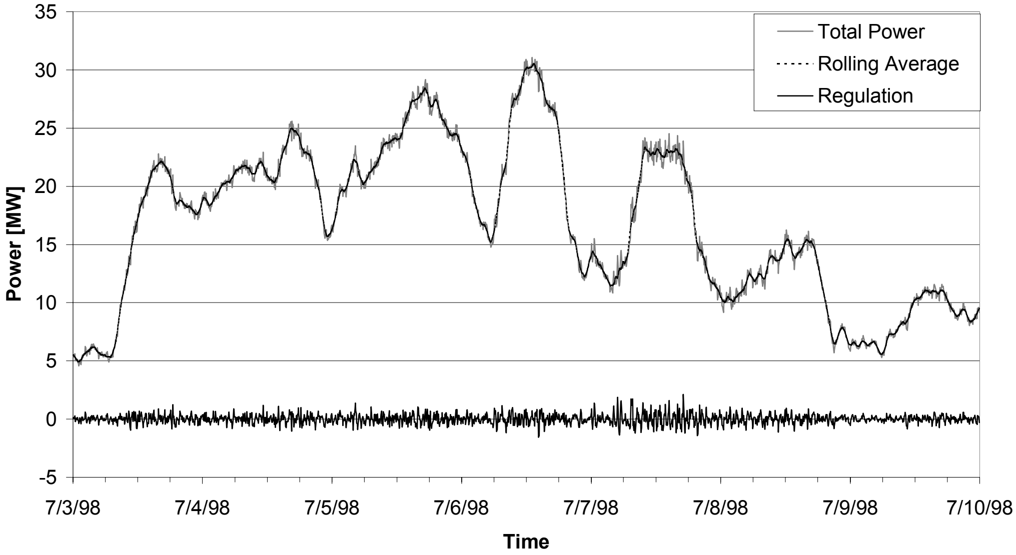


Figure 6. Actual power, rolling average and regulation for Group 1

CORRELATION

As seen before, more distance between turbines necessitates fewer ancillary services. This trend is due to the correlation between closely sited turbines. The farther the turbines are apart, the less they are correlated. To see how correlated they are, the linear correlation coefficients for different distances were calculated. The changes in power ΔP from one step to the next were used in the calculations instead of absolute power. When considering the ancillary services, this is more interesting than the absolute power. Five-minute data from two sites with a high availability were used. Figure 7 shows the results not only for 5-minute average times but also for as many as 12 hours as well. Because of the length of time required for these calculations, it was not done for the whole year but only for three months in the summer and three months in the winter. As there is no significant difference between the two seasons, only the average over both seasons is displayed.

The correlation coefficient for 5-minute data already drops down to almost zero after a few kilometers. The regulation calculations with 30-second or 1-minute averages suggest that turbines standing even closer would be uncorrelated.

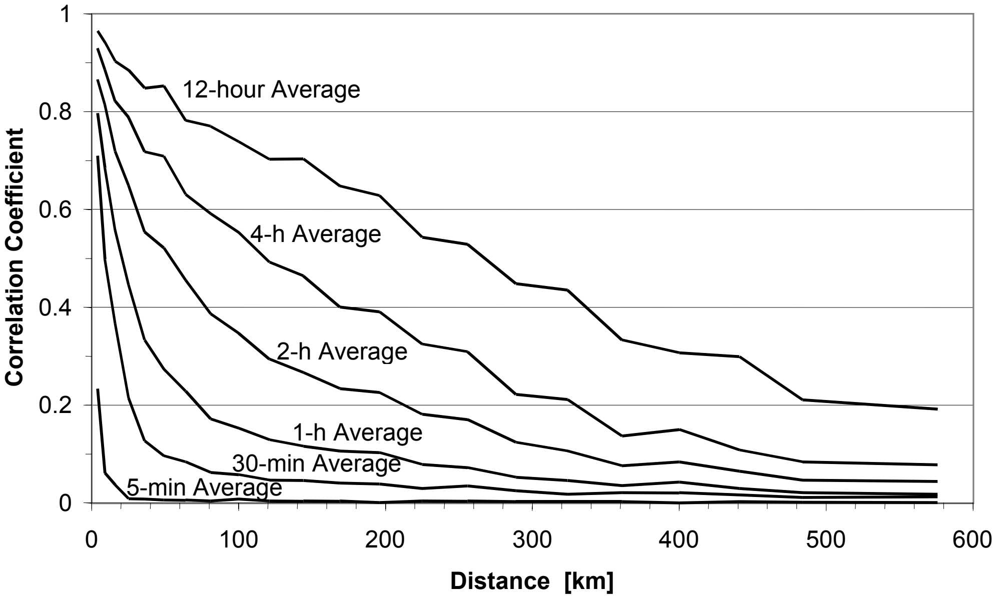


Figure 7. Correlation coefficient of Δp for different average times over the distance

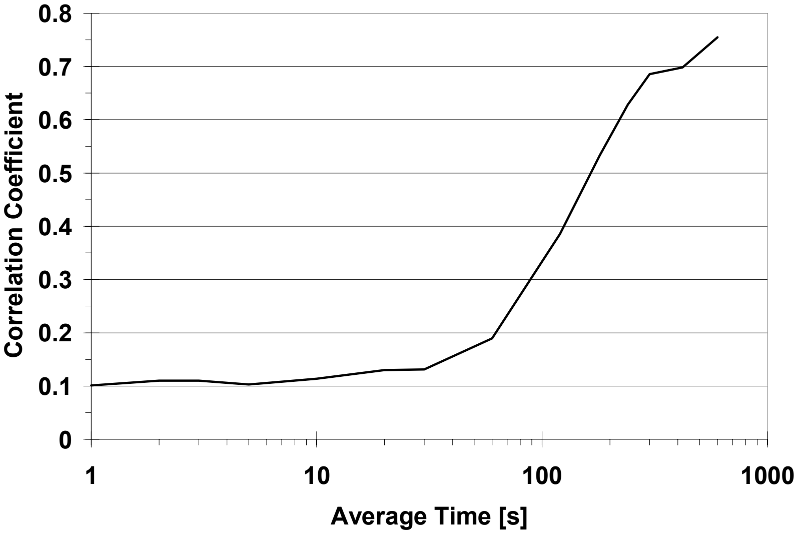


Figure 8. Correlation coefficient of *Δp* over the average time for two turbines with a distance of 170 m

After doing the calculations with 5-minute data, we used the 10-Hz data sets to examine turbines standing closer together at even shorter average times. Figure 8 shows the correlation coefficient of two turbines at a distance of 170 m (560 ft) for different average times. As expected, they are very highly correlated at an average time of 10 minutes. Up to 1 minute, the correlation coefficient is under 0.2, which means they are mostly uncorrelated, thus explaining 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

We have analyzed wind power data in the context of ancillary services. A large number of turbines and spatial spread may decrease the relative ancillary service requirements substantially. The results for load following are probably unique to the German weather conditions; it is not clear whether 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 (e.g., 5 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 has a regular pattern. It is clear from the available data that 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%) that the power output does not show a trend over the course of an hour. For wind power plants that have similar behaviors 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 has 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 United States. The National Renewable Energy Laboratory (NREL) has begun a collaborative data collection project. Analysis of this data, when it becomes available, will provide important insights regarding wind farm behavior in the United States.

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