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Technical Report

Analysis of Wind Power Ancillary Services Characteristics with German 250-MW Wind Data

Bernhard Ernst

NREL

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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, power fluctuations have 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 wind turbines are not well quantified because of a lack of actual wind farm power data. This paper analyzes individual wind turbine and aggregate power output data from the German "250 Megawatt Wind" data project. Data from as many as 175 turbines were examined. Most of the turbines are located in Northern Germany within a 120,000 square kilometer area. Electric system load following and regulation impacts are examined as a function of the number of wind turbines and turbine spacing to quantify the impacts of aggregation. The results show a significant decrease in the system regulation burden with increasing number of wind turbines, even if the wind turbines are in close proximity. Fluctuations of average power in time intervals ranging from a few seconds to five minutes are examined to help define needs for future wind farm data measurement efforts.

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1. Introduction

The application of wind energy worldwide has increased rapidly during the past 15 years. In the United States, 1500 megawatts (MW) of capacity was installed in California in the late 1980s and a tax credit program stimulated substantial new wind capacity in many of the states. Minnesota, Iowa, Texas, California, and Wyoming have either developed or are currently developing new wind capacity. Denmark, Germany and more recently, Spain also encouraged an increase in wind energy with various forms of public support. This European trend, which started in the early 1990s, has continued to present. As of April 1999, more than 10,000 MW of capacity had been installed worldwide and the capacity is expected to continue growing during the next few years.

As the application of wind power increases, the ability to integrate significant levels of wind power in the existing grid becomes more important. And because wind power has to compete with other kinds of generation plants, the quality of the electricity is also an important issue. Because of the intermittent nature of wind, the quality of the electricity is mostly affected by power fluctuations that can occur for short periods of time, such as a few seconds or minutes, or periods of time as long as a couple of hours. Ancillary services provided by utility companies can help ensure the quality of the electricity. 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.” Wind turbine (WT) operators are mainly interested in two of the ancillary services: regulation and load following. Regulation can compensate for second-to-second and minute-to-minute power fluctuations, while load following maintains sufficient generation to match hourly demand trends. Wind turbine operators must either provide or purchase these services, usually from the local utility, to connect the wind turbines to the electric power grid.

A third ancillary service, voltage control, can be provided by injecting or absorbing reactive power into the grid. Turbines with electronic power converters may be able to provide voltage control. In this case, the wind plant operator could sell this service to the utility.

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

2. Data Source

2.1 Wind data

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 Program. The Institut für Solare Energieversorgungstechnik (Institute for Solar Energy Supply Technology [ISET]) in Kassel has been commissioned with the accompanying Wissenschaftliches Meß- und Evaluierungsprogramm (Scientific Measurement and Evaluation Program [WMEP]). This program acquires statistically relevant data on the practical use of WTs.

The two main sources for relevant data are a log book for all WTs in the 250 MW Wind Program and a specific remote measurement network with data acquisition units at selected WT sites.

WMEP Remote Data Acquisition Network

At 230 selected sites, data loggers and wind measurement equipment were installed to complement the data acquired in log books. Data loggers are connected to the central database system at ISET via modem and the public telephone network. Ten Hertz (Hz) raw data can be transmitted on-line for any period without disturbing the statistical long-term measurement. The following signals are measured at a 10 Hz sample rate:

- Electrical power
- Status of the grid connection
- Wind speed
- Wind direction

Five minute mean values and 22 additional statistical measures are derived from this raw data. The results are stored as Long-Term Measurements in separate day files. Each day file contains information about:

- Long-term data (288 five minute intervals)
- Binned wind speed (19 intervals)
- Special event data (started only by pre-set triggers)
- Diagnostics of the measurement equipment
- Measurement parameters.

The day files are transferred to ISET and loaded into the central database system every night.

In addition, extreme situations can be registered by Special Event Measurements. These measurements are started only when pre-set trigger values are exceeded.

Central Database

All the project data acquired by the WMEP, including all measurement data, are managed by a database system at ISET. Most of the software used was custom-made at ISET. It serves the following purposes:

- Support in program management
- Control of data acquisition and remote data acquisition network
- Checking and handling of incoming data
- Basic data processing tasks
- Preparation of data for specific investigations

- Making data accessible to the Renewable Energy Information System on the Internet (REISI)

A relational system is used to ensure that the structure of the database can be adapted to changing requirements during the course of the project. Several additions to the data acquisition instrumentation had been integrated into the original system.

Data Flow, Remote Data Acquisition Network Control

A central database system and supplementing software for controlling the remote data acquisition network are located at ISET. From ISET, the daily transfer of measurement data is automatically initiated and controlled. The incoming data is checked for completion and plausibility and then stored. Missing data is automatically requested the following day. The activation of new measurement sites and the deactivation of faulty data loggers is also controlled by the database. After the raw data is checked, it is further processed by calculating mean and other values for each day, month, or year.

2.2 Steel mill data

Oak Ridge National Laboratory provided the sample steel mill data from a midsize utility used in the Chapter 6.

3. Summation

For the analysis of regulation and load following the first step was to calculate the aggregated power of turbines. I analyzed data from 1998 because this was an average wind year in Germany. As mentioned in Chapter 2, there are 230 turbines within the WMEP equipped with data loggers that measure power, wind speed and wind direction. Because of faulty sensors or damages caused by lightning, ice, or overvoltage, data were not available for all the sites for that year. In 1998, 176 turbines had an availability factor of 90% or more, which is the threshold I used to select the turbine data for this report.

To get the aggregated power I added the available signals for each 5-minute interval and counted the number of turbines and their rated power. For cases in which the power signals were not available, I used the wind speed and measured power curve to calculate the power signal. Using this method I derived an average availability of 97%.

For the aggregation I chose different groups of turbines:

Group 1:
All of the 176 turbines located throughout the country, totaling 46 MW rated power. This group is typical for Europe, especially Denmark and Germany (See Figure 3-1).

Group 2:
Three locations with 8, 4, and 5 turbines. These locations are 160 kilometers (km) to 370 km apart, which is typical of wind plants in the United States (See Figure 3-2).

Group 3:
Fifteen turbines close together to simulate one or two wind plants in a limited area of about 30 km in diameter (See Figure 3-3).

Group 4-8:
Respectively eight turbines each to simulate one or two wind plants in a limited area (approximately 30 km) in different constellations with different distances between the turbines.

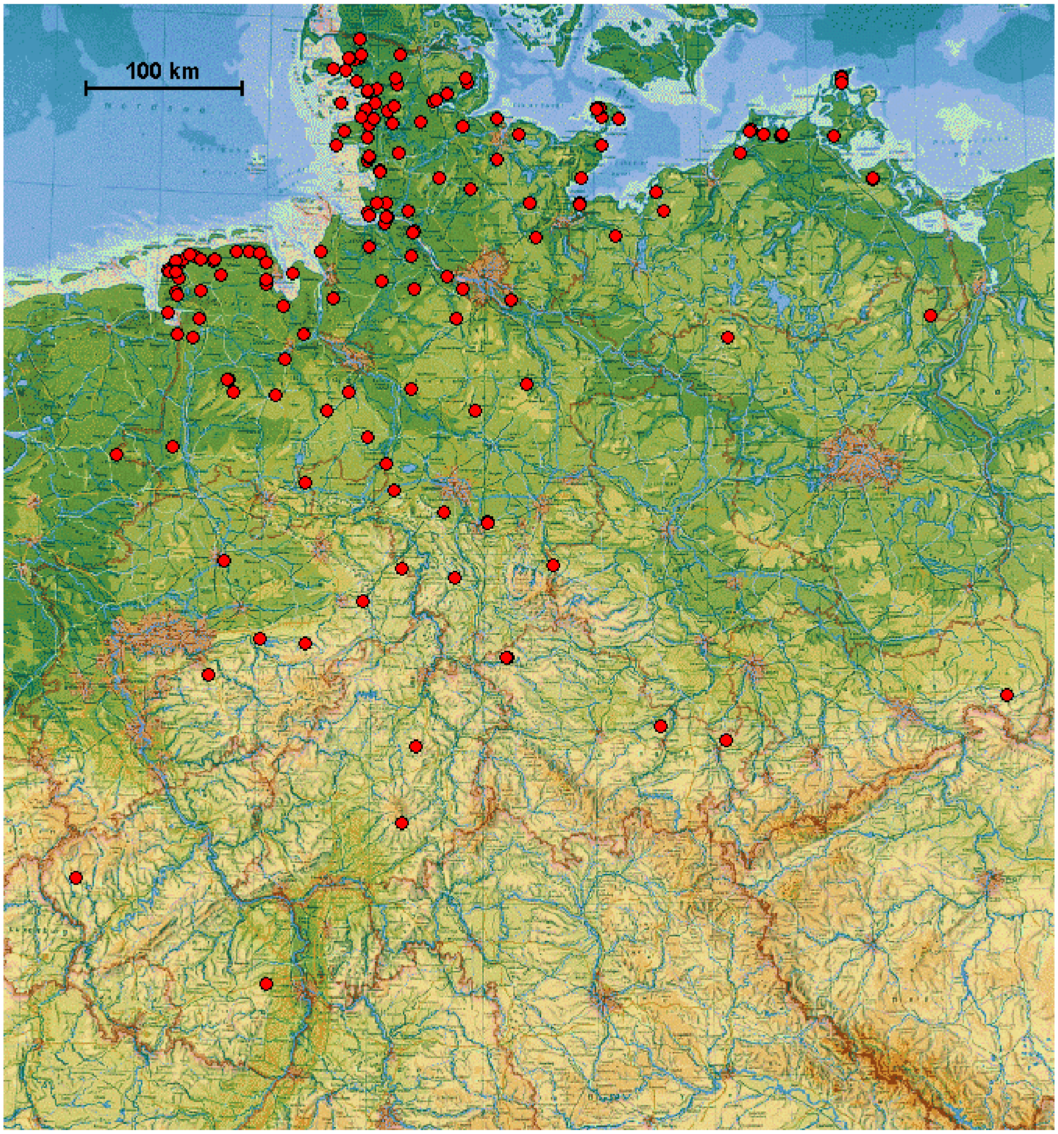


Figure 3-1. Group 1

Figure 3-2. Group 2

Figure 3-3. Group 3

4. Ancillary Services

The term "ancillary services" refers to power system services other than the simple 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 were 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.

The total costs of these services average about 10% of the generation and transmission costs. However, in some control areas they may be as much as 25%.

The following five ancillary services are relevant to wind energy.

- 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.

Wind turbine operators must either buy regulation or provide it with a conventional dispatchable generator, such as a hydropower plant or a fossil fuel-powered generator. Operators may also buy or sell load following services depending on the match of WT output and load demand.

Reactive Supply and Voltage Control from Generation
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.

Frequency Responding/Spinning Reserve
Variable speed controlled machines 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 two seconds at rated power. These turbines could provide stability by increasing or decreasing the power a little for a few seconds.

Supplemental Reserve
Although the output of a single turbine can fail abruptly because of broken components or cut-out because of high wind speed, a wind plant never stops or increases substantially within seconds. It takes at least a few minutes for the total power of a wind plant to come down. Thus, a wind plant operator may require less supplemental reserve with wind turbines than with other generation devices.

4.1 Load Following

Load following tracks the hourly trends in power output and the hourly changes in power demand for a 24 hour period within a control area. I extended the time frame to examine 1 to 4 hour trends to determine if during 24 hours the wind power correlated with power demand. I used the 5-minute average data of the aggregated power of Groups 1 to 3 for this analysis and performed linear regressions on data sets with time frames ranging from 1 hour to 4 hours. The linear regression finds a straight line that fits best for 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 for a longer time. (Short time frames [1 hour] show the momentary changes while longer-time frame regressions [2 to 4 hours] show longer trends.)

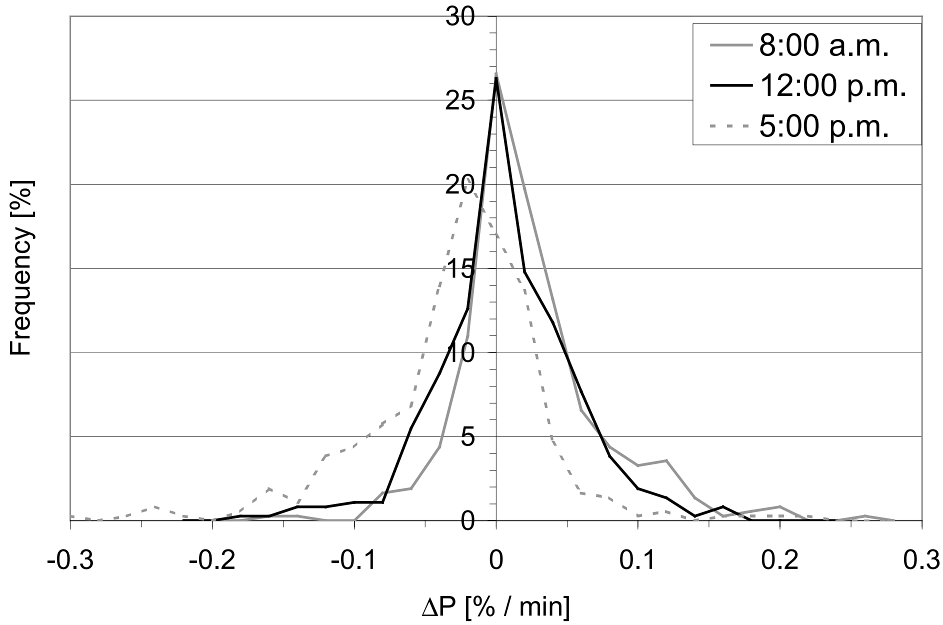


Figure 4-1. Distribution of the slope of a 1-hour regression for the total output of 176 turbines (Group 1)

I divided the resulting slope values for every hour into classes of 0.1% of rated power per 5 minutes (or 0.02 % per minute) and tabulated for every half hour to see if there were significant trends at specific times of the day. For example, for the 1-hour regression at 12 p.m. in the summer, I looked at the slope values from 12 p.m. to 1 p.m. of every summer day and counted how often each class occurred.

Several different graphs identify how often each slope occurs and display the results of this calculation for summer and the winter seasons combined. Figure 4-1 shows the distribution of the slope at 8:00 a.m., 12:00 p.m., and 5:00 p.m. for Group 1. The difference between the morning and the afternoon is evident in this graph. For a.m. hours, the graph shows more positive slopes and for p.m. hours 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. Although this graph is useful for identifying how often each slope occurs, it permits visualization of only a few specific times.

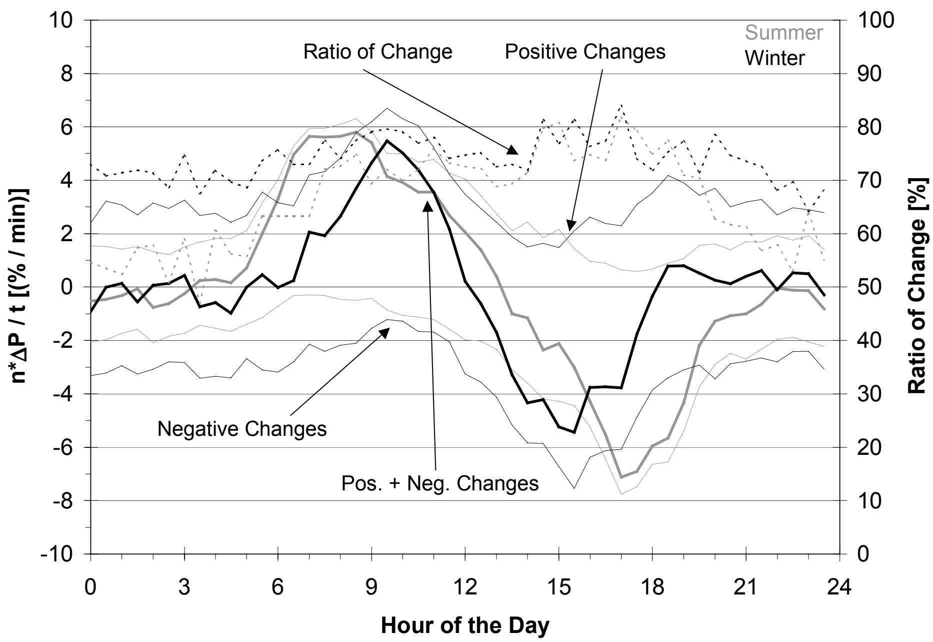


Figure 4-2. Number of occurrences weighted with the slope of the 1-hour regression for the total output of 176 turbines (Group 1)

To display data from an entire day, a weighted slope graph is used in Figure 4-2. In this graph, I multiplied the slope values by the number of occurrences for each 30 minutes time frame throughout the day. This equates one event of 0.1%/min as two events of 0.05%/min. The following definitions provide further explanation of the lines in Figures 4-2 through 4-6.

Ratio of Change
This line shows how often the slope is not equal to zero.

Positive + Negative Changes
This line shows the resulting weighted slope of positive and negative slopes. A positive slope nullifies a negative one and vice versa. A slope of 0%/min does not count.

Positive Changes and Negative Changes
These lines show the weighted regressions 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.

In Figures 4-3 to 4-6 the number of events is multiplied by the square of the slope values. One event of 0.1%/min thus counts for as much as four events of 0.05%/min. This intensifies large changes that may have a bigger impact on the utility.

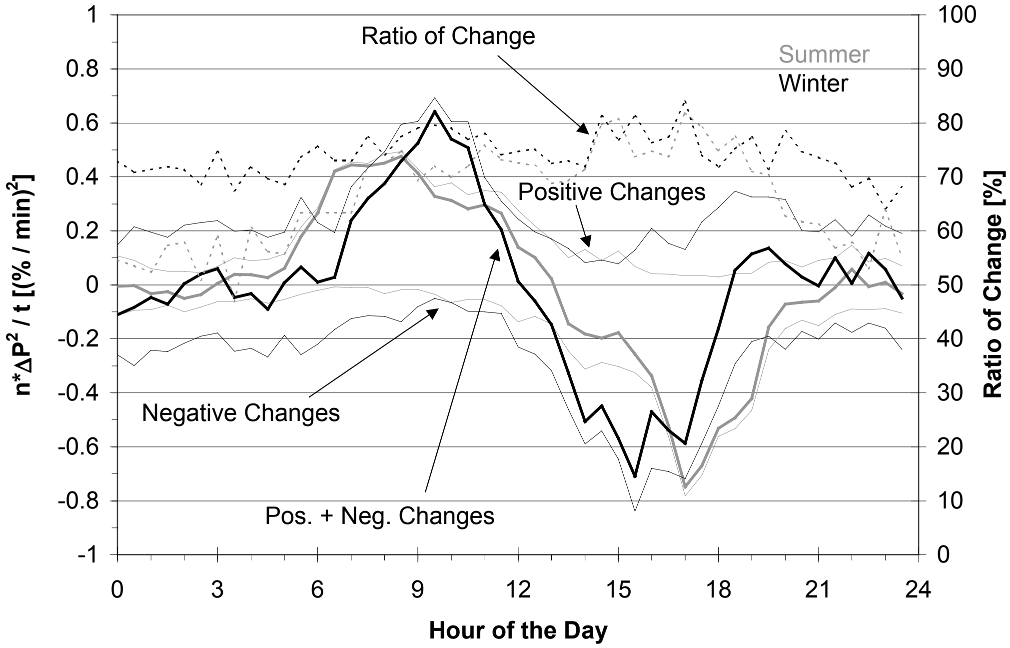


Figure 4-3. Number of occurrences weighted with the square of the slope of the one-hour regression for the total output of 176 turbines (Group 1)

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 changes occur, they will be very small. The greatest change occurs at Group 1 is 0.24 %/min or 14.4 %/h; this occurs only once. For Groups 2 and 3, changes are more likely and greater in value because of fewer turbines.

Although the wind in Germany is mostly driven by weather fronts, a daily pattern caused by the sun is also evident. Therefore, I divided the year in two parts. The first part, from October to March, has fast winds and little sunshine. The second part, from April to September, has lower average wind speeds and sunshine is more likely.

During the winter months, a daily pattern is evident. Most of the changes, including the positive and negative changes follow the daily load pattern, which actually helps the utility. During the summer months, there are almost no days with a decrease in the morning and an increase in the afternoon. This pattern is most distinctive for the Group 1 because it has many turbines located in a large area. This analysis does not show the order of changes. It is not apparent whether an increase is followed by another increase within the next time frame. To investigate longer trends, the 2- and 4-hour regressions (shown in Figure 4-4) must be studied. These trends are much smoother because of the longer time frame. However, they show that the trend of the on 1-regression is continued for a longer period.

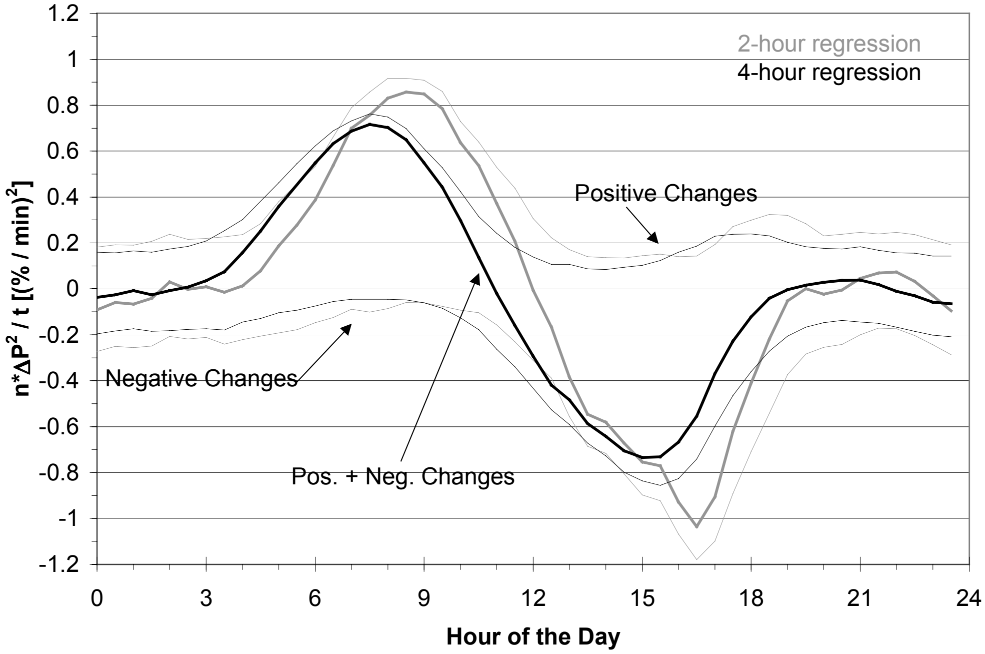


Figure 4-4. Number of occurrences weighted with the square of the slope of the 2-hour and 4-hour regression for the total output of 176 turbines (Group 1)

Although Groups 2 and 3 have almost the same number of turbines, there is a big difference between their power-output patterns. This difference could be because the turbines of Group 2 are spread over three locations along the German coastline while the turbines of Group 3 are located within a small area. However, the 4-hour regressions indicate that although Group 3 experiences more fluctuations within a few hours, it exhibits the same daily pattern found in Groups 1 and 2 (see Figures 4-5 and 4-6).

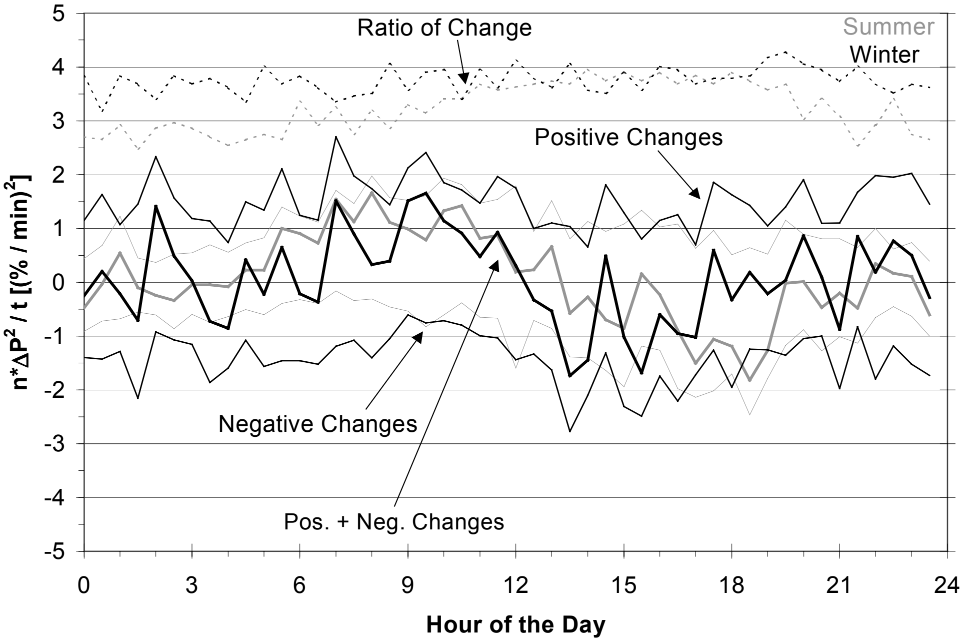


Figure 4-5. Number of occurrences weighted with the square of the slope of 1-hour regression for the total output of 17 turbines (Group 2)

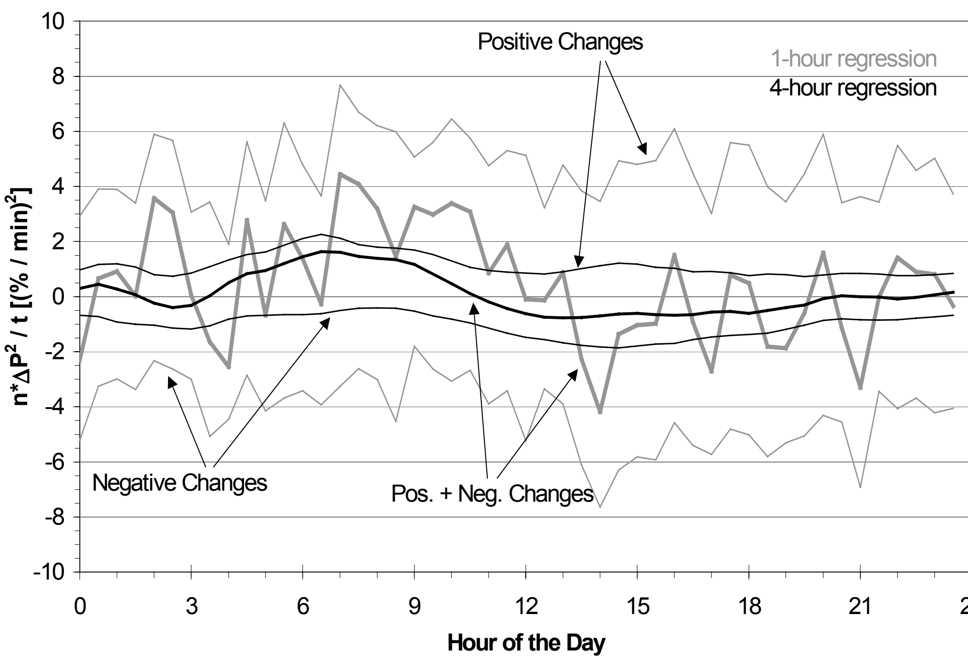


Figure 4-6. Number of occurrences weighted with the square of the slope of 1-hour regression for the total output of 15 turbines (Group 3)

4.2 Regulation

There are several ways to separate regulation from load following. One convenient method for after-the-fact analysis is to use a 60-minute rolling average (30 minutes before and 30 minutes after the hour). 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 disadvantage of the technique is that because the data must be available for 30 minutes before and 30 minutes after the analysis period, an hour of analysis is lost. This is a serious disadvantage if only a short data set is available.

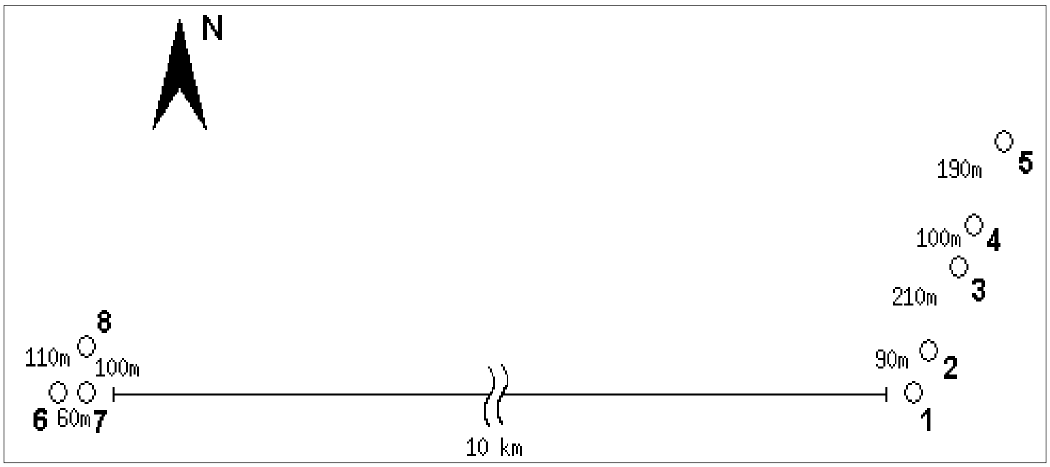


Figure 4-7. Map of turbines from site 1

Currently, utilities examine minute-to-minute fluctuations; however, they may examine 30-second average data in the future to catch faster fluctuations. Therefore, I used 30-second average data for these calculations. Although only 5-minute data is usually stored in the database within the 250 MW Wind project, it is possible to obtain 10 Hz data online via modem. For this analysis, I retrieved 13 10 Hz data sets with 45-minute to 3-hour lengths and calculated the 30-second average. I retrieved seven sets from a site with eight turbines (see Figure 4-7) and six sets from a site with four turbines (see Figure 4-8, also see Appendix B for details).

Although Groups 2 and 3 have almost the same number of turbines, there is a big difference between their power-output patterns. This difference could be because the turbines of Group 2 are spread over three locations along the German coastline while the turbines of Group 3 are located within a small area. However, the 4-hour regressions indicate that although Group 3 experiences more fluctuations within a few hours, it exhibits the same daily pattern found in Groups 1 and 2 (see Figures 4-5 and 4-6).

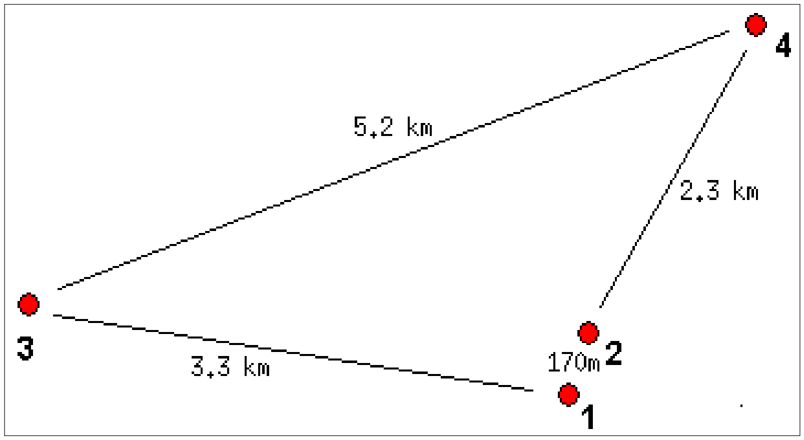


Figure 4-8. Map of turbines from the four-turbine site

The 30-second data sets are typically 1 to 2 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 so short. This procedure allowed me to use the whole 30-second data set for the regulation analysis.

Because the turbines are different in type and size on both sites, their outputs were normalized with respect to each turbine's average power in the data set to eliminate the size bias.

Analyses were carried out for different numbers of turbines and groupings to see the effects on the regulation burden. The calculation was performed for each group with all data sets and an average was taken. Because of different lengths of data sets, a weighted average was derived depending on the length of each data set.

Figure 4-9 shows an example of the regulation analysis. It shows actual power output, rolling average, and the difference for both a single turbine and a group 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 total output and the sum of the standard deviation of the regulation for the single turbines is calculated. The ratio shows the reduction in regulation burden that results from a grouping of turbines. A lower ratio means a lower relative regulation burden. The ratio for this data set is 50.2%. If the turbine output were 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 not uncorrelated (see Chapter 5 Corelation of Output Power Between Wind Turbines); and their power outputs do not have the same distribution. This explains why the ratio is higher than the theoretical value.

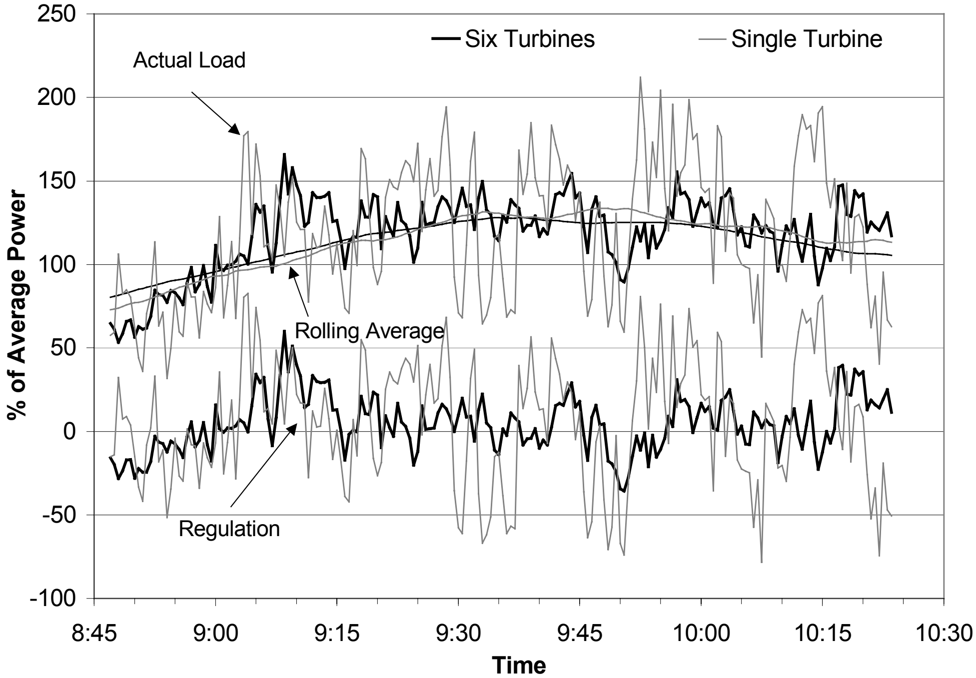


Figure 4-9. Actual power, rolling average and regulation for a wind plant and a single turbine

Table 4-1. Ratio Between the Sum of the Regulation Burden of the Single Turbines and the Regulation Burden of the Aggregated Power for Different Groupings–EighTurbine Site

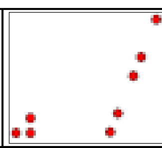
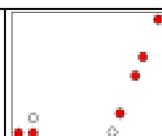
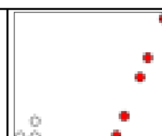
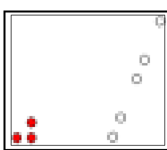
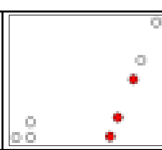
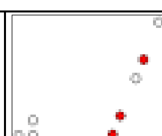
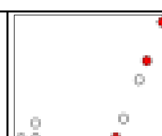
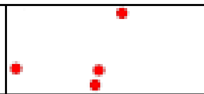
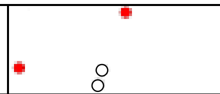
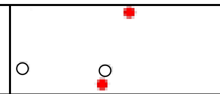
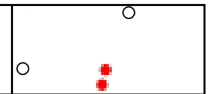
Icon							
Grouping	1	2	3	4	5	6	7
Ratio, 30-sec data	0.449	0.523	0.534	0.853	0.669	0.642	0.603
Ratio, 5-min data	0.501	0.533	0.572	0.904	0.712	0.672	0.623
Theoretical Ratio	0.354	0.408	0.447	0.577	0.577	0.577	0.577

Table 4-2. Ratio between the sum of the regulation burden of the single turbines and the regulation burden of the aggregated power for different constellations at site 2

Icon				
Grouping	1	2	3	4
Ratio, 30-sec data	0.614	0.712	0.760	0.827
Ratio, 5-min data	0.684	0.682	0.807	0.891

Tables 4-1 and 4-2 display different groupings and the analysis of calculated ratios for the two sites. The filled dots, in the icon, show which turbines were included for the grouping. In groupings one to three, the ratio increases with the decrease in the number of turbines. Groupings four to seven have three turbines each but the distances between turbines increase in each grouping from groupings four to seven. As distance increases there is a decrease in the ratio value.

In group seven, the turbines are spaced 200 m (660 ft) and 400 m (1320 ft) apart, which is typical for wind plants with large modern turbines. The ratio is 60%, and the theoretical value is 57%. This trend indicates that closely spacing the turbines (as on 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. When longer average times are analyzed (5-minutes in this case), the ratio is still close to the theoretical value. I did the calculation for all of the groupings using 5-minute data to see if I could quantify the ratio with 5-minute data. This quantification is important because, I have 5-minute data from the last few years for over 200 German wind turbines.

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 utility system where the wind plant is located. Later in the report, I will compared a wind plant with a steel mill to give some perspective on the size of fluctuations of a wind plant (see Chapter 6).

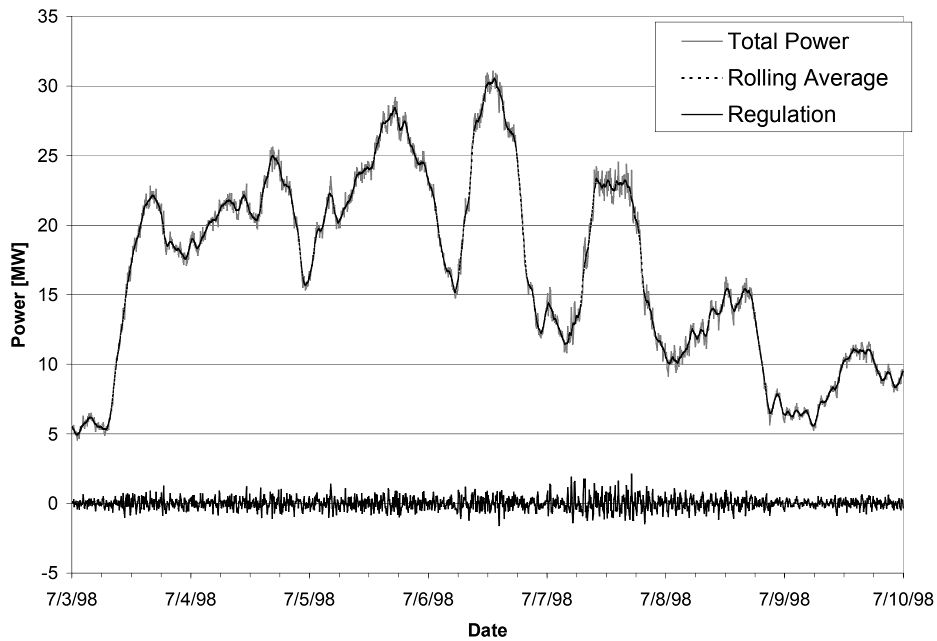


Figure 4-10. Actual power, rolling average and regulation for Group 1

Although the 5-minute data analysis cannot tell us the absolute regulation burden, the resulting ratios display a similar pattern. This finding encouraged me to do more calculations with five-minute data to learn more about the effects of the number of and the distance between turbines. I did the calculation for Groups 1 to 8 for 1998. For Group 1 I did the calculation twice: the first time using the absolute power and the second time using the power output of each wind turbine normalized to its rated power (this step treats the turbines as if they were all the same size). The size of the turbines in Group 1 varies from 30 kW to 1.5 MW. When using absolute power, large turbines have more influence. This makes it appears as though there are fewer turbines. However, with the normalization, the effects of increasing the number of turbines is clearly seen. This trend may prove interesting when the results are transferred to other areas. Figure 4-10 shows the regulation for Group 1 over a period of one week in June which shows that the regulation drops significantly compared to the absolute power of many turbines. The number of turbines, the average distance between the turbines, and the calculated ratio values for Groups 1 to 4 are shown in Table 4-3. The large distance between the turbines in Group 2 seems to indicate that the distance between turbines does not have much influence on the ratio because Group 3 shows almost the same ratio with nearly the same number of turbines standing in one area.

Table 4-3. Ratio Between the Sum of the Regulation Burden of the Single Turbine and the Regulation Burden of the Aggregated Power for Different Groupings Derived from 5-Minute Data

Group	No. of Turbines	Average Distance	Ratio	Theoretical Ratio
1	176	217.7 km	12.4%With absolute power	7.5%
1	176	217.7 km	9.5% with relative power	7.5%
2	17	3.89 km within the turbines, 266 km between the turbines	39.80%	24.2%
3	15	13.1 km	40.40%	25.8%
4	8	13.7 km	44.90%	35.4%

I used Groups 4 through 8 to see what effect the distance has on the ratio. There are eight turbines in each of these groups. The average distances, the average of the distances from each turbine to all the others, varies between 6 km and 13 km. This number does not show the actual distance between turbines, but it is best suited for comparing the groups. Figure 4-11 shows the decrease of the ratio with the increase of the average distance. Although none of the groups reaches the theoretical ratio of 35.4%, some of them come close.

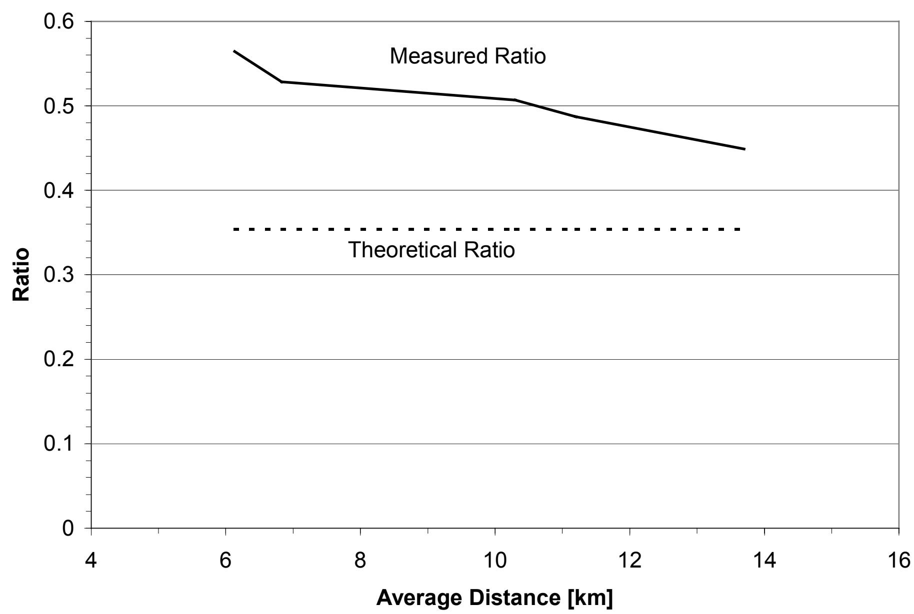


Figure 4-11. Ratio between the sum of the regulation burden of the single turbines and the regulation burden of the aggregated power for eight turbines with different distances

(Group 4 to 8)

Figure 4-12 shows the distribution of the standard deviation for 179 turbines. I did not analyze which turbine types or which sites are in which range of regulation. It is interesting to note that they are close together. The turbine size or type makes little difference for the regulation burden. However, the distribution may change with a shorter average time, such as a few seconds.

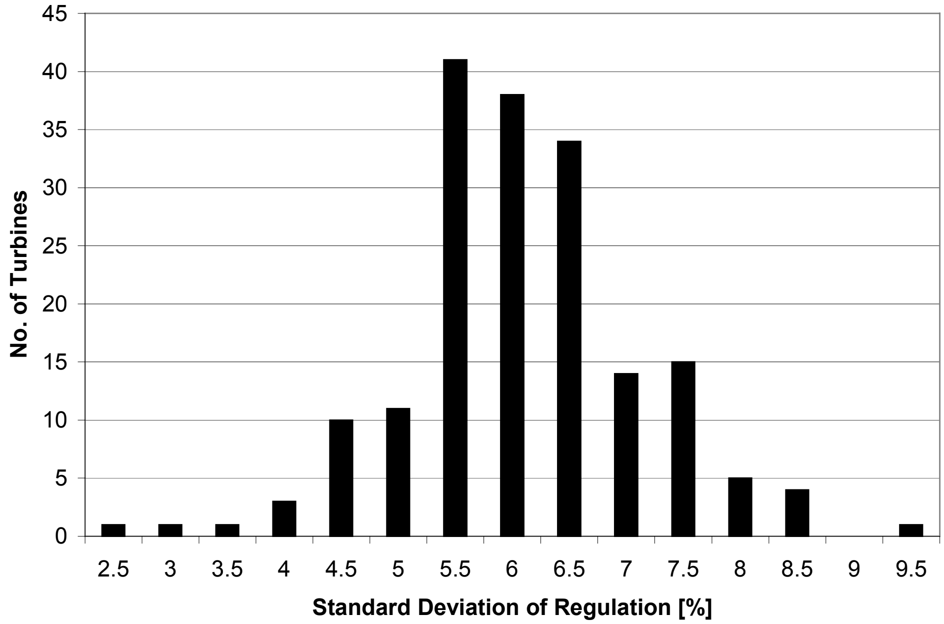


Figure 4-12. Distribution of the standard deviation of regulation for 179 Turbines

5. Correlation of output power between Wind Turbines

As seen in the Section 4.1 and 4.2, greater distance between turbines necessitates fewer ancillary services. This trend is due to the correlation between closely sited wind turbines. The greater the distance between turbines, the less they are correlated. To demonstrate this correlation, I calculate the linear correlation coefficients for different distances. I used the changes in power ΔP from one step to the next for this calculation instead of the absolute power. When considering the ancillary services, changes in power is more interesting than the absolute power. Five-minute data from two sites with a high availability were used to investigate the correlation among all wind turbines. The linear correlation coefficient r is the covariance of two signals divided by their standard deviations (Equation 5-1). The resulting correlation coefficient is normalized even if the signals have different orders of magnitude. Therefore, the absolute power data were used in the calculation. If the changes of power at both turbines were always in the same direction, r would be equal to 1 and the signals are said to be completely positive correlated. If they go always in opposite directions, r is equal to –1 and the signals would be negative correlated. The correlation coefficient r is equal to zero if the signals are totally uncorrelated.

$$r = \frac{\sum_{i=1}^{n} (\Delta P_{1,i})(\Delta P_{2,i})}{\sqrt{\sum_{i=1}^{n} (\Delta P_{1,i})^2} \sqrt{\sum_{i=1}^{n} (\Delta P_{2,i})^2}} \qquad \text{(Equation 5.1)}$$

where $\Delta P_{n,i} = P_{n,i} - P_{n,i-1}$ and $P_{1,0} = P_{2,0} = 0$.

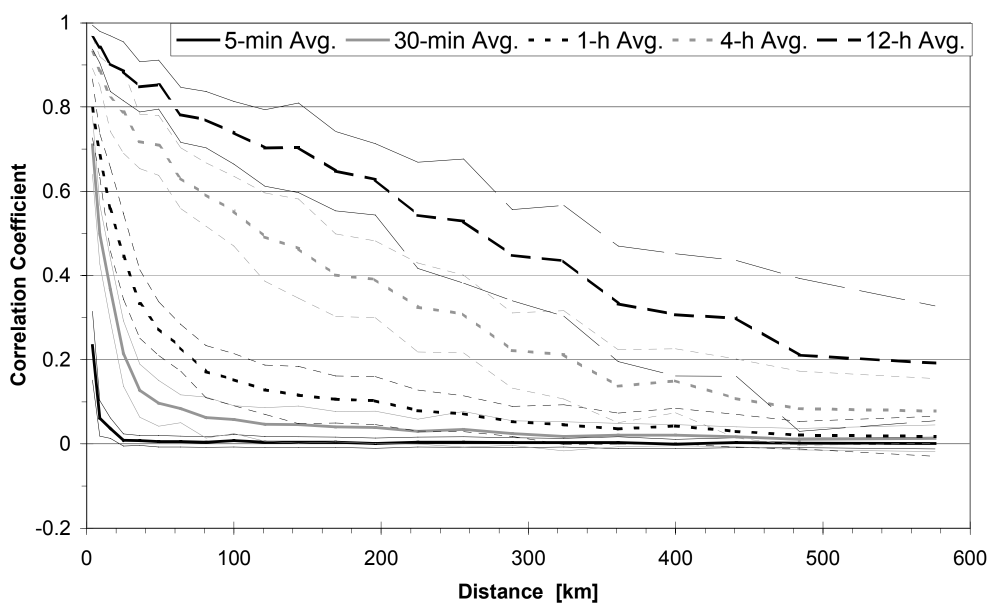


Figure 5-1. Correlation coefficient of ΔP for different average times over the distance

Figure 5-1 shows the results with power averages ranging from as short as 5 minutes to as long as 12 hours. The distances between the compared wind turbines were classified. The thick lines represent the average of these classes, and the thin lines represent the average plus and minus the standard deviation of the class. Because of the length of time required to do these calculations, they were done only for 3 months in the summer and 3 months in the winter. As there is no significant difference between the two seasons, the average for both seasons is displayed.

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

After doing the calculations with 5-minute data, I used the 10 Hz data sets to examine turbines standing closer together and shorter average times. Figure 5-2 shows the correlation coefficient of two wind turbines at a distance of 170 m (560 ft) for different average times. As expected, they are 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 wind 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.

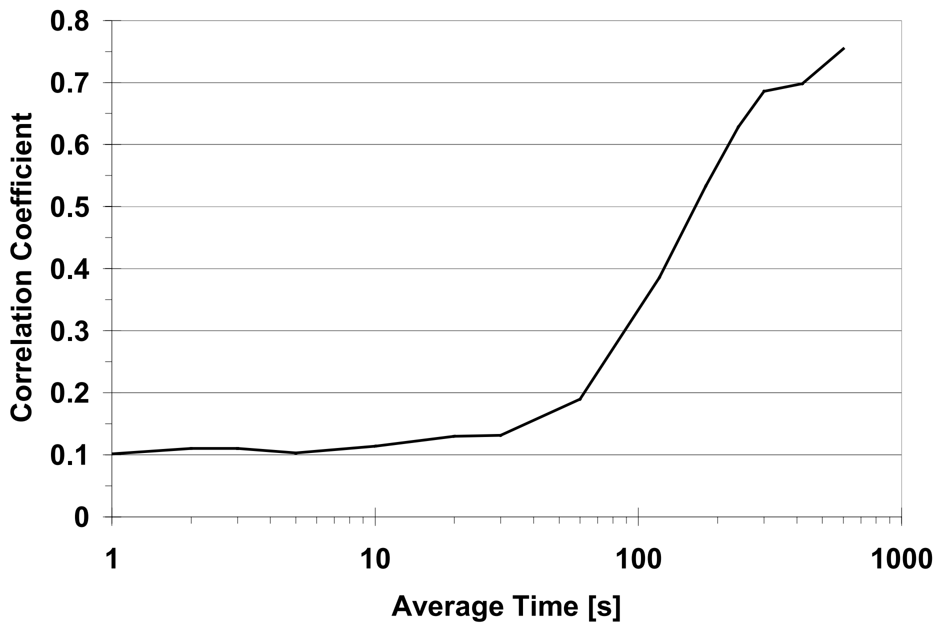


Figure 5-2. Correlation coefficient of ΔP over the average time for two turbines with a distance of 170 m

6. Comparison of a Steel Mill with a Wind Plant

The absolute value of the regulation burden caused by a wind plant to a utility is not easy to interpret. It depends on the size of the total load in the utility control area, load characteristics, and the equipment the utility uses for regulation. Thus the costs a wind plant imposes for regulation have not been determined. However, it is possible to compare these costs to costs imposed by other intermittent loads.

I compared load data from a steel mill for one day to load data from a small wind plant with 8 turbines (Group 8) and to the total output of 176 turbines (Group 1). Because of the difference in rated power, all power data were normalized to respective rated power. The output of 176 new turbines would have similar power rating of the steel mill. The capacity factor of the steel mill is 74% for the chosen day. For the wind plants, I chose a day in January 1998 with about the same average power. I used 5-minute data for both the wind plants and the steel mill.

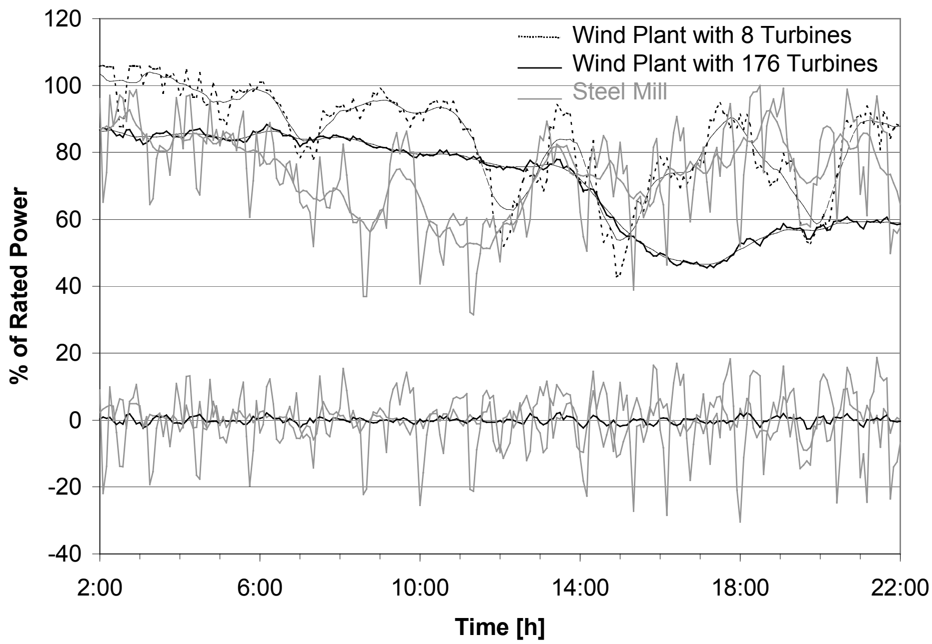


Figure 6-1. Actual power, rolling average, and regulation for two wind plants and a steel mill

Figure 6-1 shows the regulation for the wind plant and the steel mill. As seen in Table 6-1, the standard deviation of the large wind plant, which is the measurement for the regulation burden, is only 10% of the standard deviation of the steel mill. Obviously, this steel mill is an extreme fluctuating load. The example shows that wind power does not fluctuate as much.

Table 6-1 Comparison of Wind Plant and Steel Mill Load

	Rated Power (MW)	Standard Deviation of Regulation
Wind Plant with 8 Turbines	2.8	4.5 %
Wind Plant with 176 Turbines	44.6	1.0 %
Steel Mill	107.5	9.9 %

7. Conclusion

Tn this paper, I 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 pattern. However, the results of the regulation and the correlation analyses 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 5 minutes. The data also confirm that, during a shorter time period, wind turbine output within a wind plant 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. Available data show that the power level of wind generation generally increases in the morning and decreases in the afternoon. In addition, there is a 15% to 50% chance that the power output will not show a trend over an hour. For wind power plants that have patterns similar 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 plants. Comparison of a wind plant to an actual steel mill regulation burden analysis suggests that there are other intermittent loads, that have larger fluctuations than wind plant.

Finally, additional 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 to wind plant patterns in the United States.

Appendix A

Table A-1. Turbines for summation

Group	Type	Rated Power	Rotor Diameter	Data Logger No.	WMEP No.	Zip Code	City
1	Krogmann 15/50	50	15.0	1	4000-01	36355	Grebenhain
1	AN Bonus 150/30	150	23.0	4	4000-04	36355	Grebenhain
1	Tacke TW 250	250	24.0	6	4000-05	36355	Grebenhain
1	HSW 250 T	250	28.5	8	4000-07	36355	Grebenhain
1	Enercon E 32	280	33.0	201	2046-01	58091	Hagen-Dahl
1	Lagerwey LW 15/50	50	15.6	301	2029-01	48157	Münster
1	Tacke TW 60	60	16.9	701	2017-01	59602	Rüthen
1	Nordex N 27/150	150	27.0	901	2083-03	33184	Altenbeken
1	Nordex N 27/150	150	27.0	903	2083-01	33184	Altenbeken
1	DAN mark 22	95	21.8	1001	5500-01	78183	Hüfingen
1	Enercon E 33	280	33.0	1101	5501-01	79874	Breitnau
1	Lagerwey LW 15/55	55	15.6	1201	2022-01	32351	Stemwede
1	Enercon E 18	80	19.4	1301	4003-01	34639	Schwarzenborn
1	Südwind N 1230	30	12.5	1401	4508-01	54597	Feuerscheid
1	Micon M 530-175	175	26.0	1701	2024-01	59469	Ense
1	Enercon E 18	80	19.4	1801	4523-01	67271	Neuleiningen
1	Enercon E 32	300	32.0	10005	1011-05	26506	Norden-Ostermarsch
1	Enercon E 33	300	33.0	10006	1011-06	26506	Norden-Ostermarsch
1	Lagerwey LW 15/75	75	15.6	10401	1079-01	31628	Landesbergen
1	Micon M 530-250/50	250	26.0	10601	1115-01	26802	Moormerland-Terborg
1	Enercon E 17	80	17.2	10701	1075-01	26901	Rastdorf
1	Micon M 530-175	175	26.0	11201	1032-01	21762	Osterbruch
1	Südwind N 1237	37	12.5	11401	1078-01	26931	Elsfleth
1	Enercon E 18	80	18.0	11501	1008-02	26897	Hilkenbrook
1	Enercon E 18	80	18.0	11502	1008-03	26897	Hilkenbrook
1	AN Bonus 150/30	150	23.0	11601	1065-01	27612	Loxstedt
1	AN Bonus 150/30	150	23.0	11801	1099-01	26316	Varel
1	Lagerwey LW 15/75	75	15.6	12101	1040-01	29593	Schwienau
1	AN Bonus 150/30	150	23.0	12201	1089-01	27246	Borstel
1	Krogmann 15/50	50	15.0	12301	1024-01	29303	Bergen
1	AN Bonus 150/30	150	23.0	12401	1096-01	26203	Wardenburg
1	Enercon E 17	80	17.2	12501	1031-01	21717	Fredenbeck
1	Enercon E 17	80	17.2	12601	1010-01	21279	Dierstorf
1	Enercon E 32	280	32.0	13101	1019-01	31812	Bad Pyrmont-Großenberg
1	Enercon E 32	300	32.0	13301	1041-02	30974	Wennigsen
1	Enercon E 32	300	32.0	13302	1041-01	30974	Wennigsen
1	Lagerwey LW 15/75	75	15.6	13501	1056-01	38690	Vienenburg

1	Enercon E 17	80	19.4	13601	1050-01	26506	Norden-Süderneuland
1	Enercon E 17	80	17.2	13801	1047-01	26607	Aurich
1	Enercon E 32	300	33.0	13901	1120-01	26969	Butjadingen-Tossens
1	Krogmann 15/50	50	15.0	14001	1138-01	27793	Wildeshausen
1	Wind World W 2700/150	150	27.0	14101	1211-01	26831	Bunde
1	Tacke TW 80	80	21.0	14201	1231-01	49744	Geeste-Dalum
1	DWA 16/55	55	15.0	14301	1264-01	49843	Wielen
1	Lagerwey LW 27/250	250	27.0	14401	1179-02	26434	Wangerland-Neu Augustengroden
1	Südwind N 1237	37	12.5	14501	1252-01	27308	Kirchlinteln
1	Tacke TW 250	250	26.0	14601	1265-01	28857	Syke-Gessel
1	Vestas V 27/225	225	27.0	14801	1181-01	21706	Drochtersen
1	Seewind 20/110	110	20.0	14901	1294-01	37632	Eimen-Mainzholzen
1	Seewind 20/110	110	20.0	15101	1307-01	49685	Hoheging
1	AN Bonus 150/30	150	23.0	15201	1160-01	31177	Harsum
1	Enercon E 40	500	40.3	15301	1301-01	26897	Hilkenbrook
1	Südwind N 1237	37	12.5	15401	1279-01	31718	Pollhagen
1	Nordex N 52/800	800	52.0	15501	1314-01	26826	Weener
1	AN Bonus 450/37	450	37.0	15601	1218-01	27632	Padingbüttel
1	Enercon E 40	500	40.3	15701	1293-02	26506	Norden-Westermarsch
1	Vestas V 39/500	500	39.0	15801	1193-02	26529	Wirdum
1	Nordtank NTK 500/41	500	41.0	15901	1305-01	26759	Hinte
1	Wind World W 2700/150	150	27.0	16001	1245-01	26506	Norden-Westermarsch
1	Tacke TW 500	500	37.0	16101	1250-01	26506	Norden-Ostermarsch
1	Enercon E 30	200	30.0	16201	1316-01	26506	Norden-Norddeich
1	GET 41	600	41.0	16301	1318-01	26427	Dunum-Brill
1	Nordex N 27/250	250	27.0	16401	1170-01	26506	Norden-Westermarsch
1	Vestas V 42/600	600	42.0	16601	1315-01	26506	Norden-Westermarsch
1	Euroturbine ET 550/41	550	41.5	16701	1319-01	21684	Agathenburg
1	AN Bonus 450/37	450	37.0	16901	1248-01	26419	Schortens
1	GET 41	600	41.0	17001	1320-01	26419	Schortens-Sillenstede
1	Enercon E 40	500	40.3	17101	1253-05	26723	Emden-Larrelt
1	Nordtank NTK 500/37	500	37.0	17201	1282-01	26553	Nesse
1	Enercon E 40	500	40.3	17301	1285-01	26553	Dornum
1	AN Bonus 450/37	450	37.0	17401	1286-02	26524	Hagermarsch
1	Enercon E 66	1500	66.0	17501	1323-01	26723	Emden
1	AN Bonus 300/33	300	33.0	17601	1322-01	31177	Harsum-Machtsum
1	AN Bonus 450/37	450	37.0	17701	1295-01	26427	Neuharlingersiel
1	Enercon E 40	500	40.3	17801	1296-01	26434	Wangerland-Grimmens
1	Tacke TW 600	600	43.0	17901	1317-01	26427	Holtgast-Utgast

1	Tacke TW 600	600	43.0	17902	1317-02	26427	Holtgast-Utgast
1	AN Bonus 450/37	450	37.0	18001	1283-01	26427	Utgast
1	Nordtank NTK 500/37	500	37.0	18101	1290-01	26434	Wangerland-Wüppelser Groden
1	Adler 25	165	25.0	30101	0075-01	25693	St. Michaelisdonn
1	Vestas V 25/200	200	25.0	30201	0093-01	25849	Pellworm
1	Adler 25	165	25.0	30501	0086-02	23570	Lübeck-Brodten
1	HSW 250	250	25.0	30502	0086-03	23570	Lübeck-Brodten
1	HSW 250	250	25.0	30503	0086-01	23570	Lübeck-Brodten
1	Micon M 530-175	175	26.0	30601	0095-01	24229	Strande
1	Micon M 530-250/50	250	26.0	30701	0077-02	25764	Schülp
1	Micon M 530-250/50	250	26.0	30702	0077-01	25764	Schülp
1	Vestas V 27/225	225	27.0	30801	0081-04	25938	Oevenum/Föhr
1	Vestas V 27/225	225	27.0	30802	0081-05	25938	Oevenum/Föhr
1	Lagerwey LW 15/75	75	15.6	30901	0002-01	25599	Wewelsfleth
1	Vestas V 25/200	200	25.0	31001	0052-01	24407	Oersberg
1	Tacke TW 250	250	24.0	31301	0039-01	23827	Garbeck
1	Vestas V 25/200	200	25.0	31401	0110-01	25856	Hattstedtermarsch
1	Vestas V 25/200	200	25.0	31501	0024-01	25826	St. Peter-Ording
1	Lagerwey LW 15/75	75	15.6	31601	0091-01	25899	Niebüll
1	Enercon E 32	300	33.0	31701	0034-01	25899	Galmsbüll
1	Vestas V 25/200	200	25.0	31801	0046-01	25842	Ockholm
1	Vestas V 25/200	200	25.0	31901	0035-01	25899	Dagebüll
1	WTN 200/26	200	26.0	32001	0103-01	25554	Sachsenbande
1	Wind World W 2700/150	150	27.0	32101	0074-01	25860	Horstedt
1	Vestas V 25/200	200	25.0	32201	0004-01	25885	Immenstedt
1	Vestas V 25/200	200	25.0	32301	0037-01	25873	Oldersbek
1	HSW 250	250	25.0	32401	0010-01	25927	Aventoft
1	HSW 30	30	12.5	32501	0007-01	25870	Oldenswort
1	WTN 200/26	200	26.0	32601	0044-06	25889	Uelvesbüllkoog
1	Enercon E 17	80	17.2	32701	0078-01	23858	Reinfeld
1	Vestas V 25/200	200	25.0	32801	0019-01	25821	Sönnebüll
1	Enercon E 32	300	33.0	32901	0076-03	23769	Petersdorf/Fehmarn
1	Enercon E 32	300	33.0	33101	0089-02	23769	Westermarkelsdorf/Fehmarn
1	Wind World W 2700/150	150	27.0	33201	0088-01	23769	Klausdorf/Fehmarn
1	Micon M 530-250/50	250	26.0	33301	0083-01	25862	Joldelund
1	Enercon E 17	80	19.4	33401	0097-01	24872	Groß Rheide
1	Vestas V 17/75	75	17.0	33501	0003-01	24879	Neuberend
1	Krogmann 15/50	50	15.0	33601	0043-01	23730	Schashagen
1	AN Bonus 150/30	150	23.0	33801	0060-01	23779	Neukirchen
1	AN Bonus 100/30	100	23.0	33901	0020-01	22880	Wedel
1	Enercon E 17	80	17.2	34001	0023-01	24894	Twedt
1	Micon M 530-250/50	250	26.0	34101	0100-01	25821	Reußenköge
1	Vestas V 25/200	200	25.0	34201	0061-03	23769	Westermarkelsdorf/Fehmarn

1	Vestas V 25/200	200	25.0	34202	0061-02	23769	Westermarkelsdorf/Fehmarn
1	Nordtank NTK 150 XLR	150	24.6	34401	0050-01	24881	Breklingfeld
1	HSW 30	30	12.5	34601	0115-01	24407	Kragelund
1	Südwind N 1230	30	12.5	34701	3000-01	21129	Hamburg-Nincop
1	HSW 250 T	250	28.5	34801	0109-04	25845	Nordstrand
1	HSW 250 T	250	28.5	34802	0109-05	25845	Nordstrand
1	Vestas V 25/200	200	25.0	34901	0006-01	25746	Norderwöhrden
1	Nordex N 27/250	250	27.0	35001	0141-01	25541	Brunsbüttel
1	Nordex N 27/150	150	27.0	35101	0167-01	25599	Wewelsfleth
1	Nordtank NTK 150 XLR	150	24.6	35201	0064-01	25872	Ostenfeld
1	Nordtank NTK 300/31	300	31.0	35301	0137-03	25845	Nordstrand
1	Enercon E 18	80	19.4	35401	0123-01	24647	Wasbek
1	WTN 200/26	200	26.0	35601	0127-05	25899	Galmsbüll
1	WTN 200/26	200	26.0	35602	0127-06	25899	Galmsbüll
1	Tacke TW 500	500	37.0	35801	0211-02	25764	Schülp
1	Tacke TW 600	600	43.0	35802	0211-03	25764	Schülp
1	Vestas V 20/100	110	20.0	35901	0197-01	24999	Wees-Oxbüll
1	Südwind N 1230	30	12.5	36001	0105-01	24253	Passade
1	AN Bonus 150/30	150	23.0	36101	0165-01	24220	Boksee
1	Südwind N 3127	270	31.0	36201	0228-01	24940	Goosefeld
1	Tacke TW 250	250	24.0	36301	0114-01	24819	Nienborstel
1	Kano-Rotor 30	30	12.1	36401	0102-01	25779	Glüsing
1	Enercon E 32	300	33.0	36501	0159-01	24994	Jardelund
1	Micon M 750-400/100	400	31.0	36601	0187-09	25821	Reußenköge
1	Enercon E 40	500	40.3	36602	0187-07	25821	Reußenköge
1	Micon M 1500-600/150	600	43.4	36701	0213-03	24969	Lindewitt
1	AN Bonus 600/44-2	600	44.0	36801	3012-01	21039	Hamburg-Altengamme
1	GET 41	600	41.0	36901	0238-01	25541	Brunsbüttel
1	GET Danwin 27	225	29.1	36902	0238-05	25541	Brunsbüttel
1	HSW 1000/54	1000	54.0	37001	0237-01	25899	Bosbüll
1	Jacobs 41/500	500	41.0	37101	0239-01	25693	Trennewurth
1	Jacobs 43/600	600	43.0	37201	0240-01	25797	Wöhrden-Neuenkrug
1	Jacobs 41/500	500	41.0	37301	0245-01	25718	Friedrichskoog-Dieksanderkoog
1	Vestas V 63/1.5	1500	63.0	37401	0151-06	25709	Kaiser-Wilhelm-Koog
1	Nordtank NTK 150 XLR	150	24.6	50201	7507-01	18233	Rakow
1	Nordtank NTK 150 XLR	150	24.6	50202	7507-02	18233	Rakow
1	Südwind N 1237	37	12.5	50401	7508-01	23974	Zarnekow
1	Enercon E 33	300	33.0	50501	7502-01	18556	Altenkirchen/Rügen
1	Enercon E 33	300	33.0	50502	7502-02	18556	Altenkirchen/Rügen

1	Enercon E 33	300	33.0	50701	8500-01	16928	Rapshagen
1	Micon M 570-200/40	200	27.0	50801	8000-01	7554	Söllmnitz
1	Lagerwey LW 15/75	75	15.6	50901	7506-01	23936	Diedrichshagen
1	Enercon E 40	500	40.3	51201	7008-01	2708	Laucha
1	Enercon E 32	300	33.0	51401	7520-01	18311	Ribnitz-Körkwitz
1	Micon M 530-250/50	250	26.0	51501	7524-02	18356	Küstrow
1	Nordtank NTK 300/31	300	31.0	51502	7524-01	18356	Küstrow
1	Micon M 530-250/50	250	26.0	51503	7524-03	18356	Küstrow
1	Micon M 530-250/50	250	26.0	51504	7524-04	18356	Küstrow
1	Enercon E 33	300	33.0	51505	7524-06	18356	Küstrow
1	WTN 200/26	200	26.0	51601	8501-01	17291	Schmölln
1	WTN 200/26	200	26.0	51602	8501-02	17291	Schmölln
1	WTN 200/26	200	26.0	51603	8501-03	17291	Schmölln
1	AN Bonus 450/37	450	37.0	51701	7530-03	18573	Rambin
1	AN Bonus 150/30	150	23.0	51702	7530-01	18573	Rambin
1	Nordtank NTK 300/31	300	31.0	51801	7519-01	18375	Born am Darß
1	Nordtank NTK 300/31	300	31.0	51802	7519-02	18375	Born am Darß
1	Lagerwey LW 18/80	80	18.0	51901	7526-02	18356	Fuhlendorf
1	Lagerwey LW 15/75	75	15.6	51902	7526-01	18356	Fuhlendorf
1	Lagerwey LW 15/75	75	15.6	51903	7526-03	18356	Fuhlendorf
1	Nordtank NTK 500/41	500	41.0	52001	7557-02	17509	Wusterhusen
1	Nordtank NTK 500/41	500	41.0	52002	7557-01	17509	Wusterhusen
1	Lagerwey LW 30/250	250	30.0	52201	8017-01	99510	Wormstedt
1	Wind World W 4100/500	500	41.0	52202	8017-02	99510	Wormstedt
1	NedWind 44	500	43.8	52203	8017-03	99510	Wormstedt
1	Euroturbine ET 550/41	550	41.5	52301	7563-01	18356	Barth
1	Enercon E 40	500	40.3	52501	7533-01	18556	Altenkirchen/Rügen
1	Micon M 700-225/40	225	29.6	52601	8009-01	37308	Reinholterode
1	Tacke TW 300	300	33.0	52602	8009-02	37308	Reinholterode
2	Enercon E 32	300	32.0	10005	1011-05	26506	Norden-Ostermarsch
2	Enercon E 33	300	33.0	10006	1011-06	26506	Norden-Ostermarsch
2	Enercon E 40	500	40.3	15701	1293-02	26506	Norden-Westermarsch
2	Wind World W 2700/150	150	27.0	16001	1245-01	26506	Norden-Westermarsch
2	Tacke TW 500	500	37.0	16101	1250-01	26506	Norden-Ostermarsch
2	Enercon E 30	200	30.0	16201	1316-01	26506	Norden-Norddeich
2	Nordex N 27/250	250	27.0	16401	1170-01	26506	Norden-Westermarsch

2	Vestas V 42/600	600	42.0	16601	1315-01	26506	Norden-Westermarsch
2	Lagerwey LW 15/75	75	15.6	31601	0091-01	25899	Niebüll
2	Enercon E 32	300	33.0	31701	0034-01	25899	Galmsbüll
2	WTN 200/26	200	26.0	35601	0127-05	25899	Galmsbüll
2	WTN 200/26	200	26.0	35602	0127-06	25899	Galmsbüll
2	Micon M 530-250/50	250	26.0	51501	7524-02	18356	Küstrow
2	Nordtank NTK 300/31	300	31.0	51502	7524-01	18356	Küstrow
2	Micon M 530-250/50	250	26.0	51504	7524-04	18356	Küstrow
2	Enercon E 33	300	33.0	51505	7524-06	18356	Küstrow
2	Euroturbine ET 550/41	550	41.5	52301	7563-01	18356	Barth
3	Enercon E 32	300	32.0	10005	1011-05	26506	Norden-Ostermarsch
3	Enercon E 33	300	33.0	10006	1011-06	26506	Norden-Ostermarsch
3	Enercon E 17	80	19.4	13601	1050-01	26506	Norden-Süderneuland
3	Enercon E 40	500	40.3	15701	1293-02	26506	Norden-Westermarsch
3	Wind World W 2700/150	150	27.0	16001	1245-01	26506	Norden-Westermarsch
3	Tacke TW 500	500	37.0	16101	1250-01	26506	Norden-Ostermarsch
3	Enercon E 30	200	30.0	16201	1316-01	26506	Norden-Norddeich
3	Nordex N 27/250	250	27.0	16401	1170-01	26506	Norden-Westermarsch
3	Vestas V 42/600	600	42.0	16601	1315-01	26506	Norden-Westermarsch
3	Nordtank NTK 500/37	500	37.0	17201	1282-01	26553	Nesse
3	Enercon E 40	500	40.3	17301	1285-01	26553	Dornum
3	AN Bonus 450/37	450	37.0	17401	1286-02	26524	Hagermarsch
3	Tacke TW 600	600	43.0	17901	1317-01	26427	Holtgast-Utgast
3	Tacke TW 600	600	43.0	17902	1317-02	26427	Holtgast-Utgast
3	AN Bonus 450/37	450	37.0	18001	1283-01	26427	Utgast
4	Enercon E 17	80	19.4	13601	1050-01	26506	Norden-Süderneuland
4	Wind World W 2700/150	150	27.0	16001	1245-01	26506	Norden-Westermarsch
4	Tacke TW 500	500	37.0	16101	1250-01	26506	Norden-Ostermarsch
4	Enercon E 30	200	30.0	16201	1316-01	26506	Norden-Norddeich
4	Vestas V 42/600	600	42.0	16601	1315-01	26506	Norden-Westermarsch
4	Enercon E 40	500	40.3	17301	1285-01	26553	Dornum
4	AN Bonus 450/37	450	37.0	17401	1286-02	26524	Hagermarsch
4	AN Bonus 450/37	450	37.0	18001	1283-01	26427	Utgast
5	Enercon E 33	300	33.0	10006	1011-06	26506	Norden-Ostermarsch
5	Tacke TW 500	500	37.0	16101	1250-01	26506	Norden-Ostermarsch
5	Enercon E 30	200	30.0	16201	1316-01	26506	Norden-Norddeich

5	Nordtank NTK 500/37	500	37.0	17201	1282-01	26553	Nesse
5	Enercon E 40	500	40.3	17301	1285-01	26553	Dornum
5	AN Bonus 450/37	450	37.0	17401	1286-02	26524	Hagermarsch
5	Tacke TW 600	600	43.0	17902	1317-02	26427	Holtgast-Utgast
5	AN Bonus 450/37	450	37.0	18001	1283-01	26427	Utgast
6	Enercon E 33	300	33.0	10006	1011-06	26506	Norden-Ostermarsch
6	Tacke TW 500	500	37.0	16101	1250-01	26506	Norden-Ostermarsch
6	Nordtank NTK 500/37	500	37.0	17201	1282-01	26553	Nesse
6	Enercon E 40	500	40.3	17301	1285-01	26553	Dornum
6	AN Bonus 450/37	450	37.0	17401	1286-02	26524	Hagermarsch
6	Tacke TW 600	600	43.0	17901	1317-01	26427	Holtgast-Utgast
6	Tacke TW 600	600	43.0	17902	1317-02	26427	Holtgast-Utgast
6	AN Bonus 450/37	450	37.0	18001	1283-01	26427	Utgast
7	Enercon E 33	300	33.0	10006	1011-06	26506	Norden-Ostermarsch
7	Enercon E 17	80	19.4	13601	1050-01	26506	Norden-Süderneuland
7	Enercon E 40	500	40.3	15701	1293-02	26506	Norden-Westermarsch
7	Wind World W 2700/150	150	27.0	16001	1245-01	26506	Norden-Westermarsch
7	Tacke TW 500	500	37.0	16101	1250-01	26506	Norden-Ostermarsch
7	Enercon E 30	200	30.0	16201	1316-01	26506	Norden-Norddeich
7	Nordex N 27/250	250	27.0	16401	1170-01	26506	Norden-Westermarsch
7	Vestas V 42/600	600	42.0	16601	1315-01	26506	Norden-Westermarsch
8	Enercon E 32	300	32.0	10005	1011-05	26506	Norden-Ostermarsch
8	Enercon E 33	300	33.0	10006	1011-06	26506	Norden-Ostermarsch
8	Enercon E 40	500	40.3	15701	1293-02	26506	Norden-Westermarsch
8	Wind World W 2700/150	150	27.0	16001	1245-01	26506	Norden-Westermarsch
8	Tacke TW 500	500	37.0	16101	1250-01	26506	Norden-Ostermarsch
8	Enercon E 30	200	30.0	16201	1316-01	26506	Norden-Norddeich
8	Nordex N 27/250	250	27.0	16401	1170-01	26506	Norden-Westermarsch
8	Vestas V 42/600	600	42.0	16601	1315-01	26506	Norden-Westermarsch

Appendix B

Table 2. Turbines of site 1

Number	Type	Rated Power	Rotor Diameter	Data Logger No.	WMEP No.	Zip Code	City
1	Nordtank NTK 300/31	300	31	51502	7524-01	18356	Küstrow
2	Micon M 530-250/50	250	26	51501	7524-02	18356	Küstrow
3	Micon M 530-250/50	250	26	51503	7524-03	18356	Küstrow
4	Micon M 530-250/50	250	26	51504	7524-04	18356	Küstrow
5	Enercon E 33	300	33	51505	7524-06	18356	Küstrow
6	Lagerwey LW 15/75	75	15.6	51903	7526-03	18356	Fuhlendorf
7	Lagerwey LW 18/80	80	18	51901	7526-02	18356	Fuhlendorf
8	Lagerwey LW 15/75	75	15.6	51902	7526-01	18356	Fuhlendorf

Table 3. Turbines of site 2

Number	Type	Rated Power	Rotor Diameter	Data Logger No.	WMEP No.	Zip Code	City
1	Enercon E 32	300	32	10005	1011-05	26506	Norden-Ostermarsch
2	Enercon E 33	300	33	10006	1011-06	26506	Norden-Ostermarsch
3	Enercon E 30	200	30	16201	1316-01	26506	Norden-Norddeich
4	Tacke TW 500	500	37	16101	1250-01	26506	Norden-Ostermarsch

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13. ABSTRACT *(Maximum 200 words)* With the increasing availability of wind power worldwide, power fluctuations have 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. This paper analyzes wind power in the context of ancillary services, using data from a German 250 Megawatt Wind project.

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