Technical Report

Wind Power Plant Monitoring Project Annual Report

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NREL

National Renewable Energy Laboratory

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Table of Contents

Tables

Figures

1. Introduction

This report provides details on the wind power plant monitoring project at the National Wind Technology Center. It describes the project's structure and the data collected, as well as results of data analyses.

In the past 20 years, the application of wind energy has increased steadily in the United States and throughout the world. With continued research and development and improved manufacturing processes, wind turbine performance has improved. More significantly, wind power costs have dropped to the point where, on a cents-per-kilowatt-hour (kWh) basis, they are very close to being competitive with those of traditional fossil-fuel generation. With the aid of various state policies and the emerging green power market, several large- and medium-scale wind power plants with modern wind turbines have been built in the United States in the past few years.

As a result of these developments, more utilities today are seriously examining the wind option. Nevertheless, some utilities have expressed concern over short-term power fluctuations and their possible effects on the electric power system. Power fluctuations might also affect wind power's participation in the bulk-power market by affecting its ancillary-services requirements in a competitive business environment. Ancillary services are interconnected operations services identified by the U.S. Federal Energy Regulatory Commission (Order No. 888, issued April 24, 1996) as necessary to effect a transfer of electricity between purchasing and selling entities, and which a transmission provider must include in an open-access transmission tariff. They include energy imbalance, operating reserve, reactive power supply and voltage control, regulation and frequency response, and scheduling. Wind power developers and wind plant operators need to know the realistic economic impacts of ancillary services requirements for wind power that are derived from real wind power data. Real wind power data would also allow researchers to investigate the extent of the spatial and temporal diversity of wind power, as well as capacity credit issues. Despite these concerns and the need of using long-term, high-frequency real wind power plant output data to analyze the impacts, no programs have systematically collected such data.

This project was designed to remedy the situation with the following two major objectives:

1. Collect at least 2 years of long-term, high-frequency (1-hertz [Hz]) data from several medium- to large-scale wind power plants with different wind resources, terrain features, and turbine types.

2. Analyze the data for power fluctuations, frequency distribution of wind power (by deriving a probability distribution function of wind power plant output variations), spatial and temporal diversity of wind power, and wind power capacity credit issues.

Results of these analyses can provide data on the potential effects of wind power plants on power system regulation. Such information enables utilities to better understand the regulation requirements for wind power plants and assists utilities in planning and operating the electric grid to integrate wind power into the power system.

The National Renewable Energy Laboratory (NREL) awarded a subcontract to collect wind power data from wind power plants in Minnesota and Iowa. In addition, NREL initiated a separate data-monitoring program at the Lake Benton II (LB II) wind power plant, also in Minnesota. Data were collected on real power, reactive power, three-phase line-to-ground voltages, and wind speed—all at 1 Hz.

1.1 Background

The intermittent nature of the wind resource, together with short-term power fluctuations, are the two principal issues facing a utility with wind power plants in its power grid. Researchers[1] at NREL, have long recognized that these issues are barriers to utility acceptance of wind power. The utility system operator must maintain a balance between system load and power production to keep the system stable. This includes accommodating random and peak-to-non-peak load variations in the context of customary long-term planning and short-term scheduling practices of utilities. Utilities, wind power plant developers, and operators need to understand the nature of wind power fluctuations and how they affect the electrical power system, as well as to analyze ancillary service requirements with real wind power plant output data.

Furthermore, as the electric sector moves toward restructuring and developing a competitive market for power generation, the attributes of each individual generator will be more closely assessed, as opposed to assessing the whole system. As a result, all generation sources will be examined on a second-to-second and minute-to-minute basis in the context of ancillary services, which can greatly affect the competitiveness of wind power.

Neither the U.S. Department of Energy (DOE) Wind Energy Program nor industry has had the ability to accurately assess wind power's ancillary-services burdens (or benefits) or second-to-second, minute-to-minute power fluctuations in a widespread, systematic way. Examination of 1-second power output data sets and synchronized power outputs of individual machines from wind power plants of different size, geography, and wind resource type will allow industry to evaluate the potential ancillary-service impacts and costs that result from power fluctuations. Various approaches such as different control strategies, new turbine designs, and innovative business partnerships with other electric resources have been suggested to mitigate the effects of wind power fluctuations on the power system and on the ancillary service requirement of wind power. This evaluation will facilitate research that examines these approaches. It can also help researchers quantify the benefits of short-term electric storage systems with wind generation.

In addition, these new data will allow researchers to evaluate local micro-siting effects. They will also be able to investigate the correlation statistics between machines to field-test the assumption that the aggregate power variation from a larger number of machines has smaller fluctuations than those from a smaller cluster or single machine (on a percentage basis). If utility loads and incremental-cost data are available, the power outputs can be evaluated for capacity values. The power measurements could also be included in a wind-forecasting development and testing program.

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[1] For example, Y. Wan and B. Parsons, Factors Relevant to Utility Integration of Intermittent Renewable Technologies, National Renewable Energy Laboratory, NREL/TP-463-4953, 1993.

1.2 Project History

In October 1999, NREL entered a collaborative agreement with Enron Wind Corporation (EWC) to monitor wind power output at the Lake Benton II wind power plant in Minnesota. The plant has 103.5 megawatt (MW) of wind-generating capacity. Monitoring and data-recording equipment were installed at four grid-interconnection points of Lake Benton II. Complete data from this wind power plant have been available since February 2000. The data have been analyzed by staff from NREL and Oak Ridge National Laboratory (ORNL), who focused on the potential effects on ancillary services and costs (as well as other issues associated with the fluctuations of wind power).

In March 2000, NREL awarded a subcontract to Electrotek Concepts, Inc. (Electrotek), to collect power output data from two wind power plants in Minnesota and Iowa. In Minnesota, Electrotek installed data collection and communications equipment at Buffalo Ridge substation of Northern States Power Company (now Xcel Energy). About 220 MW of wind-generating capacity of various designs connect to the Buffalo Ridge substation. In Iowa, Electrotek installed equipment at MidAmerican Energy's Buena Vista substation near Storm Lake. Total wind-generating capacity being monitored at Storm Lake is about 113 MW. Electrotek will also record pertinent meteorological data such as wind speed and wind direction at the wind turbine hub height at both locations. Storm Lake data collection began in January 2001. Data collection at Buffalo Ridge started in February 2001.

A fourth wind power plant—Big Spring wind project in Big Spring, Texas—was selected by NREL to be part of the monitored sites. However, during contract negotiations, the bidder withdrew its proposal. To ensure diversity of data, NREL plans to add at least one wind power plant outside the Midwest region in the future.

1.3 Report Organization

This report consists of five sections that describe the wind power plant monitoring project, collected data, and preliminary analysis of the data. Section 1 contains the project introduction and background information. Section 2 provides information on the selected wind power plant sites and the specifications for data collected for this project. Section 3 describes in detail NREL's monitoring of Lake Benton II wind power plant. Section 4 presents the first 12 months of data, including statistics and analysis. Section 5 summarizes some prominent features of the data set related to wind power fluctuations.

2. Site Descriptions and Data Specifications

Before selecting sites to monitor, NREL decided that the minimum installed wind-generating capacity for any participating plant should be 15 MW, thus ensuring that the collected data would provide realistic information about utility-scale wind power plants. When determining actual wind power plants, researchers also considered the geography and terrain of the each site in order to maximize spatial diversity of the collected wind power data.

2.1 Descriptions of Selected Sites

Three wind power plant sites were selected for output monitoring in this project: the Buffalo Ridge substation, the Buena Vista substation, and the Lake Benton II wind power plant. The Buffalo Ridge substation is located near Lake Benton, in Pipestone county, Minnesota. It is part of Northern States Power Company's (now part of Xcel Energy) 115-kilovolt (kV) transmission system. The Buena Vista substation is located near Storm Lake, in Buena Vista county, Iowa. The Lake Benton II wind power plant is one of five wind power plants that feed into the Buffalo Ridge substation. Figure 2-1 shows a map of Minnesota and Iowa and the locations of Lake Benton and Storm Lake.
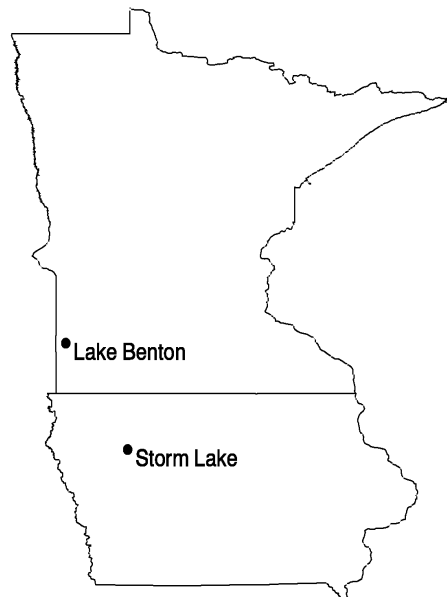
Figure 2-1. Locations of selected wind power plants for monitoring

Buffalo Ridge Substation

The Buffalo Ridge substation is located in southwestern Minnesota in the state's premier wind resource area known as Buffalo Ridge. Storm-driven winds occur as a result of the passage of weather fronts throughout the year. The wind resource is better in winter and early spring as the weather systems are more intense and numerous during that time of the year.

Several wind power plants of varying size are in this geographically diverse area. Most are connected to the Buffalo Ridge substation, which is connected to the 115-kV transmission system in that area. Total wind-generating capacity directly connected to the substation is about 220 MW. Most of the wind turbines at this area are 750-kW turbines (Z50) made by Zond Systems, Inc. There are also a small number of Micon 750-kW and Vestas 660-kW turbines.

Buena Vista Substation

The Storm Lake wind power plant is in northwestern Iowa near Storm Lake. The total installed wind-generating capacity at this site is 196.5 MW, generated by 262 Zond turbines. Of the power plant's generating capacity, 113 MW are connected to MidAmerican Energy's Buena Vista substation, where the monitoring equipment is installed. The substation is part of the 161-kV transmission system in this region. The wind resource here is similar to that of Buffalo Ridge, with weather fronts responsible for much of the energy resource.

Lake Benton II Wind Power Plant

The Lake Benton II wind power plant is part of the wind-generating capacity installed in the Buffalo Ridge area. Located near the town of Ruthton, Minnesota, it consists of 138 Zond Z-50, 750-kW wind turbines equipped with reactive power controls. Total installed capacity of the Lake Benton II plant is 103.5 MW. The wind turbines are connected to the Northern States Power Buffalo Ridge substation through four 34.5-kV feeders. The four interconnection points are designated as Delta, Echo, Foxtrot, and Golf. 30 turbines are connected to Delta, 39 to Echo, 14 to Foxtrot, and 55 to Golf. Power-monitoring equipment is installed at all four grid-interconnection points. Figure 2-2 shows the locations of the138 wind turbines at Lake Benton II.

2.2 Monitored Data

The data recorded from the selected wind power plants include real power, reactive power, and feeder voltage per second at the grid-interconnection point. Representative wind speeds and directions, temperature, and barometric pressure are also recorded. All data records have identification (ID) indicating the reporting wind power plants. Every record is date- and time-stamped with Julian day, hour, minute, and second for aggregation with other data collected for this project. Table 2-1 lists the recorded data.

Table 2-1. Specifications for Monitored Wind Power Plant Data

Variables	Units	Resolution	Comments
ID	Device		
Real power	kW	1 second	
Reactive power	kVAR	1 second	
Feed or interconnection point voltage	kV	1 second	Three-phase line-to-line or line-to-ground voltage
Wind speed	meters/second	30 seconds	Recorded at hub height or existing on-site meteorological towers
Wind direction	Degrees (from true north)	30 seconds	
Ambient temperature	Degrees C	10 minutes	
Local air pressure	Kilopascals	10 minutes	
Time of day	hh:mm:ss	1 second	All records time synched
Date	Julian days	1 second	All records time synched

Data are archived at the National Wind Technology Center. For added security, two separate data sets are maintained in two independent computer systems. All measurement instruments used for monitoring are recalibrated annually. For the duration of the project, clocks at the monitoring sites are resynchronized at least once every three months.
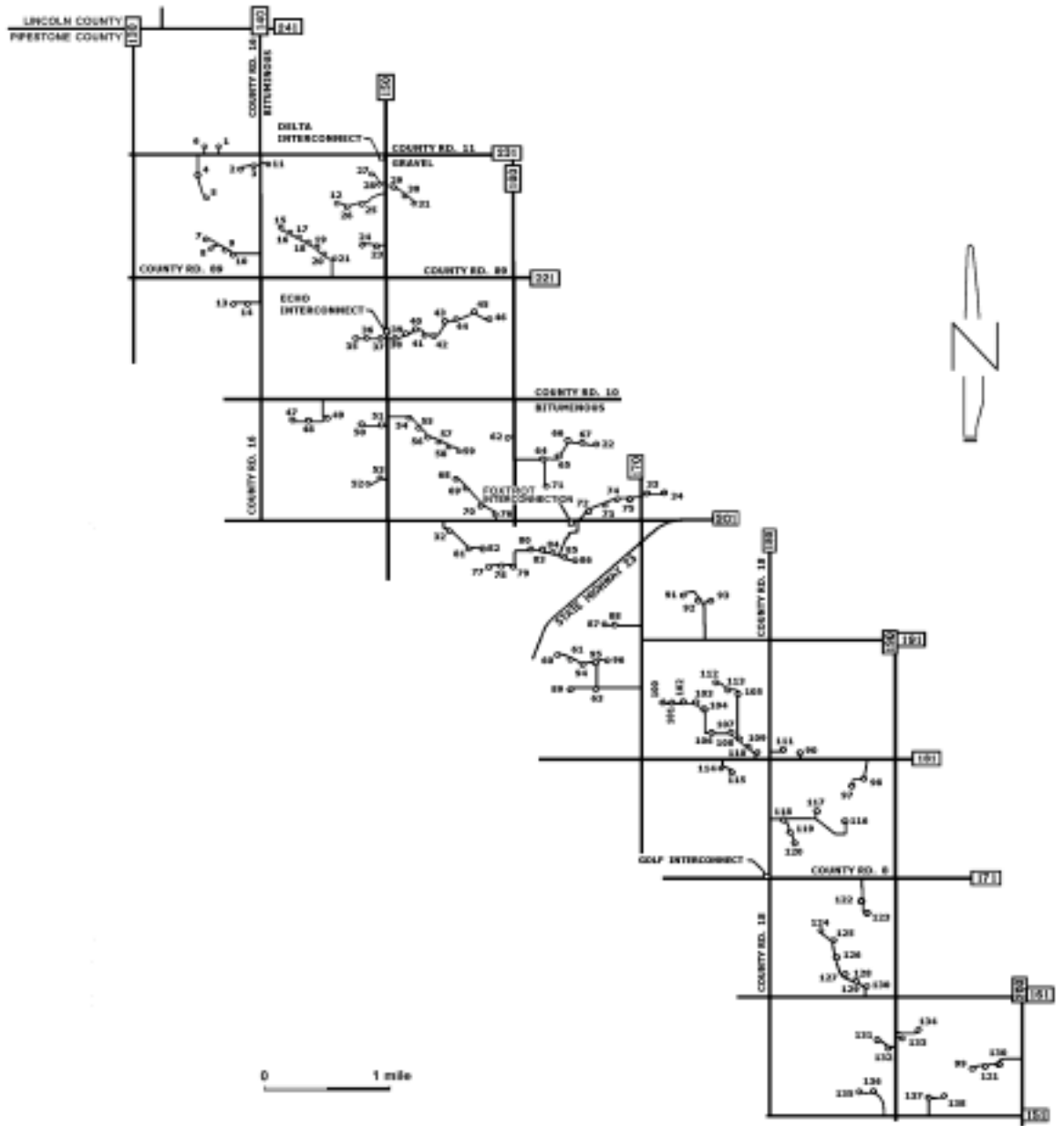
Figure 2-2. Lake Benton II site map

3. Wind Power Monitoring at Lake Benton II

NREL began monitoring Lake Benton II in November 1999 after reaching an agreement with Enron Wind Corporation in October 1999. NWTC technicians installed data-recording equipment at the Delta and Echo interconnection points first to test the design of the monitoring and communication systems. Installation of the monitoring equipment at the other two grid-interconnection points was completed by February 2000.

Figure 3-1 is a view of Echo grid-interconnection point. It shows utility bus work, circuit breaker, switches, voltage regulators, voltage and current transformers, and a small metal building inside a chain-link fence. All four interconnection points share the same design. The metal building houses EWC's metering and control equipment and NREL's monitoring equipment. The local telephone company installed underground phone lines into the metal building for data transmission to NREL.
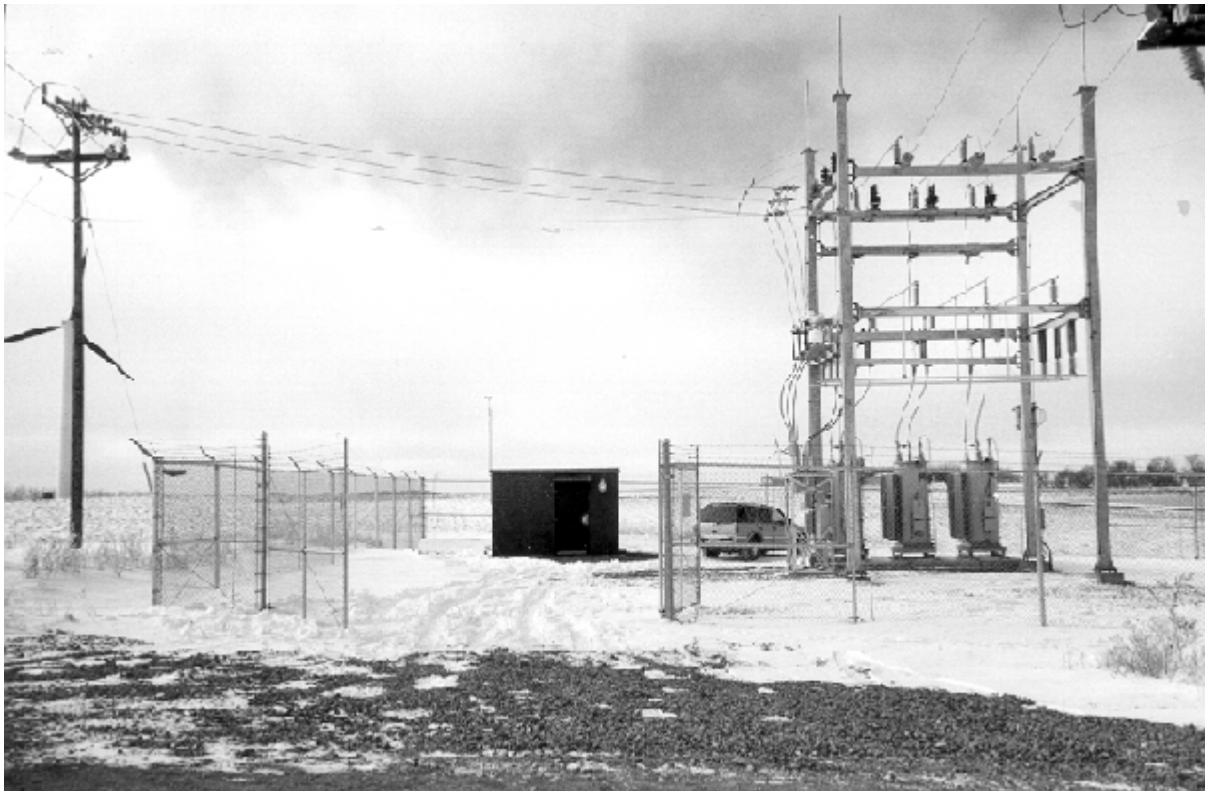
Figure 3-1. Echo interconnection point of Lake Benton II wind power plant

- The monitoring equipment used by NREL at each interconnection point includes One three-element watt/VAR transducer
- One three-element voltage transducer
- One data logger with external modem
- One uninterruptible power supply (UPS)
- One test switch
- One personal computer with Iomega external (or internal) ZIP™ 100 drive.

The equipment was chosen based on NREL staff's previous experience and economic considerations. To collect wind speed information, a simple cup-type anemometer (NRG Max40) was installed on top of a

5-foot antenna pole atop the metal building at the Echo interconnection point (Figure 3-1). Because of the location and height of the anemometer, its wind speed data does not represent true wind resource data for the site. Nevertheless, its data provide some indication of the available wind resource and a good indication of the wind speed trend, both of which are useful in analyzing the power output data. EWC agreed to provide NREL with 10-minute average wind speed data collected from two of its five on-site meteorological towers.

Voltage and current signals are provided by potential transformers and current transformers owned by EWC. Real and reactive power are calculated from voltage and current signals and stored temporary in a 2-MB random-access memory (RAM) bank in the datalogger. The RAM bank can store about 36 hours of data. When the memory is full, new data will overwrite the old data. Telephone lines are dedicated to data transmission only, and they connect directly to the datalogger modem. Figure 3-2 provides a schematic of the power-monitoring equipment at each interconnection point. Figures 3-3 and 3-4 are detailed three-line circuit diagrams of the monitoring equipment for Lake Benton II.

Data are downloaded to the NWTC's server every day via telephone and modem. As a backup, the data are written daily to on-site ZIP™ disks. EWC field personnel replace the ZIP™ disks with blank ones for NREL every two weeks and mail the disks containing data to the NWTC. At NREL's request, EWC field personnel will also inspect and report the status of monitoring equipment and, if possible, perform limited troubleshooting. With this arrangement, NREL has been able to achieve an overall data recovery rate of 98%. So far, missing data has been the result of equipment failures (damaged by lightning), phone line outages, and computer glitches.

Electrotek Concepts, Inc., uses a different approach to data-recording. Its performance will be compared to that of NREL's data-recording system. The results of the comparison will be taken into consideration when determining which monitoring equipment to use in the future.
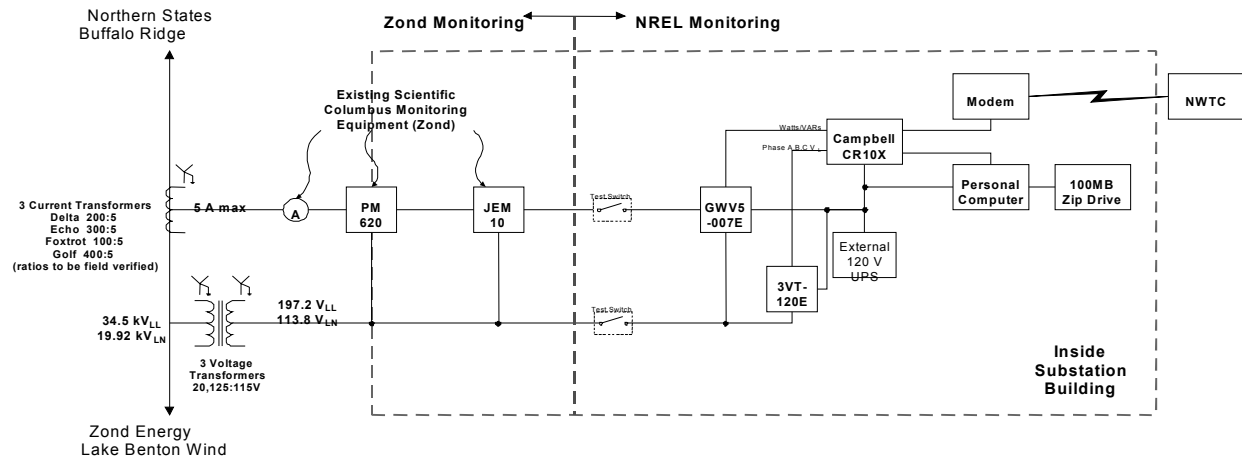
Figure 3-2. Block diagram of Lake Benton II data monitoring setup
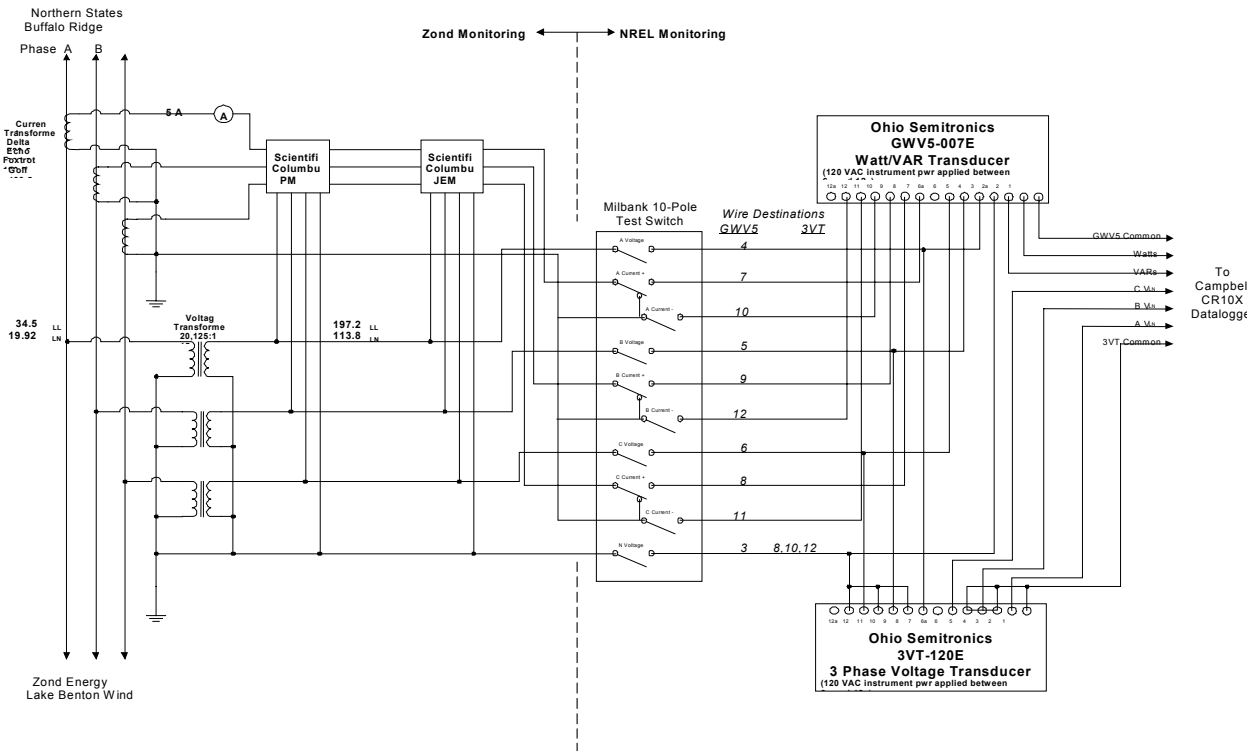
Figure 3-3. Three-line circuit diagram of Lake Benton II data monitoring setup
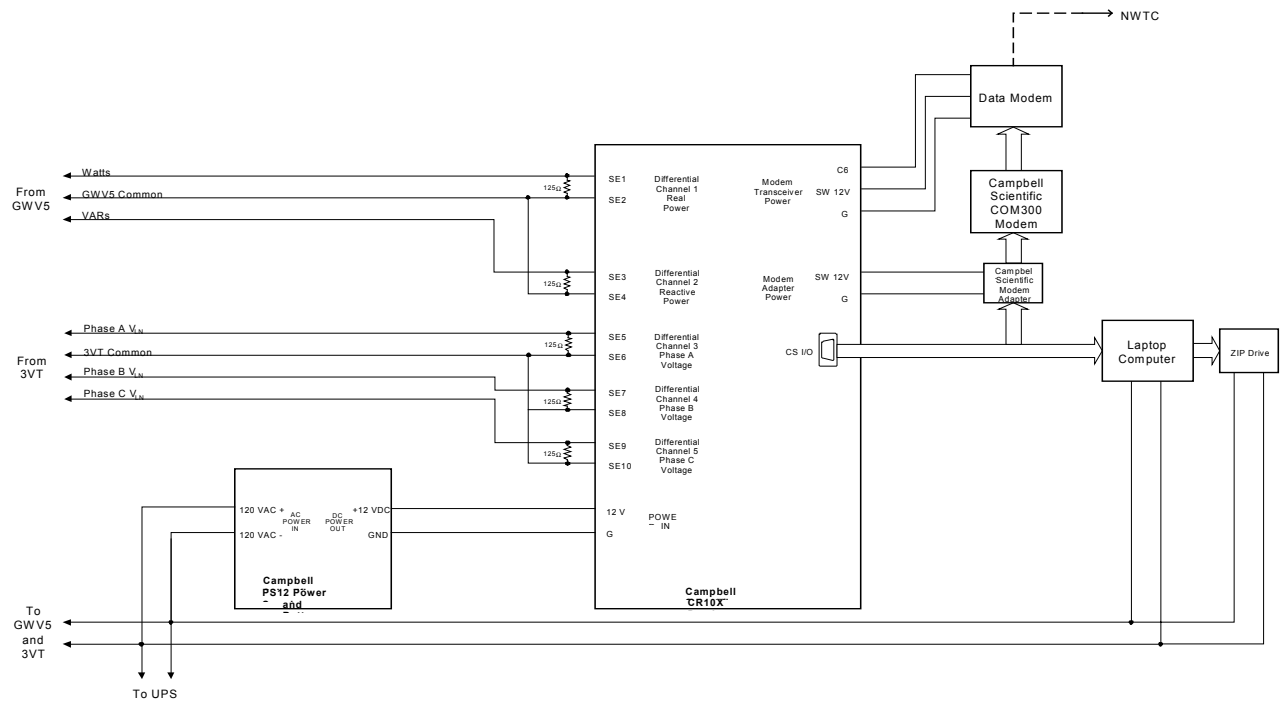
Figure 3-4. Signal flow diagram of Lake Benton II data monitoring setup

4. Data Analysis

Oak Ridge National Laboratory staff will use the data to analyze wind power plant ancillary services requirements. The data will be used to analyze power fluctuations from the wind power plant and to study how spatial and temporal diversity affect power outputs from single and multiple wind power plants. NREL's analysis will also attempt to detect any distinctive power output patterns (daily and seasonally) and trends from multiple wind power plants. Data included in this report are 12 months of real power and wind speed data from Lake Benton II (from February 2000 to January 2001) and one month of real power data from Storm Lake.

This section begins with a description of the energy production at Lake Benton II to give an overview of the wind power plant performance. It is followed by detailed analysis of power fluctuations. Transition rates of wind power from one level to another are also calculated to show the wind power persistency. This section concludes with an investigation of wind power spatial diversity and its effect on wind power variability.

4.1 Power and Energy Production

Power production at the Lake Benton II wind power plant is higher during winter than during summer. Storm Lake should have a similar pattern. Figure 4-1 shows monthly production (in megawatt-hours [MWh]) at Lake Benton II. Monthly power production varies significantly; the highest monthly production is more than twice the lowest monthly production. Generally, wind resources during the months of July and August are less favorable for power generation than other months. Low production in July was partially the result of monitoring equipment failure, which caused data losses. The many forced outages at the Lake Benton II plant during July also had an effect on production.

Lake Benton II Monthly Production
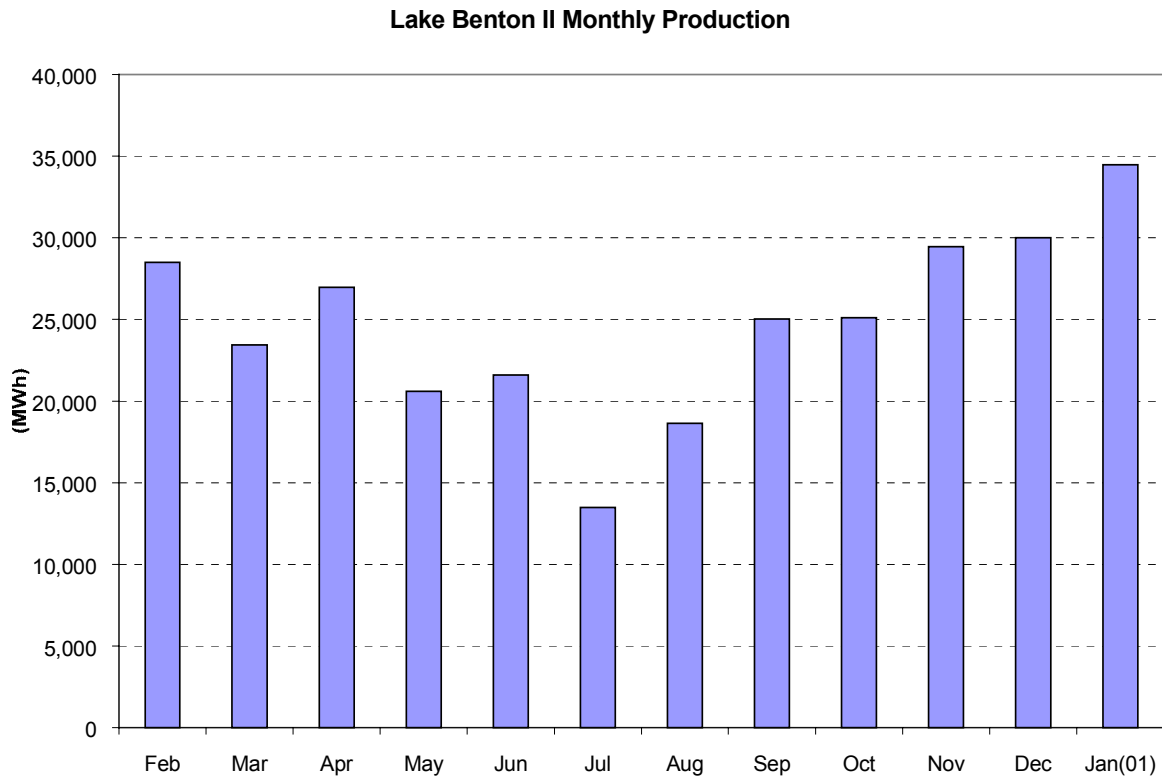
Figure 4-1. Monthly production

Figure 4-2 shows Lake Benton II average annual hourly power production superimposed with June hourly pattern. Overall the peak hourly production occurs in the early morning hours; a secondary peak occurs around noon. Summer production shows a different hourly pattern represented by the June hourly profile. A weak afternoon peak is evident, but it is not well-defined. Although other summer months appear to have a slightly different hourly pattern than that in June, their differences are not very prominent.
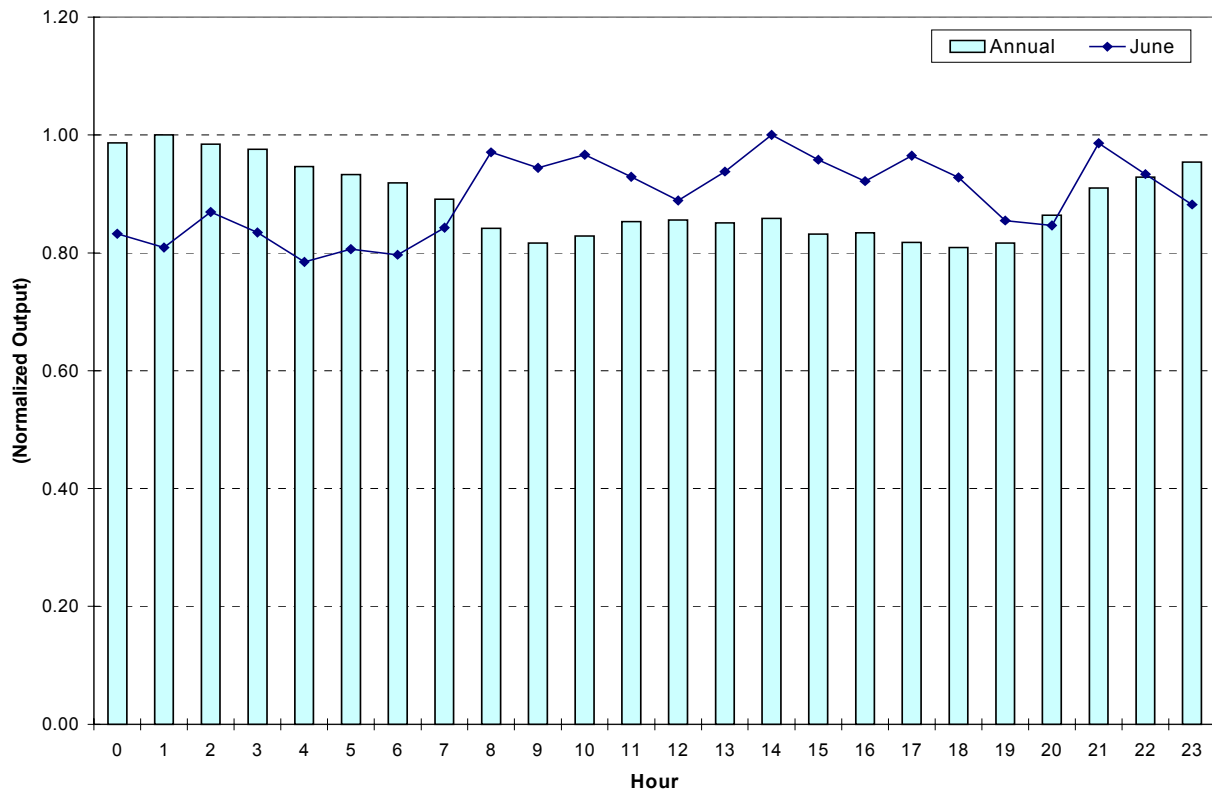
Figure 4-2. Hourly power output profile at Lake Benton II

Table 4-1 shows monthly peak power of four grid-interconnection points and Lake Benton II for three different averaging periods (1-second, 1-minute, and 1-hour). Also included is the coincident factor (CF, in the right-hand column), defined as the ratio of peak power at LB II to the sum of individual peaks at four grid-interconnection points. The turbines at the site are spread out over an area about 7 miles by 9 miles. Because wind speed differs at each individual turbine, not all turbines produce the same amount of power at any given moment. By examining the relationship between each individual grid-interconnection point at peak power and the wind power plant peak power, we can estimate the spatial diversity at Lake Benton II. If there were no spatial diversity, all turbines would produce the same amount of power and the coincident factor would be 1. In section 4.3, we will discuss spatial diversity in more detail.

Table 4-1. Lake Benton II 1-second and 1-hour Average Peak Power

Month	1-second Peak Power (kW)					
	Delta	*Echo*	*Foxtrot*	*Golf*	*Lake Benton II*	*CF*
February	22,540	29,410	10,620	41,370	101,880	0.980
March	22,470	29,390	10,650	40,500	100,210	0.973
April	22,540	28,070	10,680	39,750	98,670	0.977
May	21,560	27,850	9,870	38,310	94,610	0.969
June	21,390	27,720	9,890	39,240	92,860	0.945
July	21,440	27,590	10,580	36,730	94,410	0.980
August	20,600	26,720	9,620	38,880	90,950	0.949
September	22,290	28,420	10,320	40,830	98,920	0.971
October	21,090	29,240	10,500	40,280	98,530	0.974
November	20,780	29,050	10,630	40,680	100,110	0.990
December	21,310	28,880	10,570	40,900	99,530	0.979
January (01)	21,880	28,720	10,660	41,420	100,740	0.981

Month	1-minute Peak Power (kW)					
	Delta	*Echo*	*Foxtrot*	*Golf*	*Lake Benton II*	*CF*
February	22,138	28,708	10,442	40,642	101,143	0.992
March	22,096	28,810	10,390	40,011	99,817	0.985
April	22,148	27,598	10,412	39,113	97,866	0.986
May	21,314	27,537	9,669	37,596	93,746	0.975
June	21,078	26,693	9,616	38,555	89,744	0.935
July	20,722	27,132	10,334	35,945	92,692	0.985
August	20,332	26,260	9,461	38,386	89,126	0.944
September	21,992	28,063	10,138	40,050	97,905	0.977
October	20,753	28,985	10,181	39,512	97,840	0.984
November	20,483	28,642	10,334	40,114	98,601	0.980
December	20,974	28,435	10,313	40,151	98,589	0.987
January (01)	21,471	28,479	10,355	40,275	99,537	0.990

Table 4-1. (continued) Lake Benton II 1-second and 1-hour Average Peak Power

Monthly	Hourly Peak Power (kW)					
	Delta	*Echo*	*Foxtrot*	*Golf*	*Lake Benton II*	*CF*
February	21,996	28,356	10,403	40,240	99,125	0.981
March	21,974	28,604	10,124	39,540	98,677	0.984
April	22,083	27,455	10,373	38,807	96,470	0.977
May	20,698	27,470	9,565	36,627	92,018	0.975
June	19,855	25,521	9,466	36,392	86,975	0.953
July	19,299	24,992	10,007	34,378	86,630	0.977
August	18,840	25,431	8,722	37,132	87,133	0.967
September	20,322	26,907	10,017	39,217	94,444	0.979
October	20,665	28,620	9,832	39,293	96,451	0.980
November	20,330	28,360	10,286	39,278	98,139	0.999
December	20,859	28,224	10,154	39,613	97,658	0.988
January (01)	21,339	28,444	10,340	40,176	99,150	0.989

4.2 Fluctuations of Wind Power

Several measures are used to examine power fluctuations at the LB II wind power plant. Simple statistics and distribution regarding maximum step changes (power level differences between consecutive time steps) and ramping rates (either up or down, caused by the wind picking up or dying down) provide more insight into the nature of the wind power fluctuations.

Step Changes

The differences in output power levels between consecutive time steps indicate wind power persistency. To quantify the behavior of the wind resource, we calculated the maximum step changes in both positive and negative directions and their means and standard deviations, for three time steps (1-second, 1-minute, and 1-hour, Table 4-2). To focus on only the maximum power changes caused by decreasing or increasing wind speed, we screened the recorded data stream to eliminate power changes caused by forced or controlled outages and startups. To isolate these "artificial" power drops, we excluded those large power drops (to zero or a substantially lower value within 2 seconds) without a corresponding wind speed decrease. In a similar fashion, large power increases from zero or a very low level without corresponding wind speed increases were also excluded. However, this extra step may not totally eliminate power changes from forced outages or planned events, because sudden, significant power drops that do not decrease output power to zero (or a smaller value) will not be detected by such an algorithm.

It is clear that, for short periods, the step changes are very small. The maximum increase in power is 4,430 kW, or 4.3% of the nameplate capacity (in 1-second increments), during this 12-month period. For 1-minute increments, the maximum increase in power is 11,541 kW, or 11% of the nameplate capacity, which is equivalent to a sustained ramping-up rate of 192 kW per second, or 0.2% of the rated power per second. The maximum 1-second step drop is 7,590 kW, or 7.3% of the nameplate capacity. For the same period, the maximum 1-minute step drop is 14,448 kW, or 14.0% of the nameplate capacity. This is equivalent to a sustained ramping-down rate of 241 kW/s, which is much smaller than the maximum 1-second step change value.

Table 4-2. Maximum, Average, and Standard Deviation of Lake Benton II Step Changes

Month	1-second power (kW)				1-minute average power (kW)			
	Max. Increase	Max. Decrease	Mean	Stdev.	Max. Increase	Max Decrease	Mean	Stdev.
February	1,950	-1,980	0	194	4,969	-5,492	-1	1,091
March	1,870	-2,627	0	194	7,266	-7,957	-2	1,711
April	3,663	-4,837	0	212	11,541	-13,852	0	1,776
May	2,296	-5,241	0	191	9,661	-7,846	0	1,298
June	4,430	-7,590	0	155	10,078	-14,304	1	1,116
July	2,908	-7,138	0	88	7,545	-8,490	0	691
August	1,609	-4,560	0	92	9,706	-7,232	-1	709
September	1,810	-5,440	0	158	7,907	-14,448	-1	1,073
October	2,271	-1,260	0	139	9,818	-8,487	2	860
November	1,900	-4,900	0	161	5,750	-4,251	0	816
December	2,200	-6,217	0	168	6,669	-5,217	-1	677
January ('01)	2,240	-2,810	0	207	8,711	-5,075	1	685
12-month			0	168			0	1,103

Month	Hourly power (kW)			
	Max. Increase	*Max. Decrease*	*Mean*	*Stdev.*
February	42,024	-50,395	-177	11,245
March	53,567	-39,605	-149	11,007
April	49,919	-51,653	-98	11,478
May	44,420	-38,712	-69	10,080
June	61,949	-38,378	73	9,955
July	42,110	-45,712	-131	7,573
August	47,425	-42,012	29	9,757
September	65,410	-35,646	27	10,097
October	50,448	-36,868	24	9,231
November	61,159	-34,480	-141	10,069
December	53,367	-48,510	-91	10,956
January ('01)	61,033	-43,496	21	10,801
12-month			-56	10,220

Because wind speed can change substantially during an hour, hourly power changes can be very large. The maximum 1-hour increase during the 12-month period (from February 2000 to January 2001) is 65.4 MW (63% of total capacity), and the maximum 1-hour decrease is 51.7 MW (50% of total capacity). In terms of kW per minute, this is equivalent to a positive 1,090 kW/min and a negative860 kW/min, respectively; both are much less than the maximum 1-minute changes. However, those are relatively infrequent events, as will be shown later in the distribution plot.

Table 4-3 lists average and standard deviation values of positive and negative monthly step changes. It also shows that positive and negative step changes have about the same average absolute values, which implies that step changes are evenly distributed around their means. The averages of all step change values are nearly zero for all cases. The standard deviation for 1-second step changes is 168 kW, less than 0.2% of total capacity. For 1-minute step changes, the standard deviation is 1,103 kW, or 1% of total capacity. For hourly step changes, it is 10,220 kW, or about 9.9% of total capacity. These relatively small standard-deviation values also suggest that step change distributions are tightly centered around their means. Plots of step change distributions for different time step sizes (Figure 4-3) confirm the even distribution.

Table 4-3. Average and Standard Deviations of Positive and Negative Step Changes

Month	1-second power (kW)				1-minute average (kW)			
	(+) Avg	*(+) Stdev.*	*(–) Avg*	*(–) Stdev*	*(+) Avg*	*(+) Stdev.*	*(–) Avg*	*(–) Stdev*
February	107	151	-103	186	499	683	-502	1,193
March	86	125	-82	233	507	897	-500	2,147
April	96	134	-92	242	606	1,335	-604	1,954
May	92	146	-88	207	552	955	-553	1,412
June	83	122	-78	151	569	781	-575	1,117
July	54	74	-49	84	363	553	-368	634
August	60	74	-55	77	426	531	-437	601
September	97	131	-92	147	560	766	-559	1,051
October	84	115	-78	126	491	674	-490	783
November	99	135	-95	139	489	599	-489	752
December	106	144	-102	146	452	511	-458	577
January ('01)	126	180	-121	184	422	538	-420	624
12-month	91	133	-86	170	494	783	-497	1,196

17

Table 4-3. (continued) Average and Standard Deviations of Positive and Negative Step Changes

Month	Hourly average (kW)			
	(+) Avg	*(+) Stdev.*	*(–) Avg*	*(–) Stdev*
February	7,574	7,530	-8,235	8,587
March	7,169	9,213	-6,580	8,131
April	7,818	8,805	-7,203	8,569
May	6,724	7,784	-6,373	7,490
June	6,885	7,693	-6,504	7,034
July	4,439	5,992	-4,759	6,223
August	6,219	7,098	-6,693	7,612
September	7,204	8,096	-7,352	7,287
October	6,146	7,206	-6,131	6,499
November	7,145	8,063	-6,833	7,133
December	7,634	9,379	-6,849	7,690
January ('01)	7,069	9,056	-6,649	7,752
12-month	6,844	8,116	-6,649	7,562
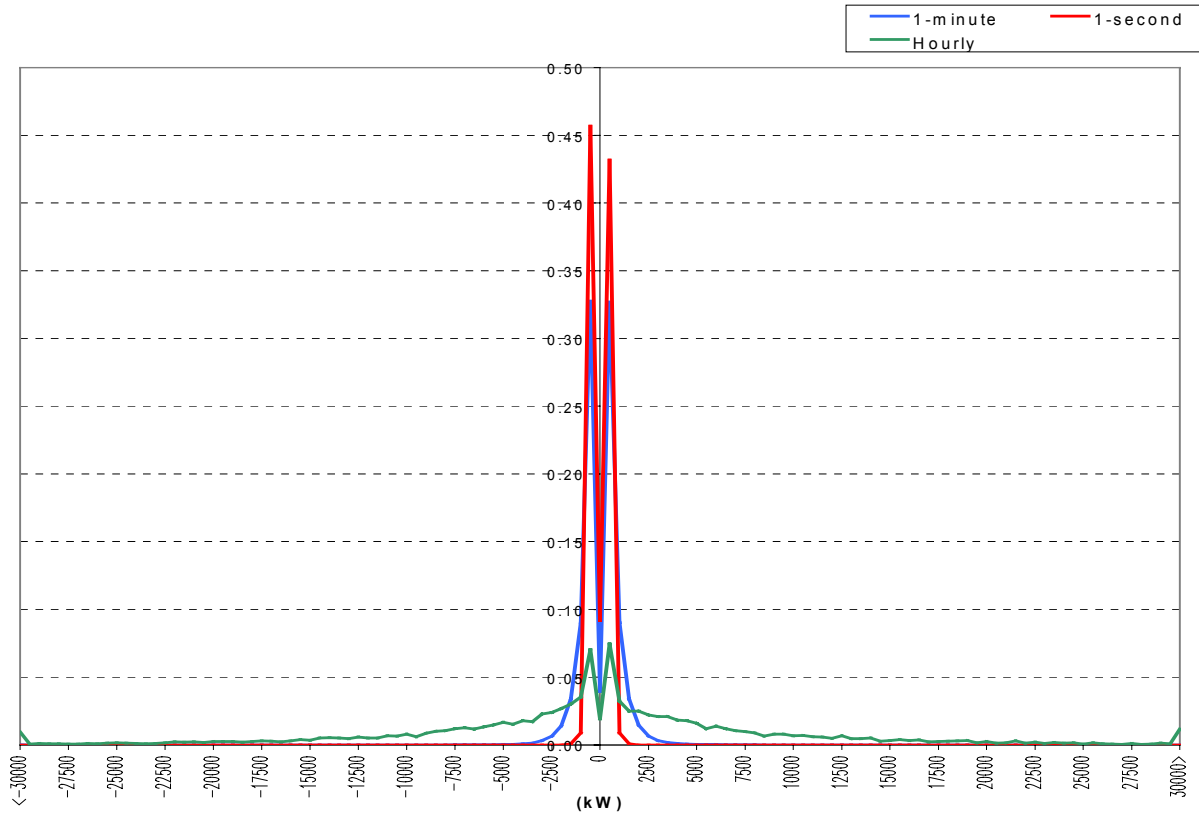
Figure 4-3. Distribution of step changes

These curves do not resemble the familiar bell-shaped normal distribution because of a deep notch at the zero value. The low probability of zero step change values confirms the observation that wind speed and wind power plant output are not static. This low probability is largely the result of zero output values in the data stream (caused by planned and forced outages). Without these zero output values in the data stream, the actual probability of zero step changes would be almost zero. These plots confirm that the short-term power fluctuations are confined to a very narrow range and that the frequencies of positive and negative changes are about the same. Large step changes rarely occur. Most of the step changes have small values.

From the hourly step change distribution curve, we calculated that 78.7% of the possible step changes are confined within the range of ±10,500 kW (roughly ±1σ), which is about 10% of total capacity. Further, 93.6% of the possible step change values are within ±20,500 kW (approximately ±2σ), or only about 20% of total capacity. For 1-minute data, the concentration is more prominent: 87.5% of the possible step changes are within ±1,000 kW (±0.9σ) and 94.5% within ±1,500 kW (±1.4σ), which is only 1.4% of the total wind power plant capacity. For 1-second step change, 98% of the values are within ±500 kW (±3 σ), or less than 0.5% of total capacity.

The statistics of step changes for combined output (for the month of January 2001) from Lake Benton II and Storm Lake are listed in Table 4-4. The numbers in parentheses show the quantities as a percentage of total installed capacity of these two wind power plants.

19

Table 4-4. Step Changes of Combined Output

1-hour data			
	Lake Benton II	*Storm Lake*	*Combined Output*
Maximum (+)	61,033 (59%)	29,282 (26%)	63,142 (29%)
Maximum (-)	-43,496 (42%)	-41,143 (36%)	-46,290 (21%)
Average	35	79	111
Standard Deviation	10,724 (10%)	7,609 (6.7%)	12,800 (5.9%)

1-minute data			
	Lake Benton II	*Storm Lake*	*Combined Output*
Maximum (+)	8,711 (8%)	9,524 (8%)	5,068 (3%)
Maximum (-)	-5,075 (5%)	-4,372 (4%)	-5,445 (3%)
Average	1	1	2
Standard Deviation	707 (1%)	559 (1%)	885 (0.4%)

1-second data			
	Lake Benton II	*Storm Lake*	*Combined Output*
Maximum (+)	2,240 (2%)	2,864 (3%)	2,850 (1%)
Maximum (-)	-2,810 (3%)	-2,791 (3%)	-3,073 (1%)
Average	0	0	0
Standard Deviation	207 (0.2%)	95 (0.1%)	229 (0.1%)

These data reveal that if the output from the Lake Benton II and Storm Lake wind power plants are combined, the average magnitude and standard deviation of power fluctuations may be slightly higher. However, if the step changes are expressed as a percentage of total power, the fluctuations from the combined power output are always smaller than those from either wind power plant. Because these two outputs are not totally independent (the correlation coefficient is not zero), the average value of combined power step changes will not be the sum of two individual averages of power step changes, nor is the combined standard deviation the sum of two individual standard deviations. The maximum values of step

changes of the combined power can be higher or lower than the maximum values from individual wind power plants. They depend on whether the extreme values from these two sites coincide. Again, this is the result we would expect from two weakly correlated signals.

Ramping Rate

Step changes show all the single extreme values (instant changes) that the wind power plant can experience; however, those maximum values in either direction occur only infrequently. To investigate sustained power changes, we calculated ramping rates in either direction for various periods. The ramping rates discussed here are slopes of a straight line used to fit the wind power data points. Table 4-5 lists the ramping rates in kilowatts per second calculated with 1-second power data in three time intervals: 5, 10, and 15 seconds. Table 4-6 lists ramping rates in kW per minute, calculated with 1-minute average power in two time intervals: 5-minute and 10-minute. Sudden power drops and rapid power increases caused by forced or maintenance outages and manual startups are excluded from the maximum (+) and minimum (−) ramping rates in Tables 4-5 and 4-6. However, when calculating average and standard deviation of ramping rates, unaltered data streams are used for the sake of computation expediency (to avoid the problems of data discontinuity).

Ramping rates are higher when computed at shorter time intervals. In Table 4-1, short-term maximum up and down ramping rates are lower than single step change values, indicating the changing nature of the wind speed. Wind power does not move in either up or down direction very long before it reverses itself. It is common for wind power to display a general up-or-down trend over longer periods, e.g., several hours. Tables 4-5 and 4-6 show that average positive (up) and negative (down) ramping rates have approximately the same magnitude on a monthly basis. On a daily basis, this is not necessarily true.

Table 4-5. Ramping Rates (kW/s) Based on 1-Second Power Data

Month	5-second interval					
	Max. (+) ramp	*Average*	*Std. Dev.*	*Max. (-) ramp*	*Average*	*Std. Dev.*
February	1,075	41	48	-568	-42	95
March	1,055	35	49	-1,248	-38	145
April	2,921	43	57	-1,553	-44	146
May	1,282	36	48	-4,679	-41	104
June	3,009	42	52	-3,982	-42	80
July	3,299	27	40	-2,901	-30	47
August	649	35	43	-1,985	-35	46
September	4,166	47	56	-1,971	-48	72
October	1,385	39	53	-3,509	-43	63
November	960	39	47	-805	-43	57
December	1,758	36	45	-821	-43	51
January (01)	968	36	44	-3,777	-43	56
12-month		37	49		-41	88

Table 4-5. (continued) Ramping Rates (kW/s) Based on 1-Second Power Data

Month	10-second interval					
	Max. (+) ramp	*Average*	*Std. Dev.*	*Max. (-) ramp*	*Average*	*Std. Dev.*
February	946	31	36	-517	-31	70
March	855	27	38	-1,070	-28	109
April	2,778	32	46	-1,443	-32	106
May	1,236	27	37	-1,257	-30	74
June	2,626	32	39	-2,157	-33	60
July	1,699	22	31	-1,513	-23	36
August	525	28	34	-1,020	-28	37
September	2,090	37	44	-1,090	-37	56
October	1,232	31	42	-2,543	-34	49
November	464	29	35	-646	-32	43
December	733	26	32	-635	-31	37
January (01)	575	24	31	-2,086	-30	40
12-month		28	37		-31	65

Table 4-5. (continued) Ramping Rates (kW/s) Based on 1-Second Power Data

	15-second interval					
	Max. (+) ramp	*Average*	*Std. Dev.*	*Max. (-) ramp*	*Average*	*Std. Dev.*
February	900	26	31	-376	-26	58
March	817	23	32	-781	-23	92
April	2,657	27	42	-958	-27	88
May	1,218	23	32	-859	-25	61
June	2,061	27	33	-1,585	-27	51
July	884	19	26	-1,031	-19	30
August	483	24	29	-709	-24	31
September	1,376	31	37	-777	-31	47
October	1,068	26	36	-1,975	-28	41
November	378	24	30	-415	-27	36
December	585	21	27	-579	-26	30
January (01)	479	19	25	-1,439	-24	33
12-month		24	32		-26	54

For 5-second intervals, the maximum ramping-up rate is about 4,166 kW/s, or 4.0% of total capacity per second. The maximum ramping-down rate is –4,679 kW per second, or 4.5% of total capacity. The average values for both ramping-up and ramping-down rates are much smaller, with a magnitude of 37 kW/s and 41 kW/s, respectively. They are less than 0.04% of total capacity per second.

Table 4-6. Ramping Rates (kW/min) Based on 1-minute Average Power Data

Month	5-minute interval					
	Max. (+) ramp	Average	Std. Dev.	Max. (-) ramp	Average	Std. Dev.
February	4,209	367	542	-4,536	-368	766
March	4,162	358	675	-3,881	-356	1,196
April	7,375	424	842	-9,569	-425	1,170
May	6,024	356	648	-5,115	-381	860
June	8,038	385	555	-7,379	-387	701
July	8,797	237	369	-6,097	-244	409
August	6,421	285	372	-5,992	-293	416
September	4,220	368	498	-4,581	-364	629
October	8,378	297	428	-11,894	-319	479
November	4,123	305	417	-4,575	-337	478
December	5,941	271	376	-4,690	-326	401
January (01)	5,421	266	403	-4,540	-320	437
12-month		320	530		-343	723

Table 4-6. Ramping Rates (kW/min) Based on 1-minute Average Power Data (continued)

Month	10-minute interval					
	Max. (+) ramp	Average	Std. Dev.	Max. (-) ramp	Average	Std. Dev.
February	2,896	312	470	-3,651	-315	555
March	3,780	299	570	-2,785	-295	809
April	4,823	337	610	-6,492	-335	763
May	4,985	287	500	-6,617	-295	590
June	5,429	312	450	-5,627	-310	515
July	5,238	191	304	-5,562	-194	322
August	4,577	238	318	-4,970	-244	344
September	3,257	292	403	-3,911	-286	447
October	6,918	240	343	-6,145	-255	356
November	3,531	255	345	-2,789	-275	366
December	4,933	230	328	-3,848	-270	330
January (01)	4,625	233	346	-3,864	-271	342
12-month		264	426		-278	509

Ramping rates calculated with 1-minute average power data show a similar pattern—longer time intervals always result in lower ramping-up and ramping-down rates. Within a 5-minute interval, the wind power plant can ramp up at a rate of 8.8 MW/minute (8.5% of total capacity per minute). The maximum ramping-down rate for a 5-minute interval is -12 MW/min (11.5% of total capacity per minute). For a 10-minute interval, the maximum ramping-up and ramping-down rates are about half of that for a 5-minute interval. Again, in all cases, their average values are much smaller—less than 0.4% of total wind power plant capacity per minute. The small standard deviation values of ramping rates also indicate that short-term ramping rates are small and confined within a narrow range.

The distributions of ramping rates are plotted in Figure 4-4 for 5-second, 10-second, and 15-second intervals and Figure 4-5 for 5-minute and 10-minute intervals. The shapes of the curves are almost identical to those of step changes. From the distribution curves, we can calculate that for 5-second intervals, 90.3% of the apparent ramping rates are within ±100 kW/s. For 10-second intervals, 94.9% of apparent ramping rates are within ±100 kW/s, and for 15-second intervals, 96.8% are within ±100 kW/s. For longer time, the ranges are even narrower. For 5-minute intervals, 90% of apparent ramping rates are

within ±780 kW/min (or 13 kW/s). For 10-minute intervals, 90% of apparent ramping rates are within ±640 kW/min (or 11 kW/s).

These results suggest that if another power plant were to be dedicated to regulate[2] the output of Lake Benton II, the duty requirement for the dedicated power plant will be ±220 kW/s (or about 0.2% of the total installed capacity per second). This range would cover 99% of all apparent ramping rates for Lake Benton II.
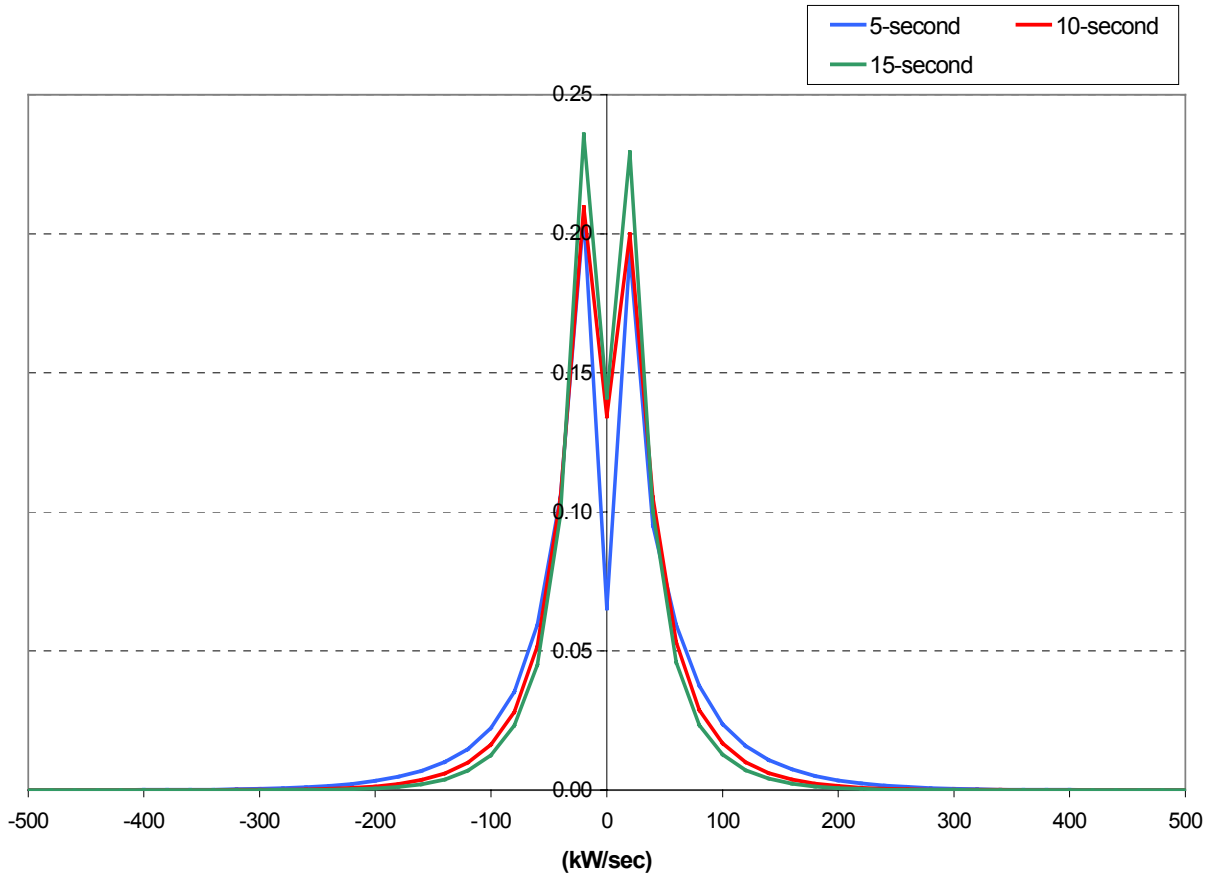
Figure 4-4. Distribution of ramping rates (1)

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[3]   This is not load following as normally applied to electric power systems. In order to do load following, target power levels and generators are controlled to match the changing load level. How fast the target power level can change in any given time interval will determine the duty requirements (ramping rates) of generators that are used to follow it. Here, the rates of change in wind power plant output are used directly as the duty requirements of generators, as if these generators will be running in opposite directions of the wind power plant to cancel those changes.
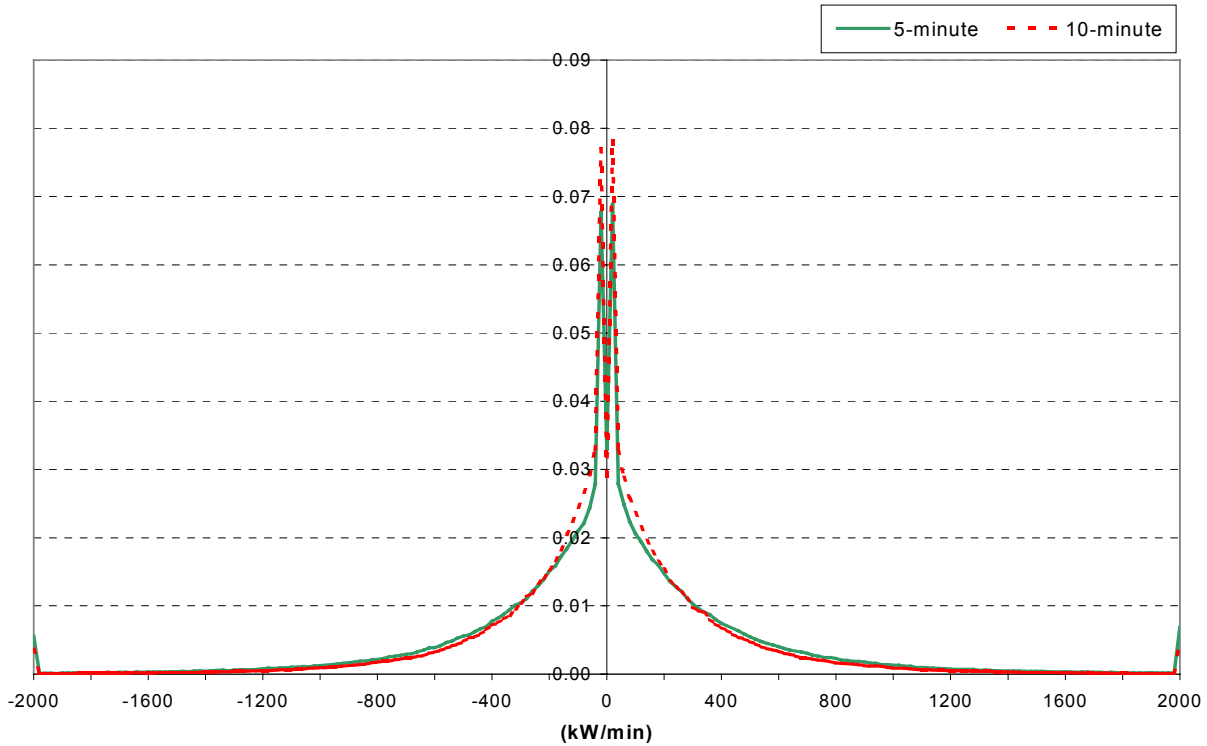
Figure 4-5. Distribution of ramping rates (2)

Average ramping rates and their standard deviations are affected by many forced outages of the wind power plant from February until July, which is reflected in higher standard deviation values during these six months (especially for negative ramping [power levels ramping down] rates). This is because forced and maintenance outages will result in precipitous power drops and, consequently, very large negative ramping rates. Lake Benton II experienced many outages prior to summer of 2000. The data collected at the grid interconnection points are not sufficient to determine the causes of these outages. However, data have shown significant improvement in the operations of Lake Benton II wind power plant since July 2000. The average and standard deviation values of ramping rates listed in Tables 4-5 and 4-6 include extreme values not caused by wind. For the six-month period from February to July (Table 4-5), the average coefficient of variations of negative ramping rates (the ratio of standard deviation to average) is 2.7, dropping to 1.4 for the next six-month period. In Table 4-6, they are 2.2 and 1.4, respectively. Wind power plants operating normally can be expected to have smaller values.

State Transitions

Maximum step changes establish the outside boundaries of wind power fluctuations, while ramping rates indicate that wind power does not change very fast; both of these provide strong evidence of wind power persistency. When wind power data are analyzed for the rates of transition from one power level to another, the persistency of wind power from large wind power plants is even more obvious. Table 4-7 shows the rates of transition from one power level to the next in 1-second intervals for Lake Benton II for the 12-month period. The row headings indicate power levels in the first-second time step, and the column headings indicate power levels in the next-second time step. For example, if the current step power level of Lake Benton II is at 40% of its nameplate power at any particular second (row labeled with 40%), 99.34% of the time its output will stay at the same level (column with 40% heading) at the next second. The next second, its power may jump to 50% of the rated value only 0.32% of the time, and its

power level may drop to 30% of the rated value the next-second 0.34% of the time. This should not come as a surprise, because all 138 wind turbines at the wind power plant are not likely to change their output at the same instant.

Table 4-7. State Transition Rates with 1-Second Power Data

	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
10%	0.9993	0.0007	0	0	0	0	0	0	0	0
20%	0.0016	0.9968	0.0016	0	0	0	0	0	0	0
30%	0	0.0020	0.9955	0.0025	0	0	0	0	0	0
40%	0	0	0.0029	0.9940	0.0031	0	0	0	0	0
50%	0	0	0	0.0038	0.9924	0.0039	0	0	0	0
60%	0	0	0	0	0.0046	0.9892	0.0062	0	0	0
70%	0	0	0	0	0	0.0068	0.9852	0.0080	0	0
80%	0	0	0	0	0	0	0.0077	0.9813	0.0111	0
90%	0	0	0	0	0	0	0	0.0107	0.9764	0.0128
100%	0	0	0	0	0	0	0	0	0.0195	0.9805

As seen in Table 4-8, state transition rates computed with 1-minute average power data show a different pattern. Non-zero values are no longer clustered diagonally, indicating that given more time, much larger power level changes will occur. It should be noted that many of the outlying values in Table 4-8 are the result of forced or planned outages of the wind power plant, not of dramatic wind speed changes. For example, from Table 4-2 (where large step changes caused by outages were excluded) the maximum 1-minute power drops at Lake Benton II from February 2000 to January 2001 was 14.4 MW, or only 14% of total capacity. A power level change of more than 20% of the installed capacity in 1 minute is clearly not induced by wind speed change.

29

Table 4-8. State Transition Rates with 1-Minute Average Power Data

	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
10%	0.9923	0.0077	0	0	0	0	0	0	0	0
20%	0.0168	0.9632	0.0198	0.0001	0	0	0	0	0	0
30%	0.0003	0.0239	0.9481	0.0275	0.0001	0	0	0	0	0
40%	0.0002	0.0001	0.0315	0.9358	0.0322	0.0001	0	0	0	0
50%	0.0002	0.0001	0.0001	0.0380	0.9267	0.0347	0.0002	0	0	0
60%	0.0002	0.0001	0.0002	0.0002	0.0414	0.9157	0.0422	0	0	0
70%	0.0001	0.0002	0.0001	0.0001	0.0003	0.0426	0.9176	0.0389	0.0001	0
80%	0.0002	0.0001	0	0.0001	0.0001	0.0002	0.0361	0.9251	0.0382	0
90%	0.0002	0	0.0001	0	0	0	0.0002	0.0361	0.9416	0.0218
100%	0	0.0001	0	0	0	0	0.0001	0.0004	0.0324	0.9667

4.3 Spatial Diversity

The 138 turbines at Lake Benton II are arranged along a northwest to southeast diagonal line about 17 km (10.6 miles) long. The operation of turbines is not synchronized, and their outputs do not rise and fall at the same time. When a wind gust sweeps through the site, it reaches some turbines sooner than others. If we monitored the output of every turbine, we should detect an output with a wave-like pattern. Even with data from only four interconnection points, this effect is still detectable.

An example of this effect is given in Figure 4-6, which shows output profiles of the four grid-interconnection points and their sums for a summer day in 2000. They are plotted with 1-minute average power data. The graph shows that, shortly after 21:21, a gust passed through the site, resulting in a power surge of 42 MW within about 13.5 minutes (a ramp rate of 3.1 MW/min or 52 kW/s). It is also clear from the graph that not all four grid-interconnection points rise to their peak power at the same time. Figure 4-7 shows the details of the gust and power surge in a 20-minute window (from 21:22 to 21:41) plotted with 1-second power data from these four interconnection points and their sum.
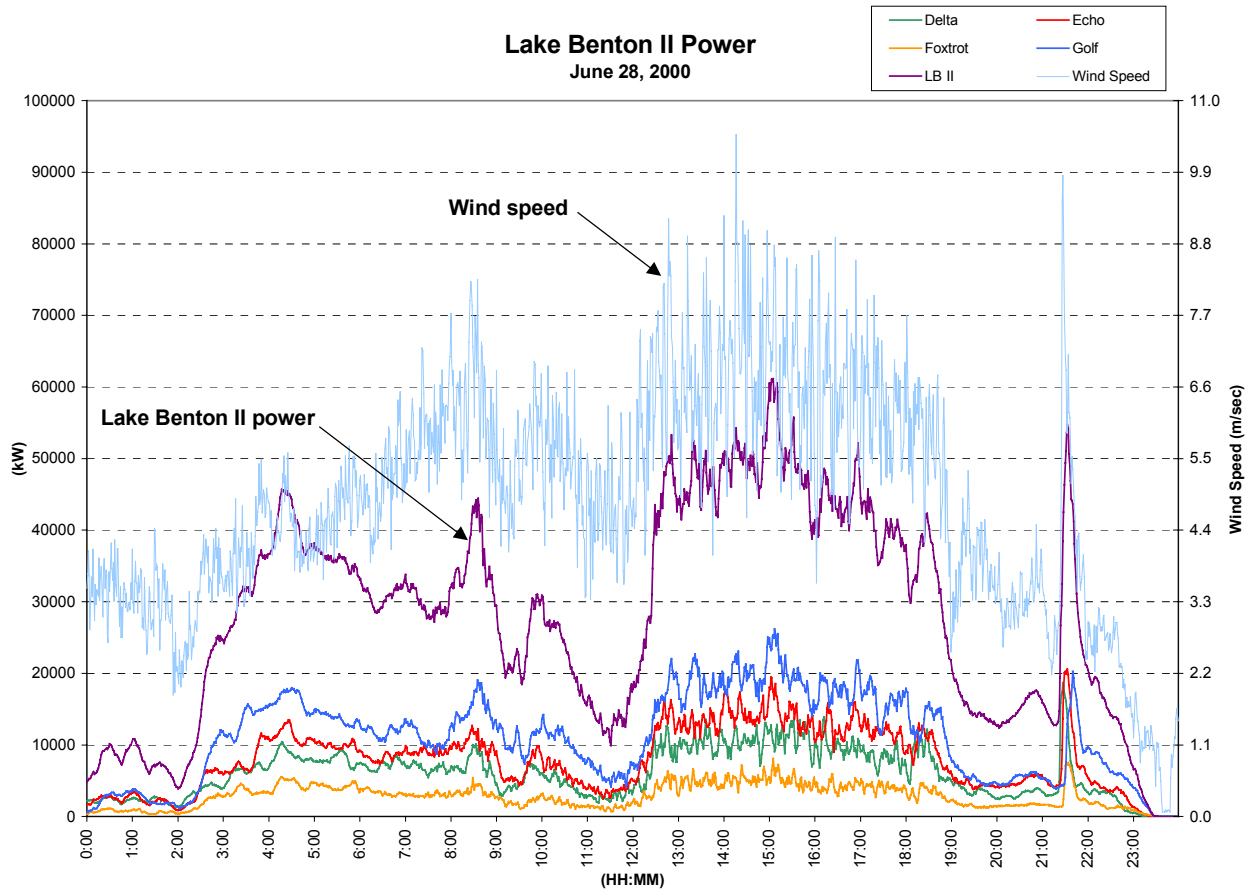
30

Figure 4-6. Sample daily power output profile

Wind speed data in Figures 4-6 and 4-7 are from an anemometer located at the Echo interconnection point, which is near the middle of the wind power plant. It appears that the direction of the gust is northwest to southeast. The effect of wind turbine separation is clearly seen. Power at the Delta interconnection point rises first, followed by Echo, Foxtrot, and then Golf. The entire plant reaches a peak output of 55.74 MW at 21:33:33, although output power from the Golf interconnection point does not reach its peak until about 7 minutes later at 21:40:29. The peak gust recorded at Echo is about 11 m/sec during this period. Golf peak gust occurs about 16 minutes later than the Delta's first peak. This sequential timing corresponds well with the straight-line distance of 10.8 km between the Delta and Golf interconnection points. The noncoincidental peak during this 20-minute period (the sum of the four individual peaks in the period) is 69.25 MW, if the same gust would have hit all turbines at the same instant. However, the turbines are scattered, and it takes time for the gust to sweep through them. When power from the last group of turbines (Golf interconnection point) begins to rise, power from the first group of turbines (Delta interconnection point) has already begun to drop. As a result, the coincidental peak during this 20-minute period is only 55.74 MW. The coincident factor for this 20-minute period is 0.805.
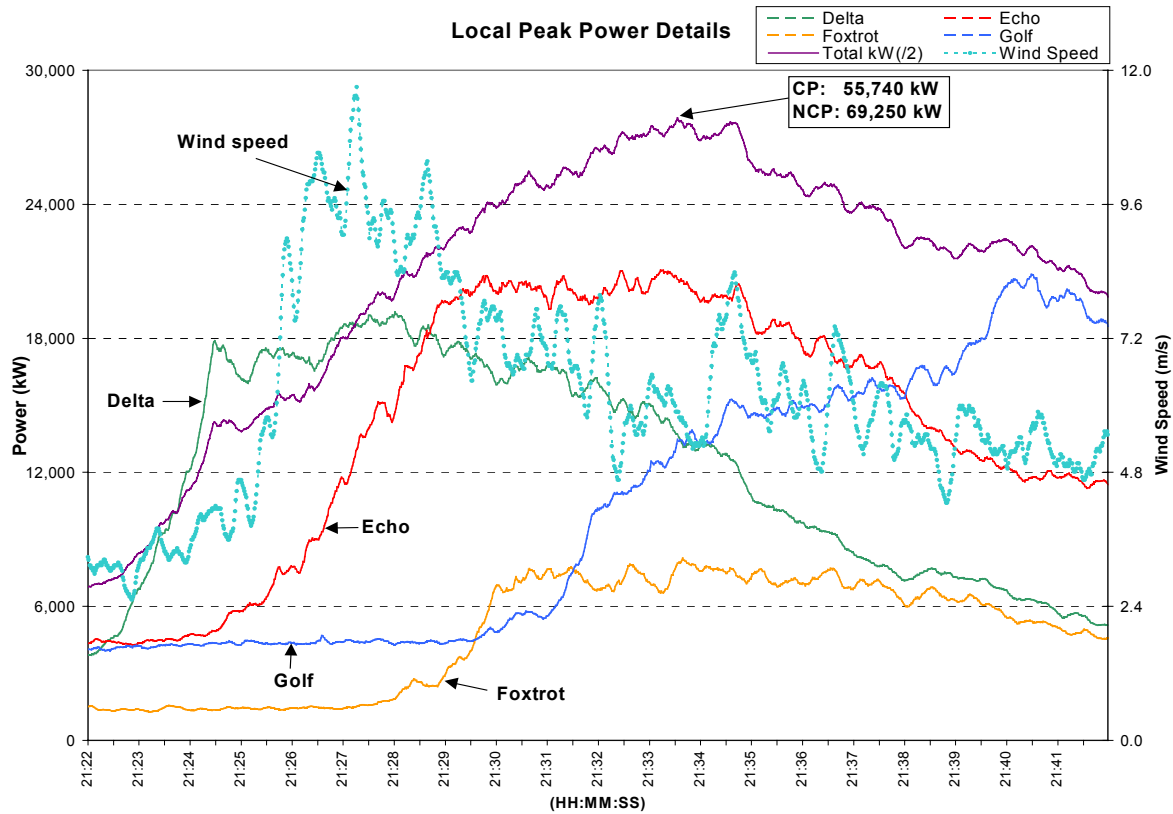
Figure 4-7. Detailed local peak with 1-second data

The coincident factors listed in Table 4-1 are all very high and show only small variations from month to month. The reason for these high coincident factor values in Table 1 is that only one value is taken from each monthly grid-interconnection point to calculate the coincident factors. The example above demonstrates that the coincident factor can have low values. To show their variability, coincident factors are calculated with continuous 1-second data streams from four grid-interconnection points using three window sizes: 60 seconds (60 data points), 10 minutes (600 data points), and 30 minutes (1,800 data points). Table 4-9 shows the monthly averages, standard deviations, and minimum values of coincident factors. The maximum coincident factor values, which equal to 1.0 for all cases, are not included in Table 4-9.

Table 4-9. Coincident Factors

	60-second			10-minute			30-minute		
	Avg	*Stdev*	*Minimum*	*Avg*	*Stdev*	*Minimum*	*Avg*	*Stdev*	*Minimum*
February	0.977	0.049	0.356	0.944	0.089	0.316	0.931	0.097	0.343
March	0.968	0.067	0.330	0.921	0.116	0.315	0.902	0.131	0.309
April	0.974	0.052	0.315	0.932	0.098	0.300	0.916	0.110	0.306
May	0.972	0.055	0.352	0.930	0.100	0.326	0.913	0.113	0.325
June	0.967	0.062	0.340	0.920	0.103	0.310	0.906	0.109	0.329
July	0.958	0.070	0.323	0.902	0.118	0.284	0.885	0.127	0.308
August	0.963	0.067	0.326	0.913	0.114	0.290	0.896	0.122	0.307
September	0.971	0.058	0.352	0.932	0.098	0.301	0.915	0.110	0.307
October	0.967	0.062	0.318	0.923	0.105	0.337	0.906	0.114	0.328
November	0.976	0.050	0.370	0.945	0.085	0.305	0.933	0.094	0.327
December	0.978	0.045	0.354	0.948	0.082	0.326	0.936	0.091	0.335
January (01)	0.979	0.045	0.411	0.951	0.084	0.303	0.938	0.096	0.326

The results show that a wider window size tends to increase the range of coincident factors, as indicated by higher standard deviation values and lower minimum values. For a 30-minute window, the average coincident factors range from 0.89 to 0.94. The range of standard deviation values is from 0.10 to 0.13, suggesting that spatial diversity at the Lake Benton II site is probably responsible for an approximately10% reduction in peak wind power seen by the utility grid.

Table 4-10 shows the coincident factors calculated with Storm Lake output and Lake Benton II output. Average coincident factors of the combined output power from both Lake Benton II and Storm Lake have a much narrower range compared to the average coincident factors of four grid-interconnection points at Lake Benton. This suggests that if the outputs of these two wind power plants are combined, less peak power reduction will be realized. This result can be attributed to the following:

1. Table 4-9 is calculated with four data streams but Table 4-10 is calculated with only two data streams.
2. The Lake Benton II and Storm Lake power outputs are not totally independent. As discussed in the next section, a closer look at these two power streams will reveal a more complicated co-relationship between Lake Benton II and Storm Lake.

Table 4-10. Coincident Factors of Lake Benton II and Storm Lake

Month	60-second			10-minute			30-minute		
	Avg	*Stdev*	*Minimum*	*Avg*	*Stdev*	*Minimum*	*Avg*	*Stdev*	*Minimum*
January (01)	0.996	0.007	0.853	0.987	0.019	0.785	0.977	0.032	0.716

Output Correlation between Grid-Interconnection Points

The degree of spatial diversity can be examined with the aid of linear correlation coefficients between outputs measured at grid-interconnection points. Wind turbines in close proximity should have output patterns similar to each other, and wind turbines that are spaced farther apart should have more differences in their output patterns. Table 4-11 shows monthly correlation coefficients between grid interconnection points. Calculated linear correlation coefficients show the predicted relationship among power outputs from the four interconnection points. Interconnection points that are adjacent to each other have higher correlation coefficients than those points that are not. In addition, correlation coefficients calculated with longer timeframe data have higher values than those calculated with shorter timeframe data, because the averaging process smoothes out short-duration (high-frequency) variations. The results also suggest that the spacing between individual turbines and the distances between grid-interconnection points are not large enough to cause a more prominent spatial diversity.

Table 4-11. Output Power Correlation Coefficients Among Interconnection Points

	1-hour data			10-minute data			1-minute data		
	Echo	*Foxtrot*	*Golf*	*Echo*	*Foxtrot*	*Golf*	*Echo*	*Foxtrot*	*Golf*
February									
Delta	0.991	0.980	0.974	0.986	0.970	0.963	0.983	0.965	0.959
Echo		0.986	0.988		0.981	0.980		0.978	0.977
Foxtrot			0.983			0.977			0.973
March									
Delta	0.983	0.910	0.964	0.978	0.894	0.946	0.973	0.885	0.942
Echo		0.924	0.978		0.913	0.965		0.905	0.961
Foxtrot			0.933			0.925			0.917
April									
Delta	0.985	0.948	0.918	0.977	0.932	0.901	0.971	0.921	0.893
Echo		0.959	0.930		0.949	0.917		0.942	0.912
Foxtrot			0.959			0.950			0.942
May									
Delta	0.916	0.782	0.796	0.921	0.769	0.787	0.919	0.702	0.796
Echo		0.805	0.838		0.795	0.822		0.751	0.828
Foxtrot			0.812			0.797			0.728
June									
Delta	0.974	0.941	0.895	0.963	0.918	0.875	0.956	0.908	0.868
Echo		0.951	0.909		0.938	0.894		0.930	0.888
Foxtrot			0.897			0.883			0.875

Table 4-11. (continued) Output Power Correlation Coefficients Among Interconnection Points

	1-hour data			10-minute data			1-minute data		
	Echo	*Foxtrot*	*Golf*	*Echo*	*Foxtrot*	*Golf*	*Echo*	*Foxtrot*	*Golf*
July									
Delta	0.976	0.964	0.978	0.969	0.952	0.966	0.964	0.944	0.960
Echo		0.967	0.976		0.962	0.968		0.957	0.964
Foxtrot			0.977			0.971			0.965
August									
Delta	0.985	0.961	0.946	0.975	0.944	0.926	0.970	0.936	0.920
Echo		0.981	0.970		0.974	0.957		0.969	0.952
Foxtrot			0.978			0.968			0.963
September									
Delta	0.988	0.963	0.964	0.982	0.950	0.950	0.977	0.942	0.944
Echo		0.972	0.976		0.962	0.964		0.956	0.959
Foxtrot			0.984			0.978			0.973
October									
Delta	0.889	0.876	0.886	0.884	0.867	0.874	0.881	0.862	0.871
Echo		0.978	0.983		0.971	0.973		0.967	0.970
Foxtrot			0.985			0.978			0.974
November									
Delta	0.987	0.884	0.869	0.983	0.877	0.860	0.980	0.874	0.857
Echo		0.912	0.898		0.908	0.890		0.905	0.887
Foxtrot			0.959			0.950			0.947
December									
Delta	0.987	0.977	0.976	0.983	0.969	0.966	0.981	0.966	0.964
Echo		0.979	0.979		0.974	0.972		0.971	0.970
Foxtrot			0.985			0.980			0.978

Table 4-11. (continued) Output Power Correlation Coefficients Among Interconnection Points

	1-hour data			10-minute data			1-minute data		
	Echo	*Foxtrot*	*Golf*	*Echo*	*Foxtrot*	*Golf*	*Echo*	*Foxtrot*	*Golf*
January (01)									
Delta	0.989	0.984	0.983	0.986	0.978	0.976	0.984	0.976	0.974
Echo		0.986	0.988		0.982	0.982		0.980	0.980
Foxtrot			0.989			0.985			0.983

Correlation between Two Wind Power Plants

The distance between the Storm Lake and Lake Benton II wind power plants is about 200 km. Correlation coefficients between these two data streams are calculated to gauge the relationship between the power outputs of these two wind power plants. Table 4-12 lists the correlation coefficients between Lake Benton II and Storm Lake power output based on 1-second, 1-minute, and 1-hour average power and the ranges of daily correlation coefficients for the month of January 2001.

Table 4-12. Correlation Coefficient Between Lake Benton II and Storm Lake

	1-second data	1-minute data	Hourly data
January (01)	0.1928	0.1928	0.1967
Daily Range	(-0.781~0.876)	(-0.781~0.876)	(-0.817~0.897)

Daily correlation coefficients for these two sites during the month vary from 0.897 (strong positive correlation, i.e., they often are synchronized) to –0.817 (strong negative correlation, i.e., they move in opposite directions). The correlation coefficient for the entire month suggests only a weak co-relationship between power outputs from these two sites.

Figure 4-8 is a plot of the profiles of 10-minute average power output for Lake Benton II and Storm Lake for the first 7 days of year 2001 (from January 1 to January 7, 2001). The correlation coefficient during this period is 0.198. The low correlation coefficient indicates that these two output streams are not related, but the plot shows that these two output streams are not as random as the simple correlation coefficient calculations have suggested. For example, a closer look at the figure reveals that the output pattern from Storm Lake is actually similar to that of Lake Benton II with a time delay. One of the prominent features in the figure is a plateau in the middle, representing a period of high output at Lake Benton II from 9:00 p.m. on January 3 to 3:00 p.m. on January 5. An almost identical plateau (of lower height because of less generating capacity) from Storm Lake shows up about 9 hours later (beginning 6:00 a.m. on January 4). A calculated correlation coefficient of 0.885 for these two plateaus during this 42-hour period confirms the observation, suggesting that the same weather event that drives the wind regimes of both sites arrives at Storm Lake about 9 hours later. There is also an output power rise at Storm Lake (from 11:40 p.m. on January 1 to 11:30 p.m. on January 2) that corresponds to the first prominent plateau from Lake Benton II

shown in Figure 4-8 (from 6:40 a.m. on January 1 to 6:30 a.m. on January 2). A calculated correlation coefficient of 0.891 during this 24-hour period confirms that these patterns match. However, it has a time delay of 17 hours, longer than the 9-hour delay observed from the second plateau in the figure. Obviously, wind speed and direction probably account for the difference in time delay.

Similar behaviors can be observed at many other times (Figure 4-9). The 10-minute average power profiles of Lake Benton II and Storm Lake for another 7-day period (from January 8, 2001 to January 14, 2001) illustrates this. Output profiles from these two wind power plants have very similar shape during this period. The power output of Storm Lake has a shape that is very similar to that of Lake Benton II with a time delay of about 12 hours for the first prominent feature[3] in the figure and no time delay for the second prominent feature. Calculation of correlation coefficients again confirms the observation. During the 4-day period from January 8 to January 11, the correlation coefficient is only 0.265, whereas the correlation coefficient of the Lake Benton II plateau and the time-delayed plateau from Storm Lake is 0.762.
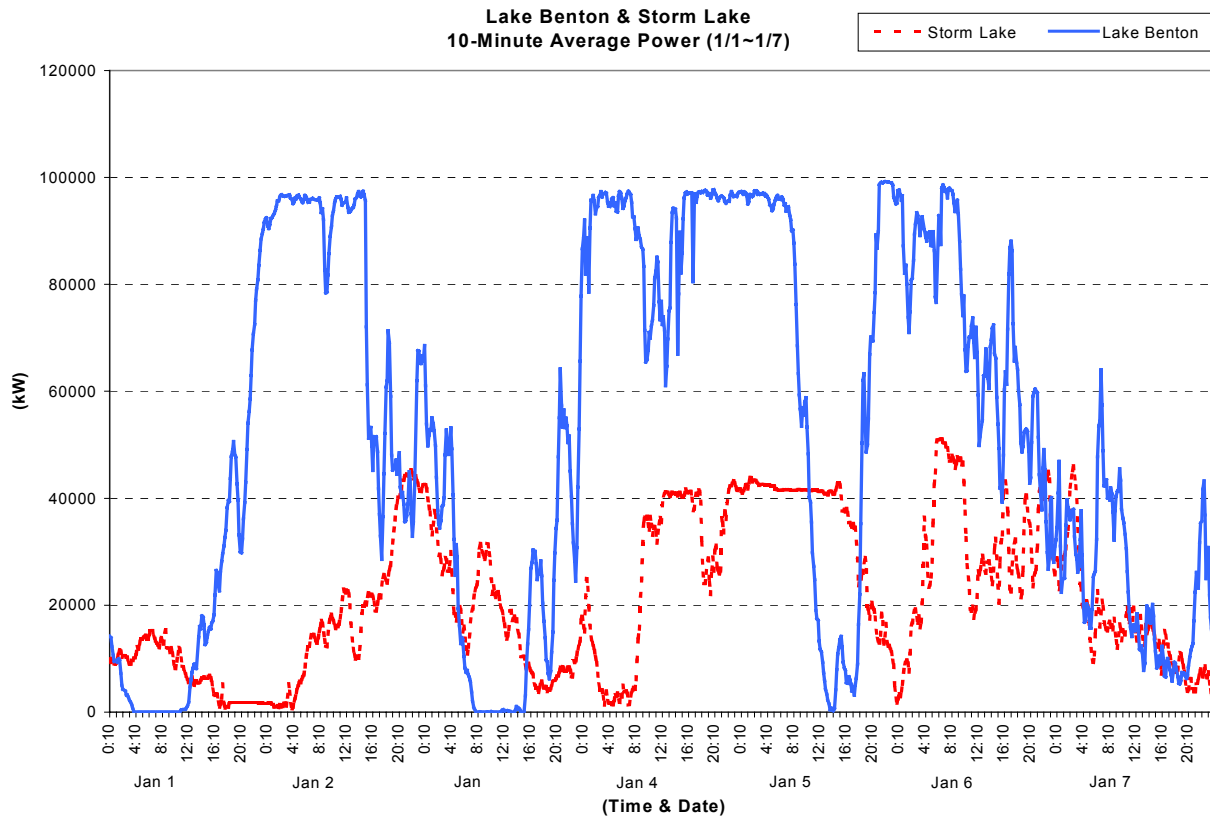

Figure 4-8. Output profiles of Lake Benton II and Storm Lake

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[3] For Lake Benton II it is a plateau beginning at 9:00 on January 8 and ending at 6:50 on January 11. for Storm Lake it is a plateau beginning at about 21:00on January 8 and ending at 18:50 on January 11.
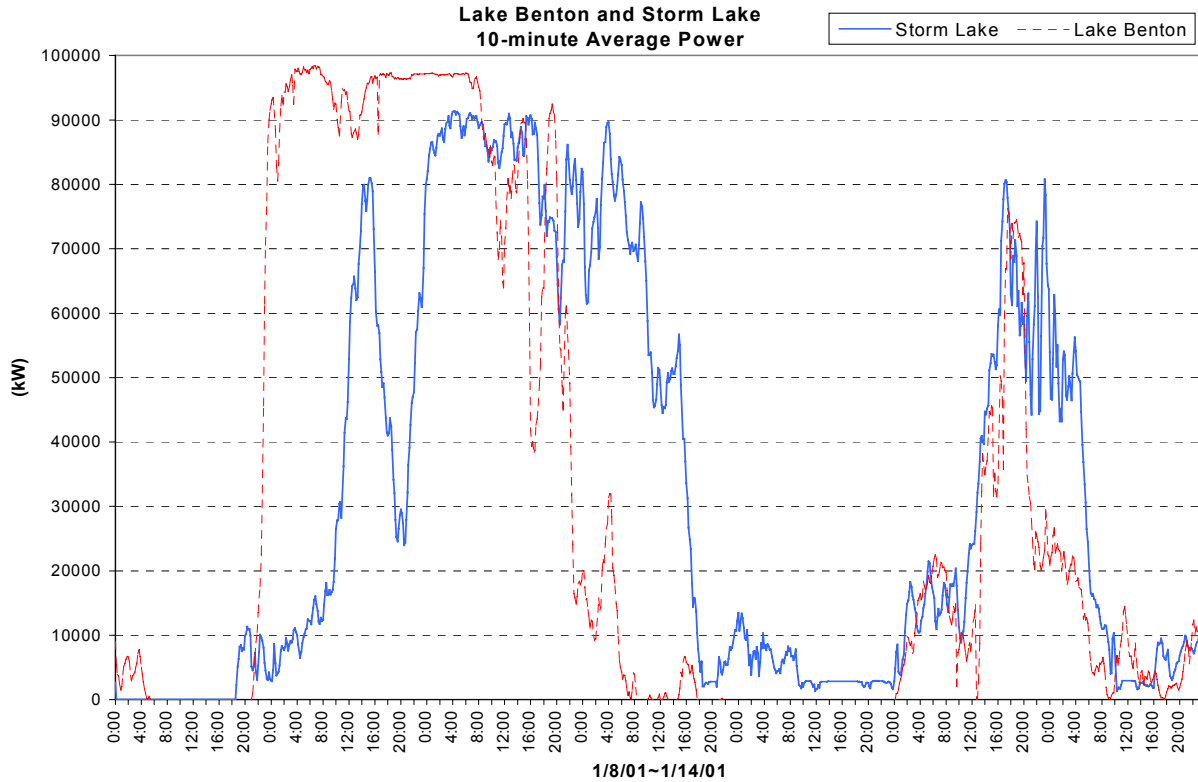
Figure 4-9. Another output profile of Lake Benton II and Storm Lake

4.4 Wind Power Variability

Another way to examine the variability of wind speed at different sites is to look at the coefficient of variation (COV), which is the ratio of the standard deviation of wind speed to the mean wind speed. COV of wind speed is known as turbulence intensity of wind. A higher COV indicates more turbulent wind and more fluctuations of wind power. However, a wind power plant with many turbines will attenuate the resulting output power fluctuations. Obviously, this output leveling effect is more prominent with an increasing number of turbines and greater distance between the turbines.

For the wind speed measured at the Echo interconnection point, the calculated COVs range between 0.47 and 0.64. Table 4-13 lists monthly COV values calculated from 1-second, 1-minute, and 10-minute average wind speed data.

39

Table 4-13. Coefficient of Variation of Wind Speed at Echo

Month	1-Second Data	1-Minute Data	10-Minute Data
February	0.480	0.474	0.467
March	0.639	0.632	0.623
April	0.596	0.589	0.579
May	0.535	0.526	0.513
June	0.546	0.536	0.514
July	0.677	0.661	0.643
August	0.513	0.489	0.467
September	0.645	0.625	0.608
October	0.518	0.510	0.496
November	0.453	0.451	0.444
December	0.525	0.524	0.518
January (01)	0.728	0.727	0.724
12-month	0.623	0.616	0.607

Available power in the wind is proportional to the cube of wind speed. If the COV is calculated with wind speed cubed and the results are compared to the calculated COV of measured power from the wind plant, a pattern of much reduced variability emerges. Table 4-14 shows the COV values of wind speed cubed and power output at the Echo interconnection point, as well as the entire wind power plant. The reduction in variability is very clear. On average, variability of power output is only about half the variability of wind speed cubed.

Table 4-14. COV of Wind Speed Cubed, Echo Output, and Lake Benton II Output

Month	1-second Data			1-minute Average			10-minute Average		
	$(m/sec)^3$	Echo kW	LB2 kW	$(m/sec)^3$	Echo kW	LB2 kW	$(m/sec)^3$	Echo kW	LB2 kW
February	1.44	0.777	0.773	1.41	0.777	0.773	1.32	0.775	0.771
March	1.86	0.989	0.978	1.80	0.989	0.978	1.74	0.992	0.974
April	1.87	0.823	0.815	1.81	0.823	0.815	1.76	0.818	0.812
May	1.75	1.008	0.922	1.70	1.008	0.922	1.64	1.003	0.919
June	1.72	0.838	0.845	1.66	0.837	0.845	1.59	0.833	0.843
July	1.78	1.228	1.172	1.66	1.228	1.172	1.56	1.223	1.171
August	1.44	0.918	0.899	1.32	0.917	0.899	1.19	0.914	0.898
September	1.64	0.894	0.868	1.51	0.893	0.868	1.41	0.890	0.867
October	1.29	0.936	0.911	1.26	0.936	0.911	1.18	0.933	0.910
November	1.31	0.774	0.771	1.29	0.774	0.771	1.25	0.772	0.771
December	1.44	0.807	0.803	1.43	0.807	0.803	1.39	0.806	0.802
January (01)	1.64	0.756	0.750	1.64	0.790	0.784	1.61	0.788	0.783
12-month	1.91	0.912	0.896	1.87	0.911	0.897	1.82	0.908	0.894

Table 4-14 also shows a reduction in power variability between outputs from a single interconnection point Echo and the entire Lake Benton II wind power plant. This reduction in power variability is expected from large wind power plants with hundreds of wind turbines scattered over a wide area. The effect becomes more prominent when calculations are extended to the combined output of Storm Lake and Lake Benton II. Table 4-15 lists COVs of output power from four grid-interconnection points of Lake Benton II, Lake Benton II, Storm Lake, and combined Storm Lake and Lake Benton II output. Numbers in Table 4-15 are calculated with 1-second power data. As turbine output power becomes increasingly aggregated, the variability of the overall power level drops further. In the case of combined Storm Lake and Lake Benton II output, the result is a 20% reduction in power level variability.

Table 4-15. Individual Grind-Interconnection Points and Wind Power Plant Output COVs

Month	Delta	Echo	Foxtrot	Golf	Lake Benton II	Storm Lake	Combined
February	0.800	0.777	0.824	0.766	0.773		
March	1.015	0.989	1.028	0.988	0.978		
April	0.835	0.823	0.876	0.842	0.815		
May	1.009	1.008	1.159	0.935	0.922		
June	0.852	0.838	0.867	0.927	0.845		
July	1.220	1.228	1.214	1.141	1.172		
August	0.933	0.918	0.905	0.909	0.899		
September	0.874	0.894	0.877	0.878	0.868		
October	0.979	0.936	0.917	0.919	0.911		
November	0.773	0.774	0.826	0.826	0.771		
December	0.823	0.807	0.807	0.809	0.803		
January (01)	0.753	0.756	0.757	0.756	0.750	0.829	0.638
12-month	0.921	0.909	0.937	0.909	0.893		
February (01)	0.733	0.743	0.740	0.740	0.728	0.834	0.576

5. Summary and Conclusions

This is the first project in this country to monitor large wind power plant outputs by systematically collecting long-term, high-frequency data from large commercial wind power plants. Utilities, wind power plant developers, and operators need to understand the fluctuations in wind power and how they affect the electrical power system, as well as to analyze ancillary service requirements with real wind power plant output data. This project is designed to satisfy the need.

Over the past 13 months, more than 150 million data points have been collected and cataloged from two Midwest operating commercial wind power plants. Analysis of these data has provided useful insight on the behavior of wind power. This data set has been made available for Oak Ridge National Laboratory to investigate the ancillary service issues. It will also be available for others to study the operational impact issues of wind power plant on the utility power systems.

The first thing to notice from the collected data is that the actual magnitude of power fluctuations does not appear to be extraordinary. Changes of wind speed rarely cause extreme power-level changes of a large wind power plant. The variations in wind power plant output as a result of natural wind speed variations are well within the capability of an interconnected power system. When step changes are used to gauge the wind power fluctuations, changes appear small in value and are within a very narrow range. On a second-by-second basis, the maximum step changes are 4.4 MW up and 7.6 MW down; however, the standard deviation value (σ) of all 1-second step changes is only 168 kW, with an average value of zero. Ninety-eight percent of all 1-second step change values are within ±500 kW (±3 σ), or less than 0.5% of total wind power plant generating capacity. The corresponding 1-minute standard deviation value is 1,103 kW (1% of the total generating capacity), with 94.5% of the 1-minute step change values within ±1,500 kW (±1.4 σ or 1.4% of total capacity).

The persistency of wind power from large plants is also evident in the state transition analysis of the output data. On a minute-by-minute basis, given the knowledge of current power output at any level (e.g., at 40% of the total capacity) operators can expect that at least 92% of the time, the output power will remain at the same level in the next minute. For shorter time steps, the probability of output power remains at the same level and is even higher at 94%.

In addition to the limited range of power changes, the data show that the rates of power changes are also limited. For Lake Benton II, with 138 turbines and 103.5 MW of total capacity, the maximum ramping-up rate during a 10-second period is 2.8 MW per second and the maximum ramping down rate is –2.5 MW per second. The corresponding average ramping rates are only 28 kW/s and –31 kW/s. In a 10-minute window, the maximum ramping-up rate is 6.9 MW per minute (115 kW/s) and the maximum ramping-down rate is 6.6 MW per minute (110 kW/s). Both are much smaller than the 10-second ramping rates. Furthermore, the distribution of ramp rates over the 12-month period shows that 99% of the apparent power-changing rates are within ±220 kW/s.

Actual wind power output data clearly show that spatial diversity plays a major role in reducing the variations of wind power plant output and peak power resulting from a wind gust. As expected, more wind turbines will tend to "smooth" the power output by reducing the variability of wind power.

The data also indicate the predictability of wind power plant output. Correlation analysis of power outputs from Lake Benton II and Storm Lake wind power plants shows that output from one plant can be a very good indication of output from the other plant. This suggests that, with adequate information about wind speed and direction (and other meteorological data) from strategically located places, one can predict output from a wind power plant with a reasonable degree of accuracy.

These results also clearly indicate that while wind power plants will be subject to forced outages similar to those of any other power-generating plants, changes in power output resulting from changing winds are neither severe nor unpredictable.

With more analysis, we can further quantify the relationships between the outputs of several wind power plants, as well as determine whether sophisticated regression analyses can help wind power plant and utility system operators to better predict power output levels. Analysts will also attempt to correlate feed voltage at the grid-interconnection points. Furthermore, using real and reactive power data, they will seek to verify the advantages of reactive power control of wind turbines.

This is an ongoing project and should continue for another 2 years. Electrotek Concepts has begun collecting data at the Storm Lake plant and the Buffalo substation, an effort that should produce even more statistically significant conclusions.

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13. ABSTRACT *(Maximum 200 words)*

The intermittent nature of the wind resource, together with short-term power fluctuations, are the two principal issues facing a utility with wind power plants in its power grid. To mitigate these issues, utilities, wind power plant developers, and operators need to understand the nature of wind power fluctuations and how they affect the electrical power system, as well as to analyze ancillary service requirements with real wind power plant output data. To provide the necessary data, NREL conducted a study to collect at least 2 years of long-term, high-frequency (1-hertz [Hz]) data from several medium- to large-scale wind power plants with different wind resources, terrain features, and turbine types. Researchers then analyzed the data for power fluctuations, frequency distribution of wind power (by deriving a probability distribution function of wind power plant output variations), spatial and temporal diversity of wind power, and wind power capacity credit issues. Results of these analyses can provide data on the potential effects of wind power plants on power system regulation.

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