April 2002 • NREL/SR-500-31188

Subcontractor Report

DOE/NREL Wind Farm Monitoring

Annual Report
July 2000—July 2001

J.W. Smith
Electrotek Concepts, Inc.
Knoxville, Tennessee

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Contract No. DE-AC36-99-GO10337

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NREL Technical Monitor: Yih-huei Wan

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Executive Summary

1.1 Background

The Wind Program and the wind power industry does not currently have the ability to accurately assess ancillary services burdens (or benefits) of wind-powered electricity. Second-to-second and minute-to-minute power fluctuations of wind turbines and wind farms have not been recorded in any widespread, systematic way. Time-stamped and synchronized power output of individual machines from different-sized wind farms with varying geography and wind resource types will allow industry to evaluate the potential ancillary service impacts and costs as a result of the power fluctuations. With this evaluation, the Wind Program and the industry can determine if the impacts warrant starting efforts to examine possible mitigation strategies, for example, different control strategies or other turbine design changes, business partnering with other electric resources, or installing short-term electric storage.

The data have other uses as well. They will allow better understanding of local micro sitting effects. We will also be able to investigate the correlation statistics between machines, allowing a field test of the concept that the aggregate power variation from a larger number of machines has smaller fluctuations than fluctuations from a smaller cluster or single machine (on a percentage basis). If utility load and incremental cost are available, the power outputs can be evaluated for capacity value. The power measurements could also be part of a wind forecasting development and testing program.

It is possible to simulate power fluctuations from wind speed measurements for a single turbine, but not for multiple turbines across different landforms. The accuracy of wind farm power simulation is limited by several factors. The geographic variation of wind speed across a given landform is not predictable with the required accuracy from dispersed anemometer measurements. The wind conditions and the turbine output in a wind farm may vary abruptly in space and time caused by the highly organized coherent perturbations in the boundary-layer flow and rapidly varying transition zones between the perturbations moving through a wind farm. It is difficult to model the changes in the wind field. While some wind turbulence measurements have been undertaken with the purpose of examining material fatigue, wind speed fluctuation measurements across wind farms of different landforms are not readily available. We do not have good knowledge on wind speed point-to-point correlation and how they change over time in a wind farm.

Therefore, the best solution is to implement a power measurements program based on actual wind farm installations. The purpose is to develop short-term (1-second) power output data sets from several wind farm locations. The desire is to be able to examine results from different sized wind farms with varying geography and wind resource types. Together with time synchronized utility system load, generation, and incremental cost information, NREL will analyze the wind farms for potential ancillary service impacts and costs and other issues associated with the fluctuations of wind power. To accomplish the results described above, it is necessary to perform detailed data analysis on Wind Farm facilities operating data. These analyses will include:

- Wind power fluctuations. Monitoring wind farm output variations under different conditions (daily, hourly, minute-by-minute, second-by-second changes) and its statistical properties (maximum values, mean values, standard deviations, etc.).

- Spatial and temporal correlation of wind farm output. Comparing output from individual turbines and the entire wind farm to investigate the spatial and temporal diversity. Derive an analytical function to describe the correlation quantitatively.

- Frequency distribution of wind farm output variations. Derive a probability distribution function of wind farm output variations from long-term output data.

- Coincidence with system peak and utility incremental cost. Examining system parameters and the time relation with wind farm output will allow us to determine the ancillary service cost or benefit to the utility system. In addition, this could be used to evaluate capacity credit.

Results of these analyses can provide quantitative information regarding potential impact of wind power plants on the power system regulation. Such information will enable utilities to better understand the regulation requirement of wind power plants, and assist utilities in planning and operating the electric grid to integrate the wind power into the power system.

A wind farm monitoring project was thus established to provide the necessary data to perform such analysis. A listing of the data collected is shown in Table 1.

Table 1. Table of Parameters Collected at Each Site

Wind Farm Variable	Units	Resolution	Comments
Electrical Data			
Real Power	Watts	1 second	
Reactive Power	Vars	1 second	
Collection Feeder Voltage	Volts	1 second	Three-phase RMS (V_{LN}) at the interconnection point with the utility system
Meteorological Data			
Wind Speed	Meters/sec	30 seconds	Recorded at hub height (± 1%) with cup-type anemometers. Exempt from 5 Hz cut-off frequency requirement
Wind Direction	Degrees (from true north)	30 seconds	Recorded at hub height (± 1%) with cup-type anemometers. Exempt from 5 Hz cut-off frequency requirement
Ambient Temperature	Degrees (Celsius)	10 minutes	
Local Air Pressure	Kilopascals	10 minutes	

1.2 Monitored Sites

Two sites have been chosen for participation in the wind farm monitoring project, the Storm Lake wind farm near Alta, Iowa, and the Lake Benton wind farm near Lake Benton, Minnesota.

The Buffalo Ridge site is located in southwestern Minnesota, northwest of the town of Lake Benton, along a topographic feature known as Buffalo Ridge. This is the premier wind resource area in the state of Minnesota. The wind resource arises from storm-driven winds that occur as a result of the passage of low-pressure systems throughout the year. The resource is better in winter and early spring as the low-pressure centers are more intense and numerous during that time of the year. There are several wind plants in this region, with most of this energy being collected at Xcel Energy's Buffalo Ridge Substation. Total wind generation capacity (nameplate rating) connected to the substation is 230 MW, with additional 50 MW connected to nearby substation. The substation connects to the 115 kV bulk transmission system. Monitoring at this collection point will thus provide an aggregate of multiple smaller wind farms and would be indicative of the characteristics of a single, large, geographically or topographically diverse wind plant.

Figure 1. Location of monitoring sites

The Storm Lake wind farm is located in northwestern Iowa, in Buena Vista and Cherokee counties near the community of Alta. The total project consists of 257 Zond Z-750 wind turbines producing 193 MW of power. The project is actually divided into two separate wind farms, Storm Lake I, which produces 113 MW, and Storm Lake II, which produces 80 MW of generation. MidAmerican Energy Company (MEC) provides the bulk system interconnection point for the Storm Lake I plant, while Storm Lake II interfaces to the Alliant Energy transmission system. The Storm Lake I plant interfaces to bulk transmission system at 161 kV (Buena Vista Substation), while the Storm Lake II facility connects at 69 kV. The wind resource in this region (Storm Lake) is very similar to that of Minnesota, with storm-driven winds responsible for much of the wind energy resource.

A wind rose, that is, a graphical presentation of the joint frequency of wind speed and wind direction for the Minnesota and Iowa wind plant sites is presented in Figure 2. Each bar represents one of the 16 points of the compass, and the gradations along each bar represent the percent of time the wind speed falls into each category. The persistence of the wind direction implies that wake and array effects will change only as a function of the wind speed.

The variability of wind directions implies a great variety in the wake and array effects and resulting different electrical outputs among the various wind turbines.

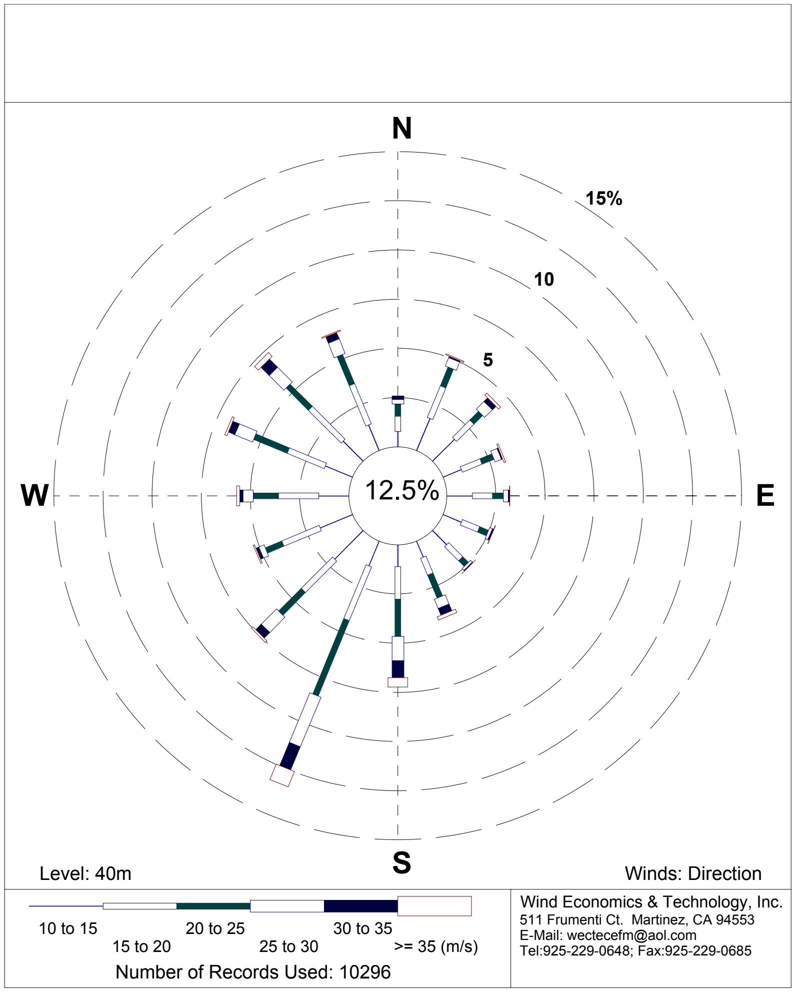


Figure 2. Minnesota/Iowa wind resource

2 Monitoring System Design

There are two components to the monitoring system – the power monitoring portion and the meteorological monitoring portion. Both components utilize the Dranetz/BMI Signature System to collect, store, and validate the data locally, permit Web-based setup and visualization, and act as a communications gateway to the central data collection point. Because the monitoring system chosen is designed for remote access, it has the benefit of providing real-time access (via a web browser), automatic downloading of data, and local storage.

2.1 Electrical

The system utilizes a Dranetz/BMI DataNode to measure the required power parameters specified in Table 1. Because the DataNode was originally designed as an event monitor, customized firmware had to be developed and incorporated into the Signature System's infrastructure to behave like a logger and collect large amounts of data. Due to the flexibility of the Signature System, this modification was made possible. After a few iterations of firmware upgrades, the system was fully functional. Although customization was required to get the necessary power data, the Signature System provided added value in that it also allows us to gather the necessary meteorological data with the same device (see the next section for more information).

The DataNode is set up to internally store the required parameters at a 1-second rate. Every 10 minutes, the last 10-minute batch of 1-second measurements is transferred to the InfoNode for validation and local storage. Retrieval at the central data collection point was to be done by using the Electrotek NodeCenter software. The NodeCenter software was originally proposed to retrieve the data from the InfoNodes at user-defined intervals (e.g., once to several times per day). However, due to the extremely large amount of data being collected, additional software needed to be developed to remotely extract the data from the InfoNode. The DataNode has enough internal storage to permit it to record without being contacted by the InfoNode for up to 30 minutes and not lose any data. Similarly, the InfoNode has enough storage to retain the data transferred from the DataNode indefinitely (the InfoNode has a 2 GB hard drive) if contact is lost with the remote downloading software.

2.2 Meteorological

The use of existing meteorological data acquisition systems was originally proposed to collect the required meteorological data. However, it was later realized that the resolution at which the wind farm operators were storing the data was unacceptable (one sample every 10 minutes). Therefore, a separate meteorological station had to be purchased and installed. Based on recommendations from the meteorological consultant on the project (Ed McCarthy, WECTEC) and requirements of the data needing to be collected, a Met One meteorological station was chosen for the project (one for each site). Taking advantage of our knowledge of the Dranetz-BMI monitoring equipment and software, a new device handler was developed that facilitates the communications between the InfoNode and the Met One data logger. Because of the flexibility of the Signature System, the meteorological data is collected, stored, and transmitted to Knoxville via the same equipment used to collect the power data.

A sample screenshot of the web interface to the data stored in the InfoNode is shown in Figure 3. Real-time data is also available via graphical meter panels or dials.

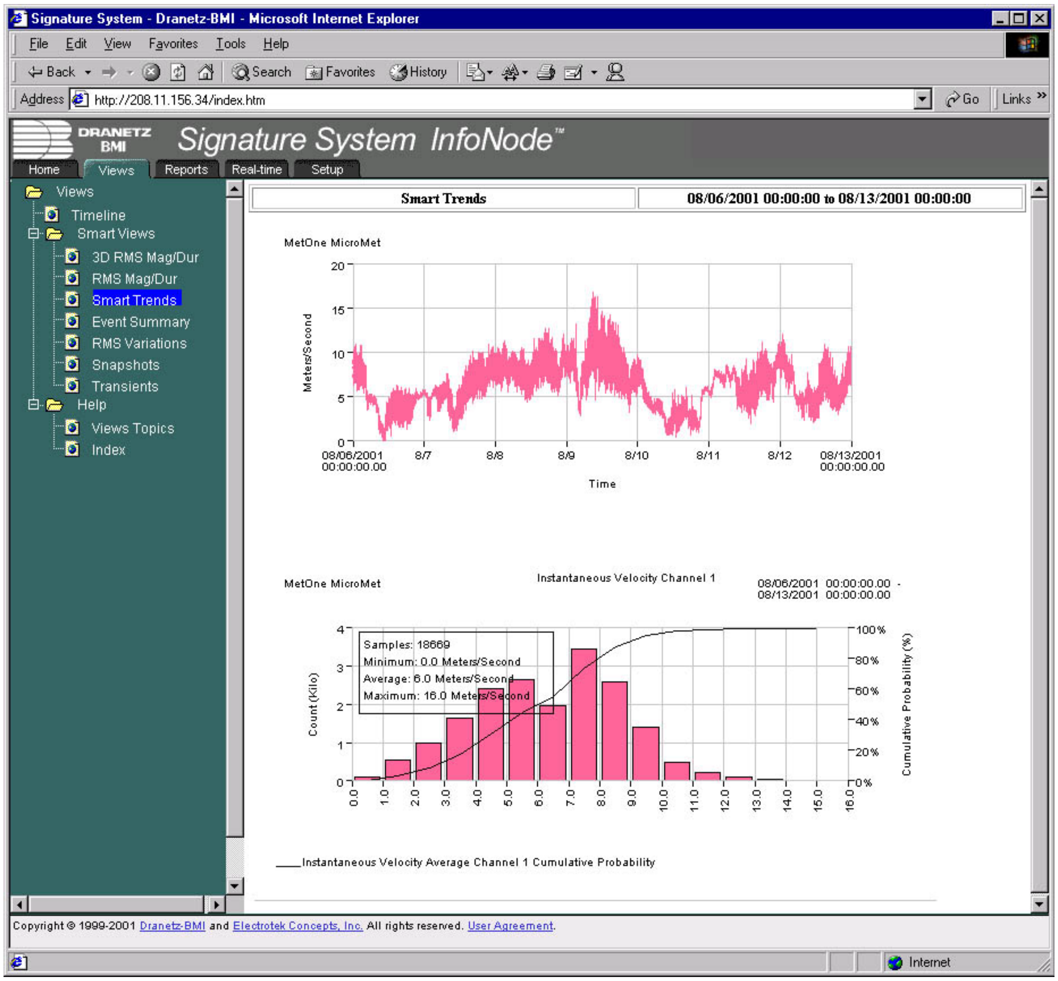


Figure 3. Screenshot of Signature System InfoNode web interface

Because the meteorological (met) station is located some distance from the InfoNode, FreeWave wireless transceivers are used to communicate the met data back to the InfoNode. The 900 MHz board level wireless RS232 spread spectrum data transceivers are capable of uncompressed data rates of 115.2 KBaud over distances of 20 miles or more. Put simply, the transceiver behaves as if it were a very long RS232 cable.

The InfoNode continuously polls the weather station to obtain the data at the necessary rate. Once the data is in the InfoNode, it is transferred to Knoxville using similar mechanisms as for the power quantities.

At each location, there will be two sets of wind direction and wind speed sensors. One set will be used as the primary source for collecting data, while the other set will be used as a backup if failure occurs (or calibration is needed). Because of the extreme cold temperatures during the winter months, the backup set consists of heated, heavy-duty sensors. These sensors will be installed before the winter of 2001.

2.3 Data Management

Each 10-minute batch of data is stored in separate raw binary files. This data is gathered from each InfoNode on a regular basis via modem access. The actual parameters stored include:

- Timestamp
- Three-phase voltage magnitude (line-to-neutral)
- Three-phase current magnitude
- Three-phase voltage angle
- Three-phase current angle
- Frequency
- Three-phase active power
- Three-phase reactive power.

Once the raw binary data files have been downloaded to the local server, an extraction utility developed for this project converts the large number of 10-minute binary files to a single ASCII text, comma-delimited file. This file is then imported into MS Access 2000™, where data checking and post-processing occurs. Once the data has been processed, it is then exported to an ASCII text, comma-delimited file, compressed using the Winzip utility, and placed on our ftp site for download by NREL personnel. The data can then be accessed at ftp.powermonitoring.com.

3 Storm Lake I Wind Farm

3.1 Wind Farm Overview

The Storm Lake wind farm is located in northwestern Iowa, in Buena Vista and Cherokee counties near the community of Alta. The total project consists of 257 Zond Z-750 wind turbines producing 193 MW of power. The project is actually divided into two separate wind farms, Storm Lake I, which produces 113 MW, and Storm Lake II, which produces 80 MW of generation. MEC provides the bulk system interconnection point for the Storm Lake I plant, while Storm Lake II interfaces to the Alliant Energy transmission system. The Storm Lake I plant interfaces to bulk transmission system at 161 kV (Buena Vista Substation), while the Storm Lake II facility connects at 69 kV. The monitoring equipment is installed at the Storm Lake I site at the Buena Vista Substation.

Storm Lake I consists of 150 Zond Z-750 wind turbines. The Z-750 (manufactured by Enron Wind) is a variable speed, constant frequency induction machine with a rated output of 750 kW. Each turbine sits atop a 63 m (208 ft) lattice tower, with each blade spanning approximately 24 m (79 ft). The actual rotor diameter is 50 m (164 ft), giving a swept area of 1,962 sq. m (21,124 sq. ft).

The 150 turbines supply energy to the two 161kV/25kV transformers via five 25kV collection feeders. A single-line diagram of the Buena Vista Substation is shown in Figure 4.

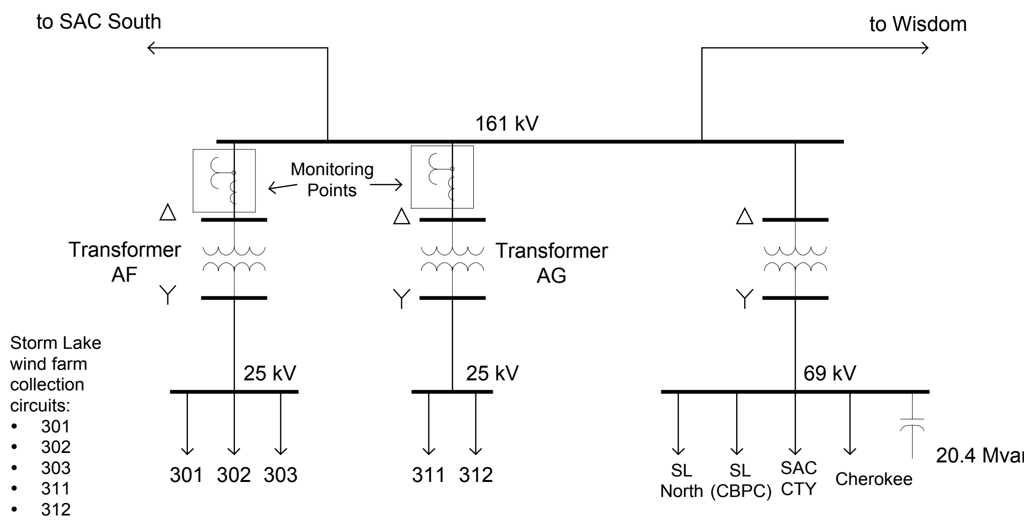


Figure 4. One-line diagram of Buena Vista Substation

3.2 Monitoring System

Both the power and meteorological data are collected at the Buena Vista Substation. The power data is gathered from the installed DataNodes, and the meteorological data is retrieved from the met station via the FreeWave radios. A simplified diagram of the monitoring equipment is shown in Figure 5.

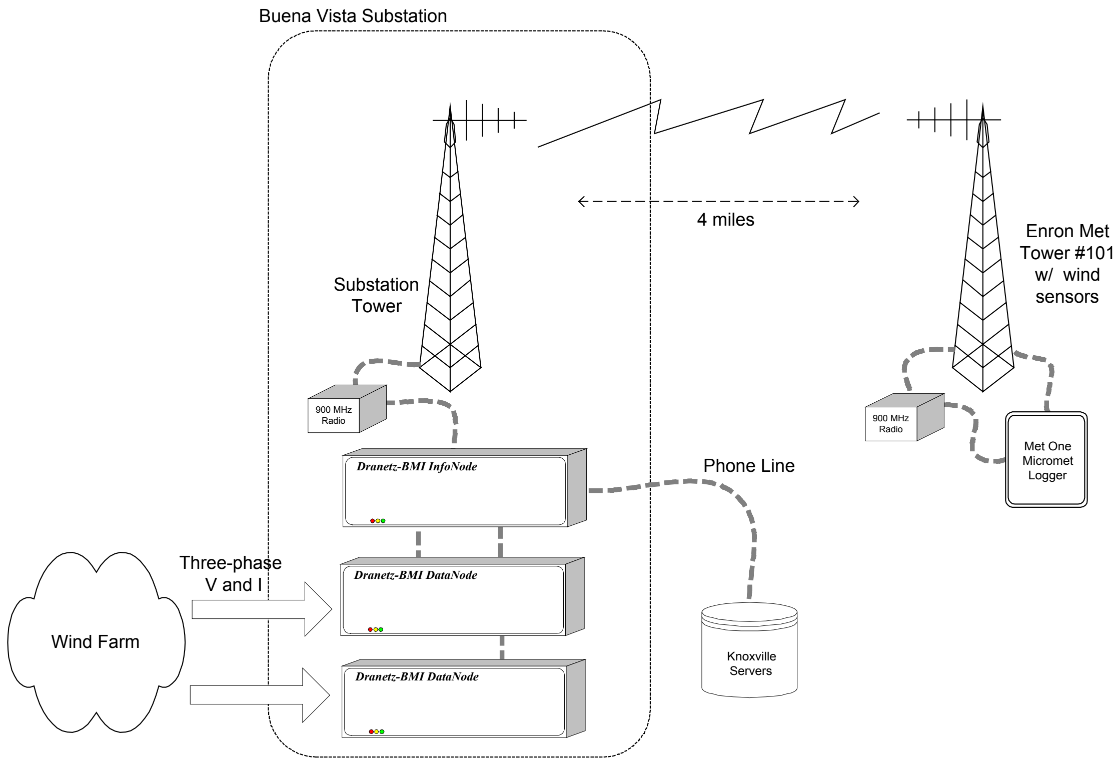


Figure 5. Diagram of Storm Lake monitoring equipment

A list of the equipment installed at the Storm Lake I wind farm includes:

- (1) Dranetz-BMI 5504 InfoNode w/ GPS antenna and receiver
- (2) Dranetz-BMI 5530 DataNode and associated voltage/current transducers
- (2) FreeWave 900 MHz transceivers
- (2) 10 dB antennas
- (1) Met One Micromet logger
- (1) Met One 020C wind direction sensor
- (1) Met One 010C wind speed sensor
- (1) Met One 023 wind direction sensor (heavy duty w/ heater)
- (1) Met One 013 wind speed sensor (heavy duty w/ heater)
- (1) Met One 064 temperature sensor
- (1) Met One 090D barometer.

3.2.1 Power Monitoring

As shown in Figure 4 and Figure 5, the entire wind plant is monitored via two points, transformers AF and AG. Three-phase voltages and currents are collected at each transformer. Two Dranetz-BMI 5530 DataNodes are used to collect the data, and a 5504 InfoNode stores the data locally until downloaded to a local server. The power monitoring equipment was installed by MidAmerican Energy in December 2000.

A picture showing the Dranetz-BMI equipment installation is shown in Figure 6 (equipment located in second cabinet from left, bottom) and Figure 7.

Figure 6. Installation of power monitoring equipment (front)

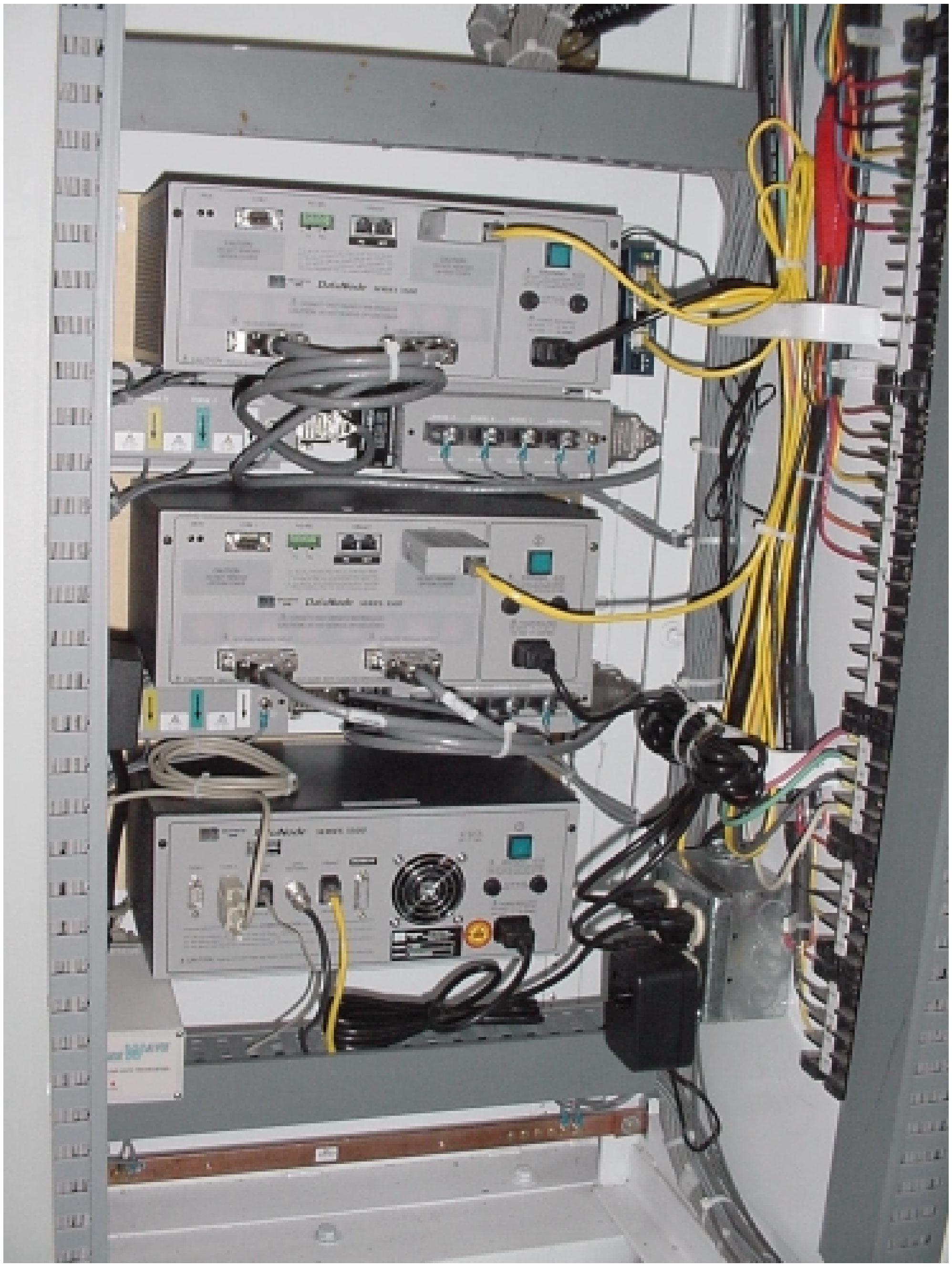


Figure 7. Installation of power monitoring equipment (back)

Five second, instantaneous data was available from MEC to validate measurements taken (see Figure 8 and Figure 9).

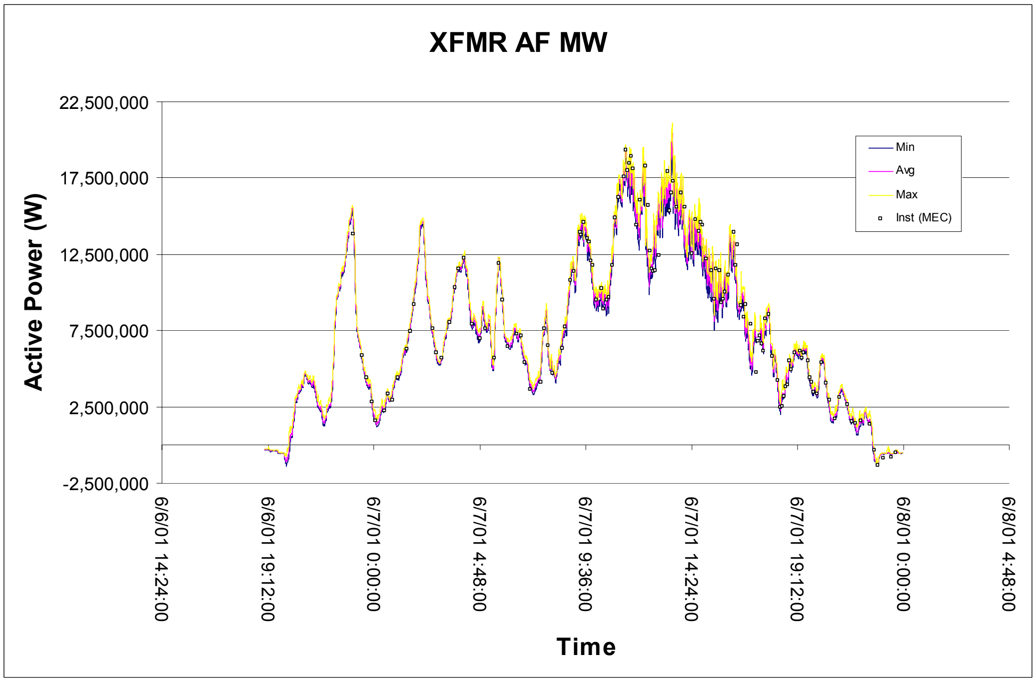


Figure 8. Comparison with MEC-collected data at Buena Vista Substation (active power)

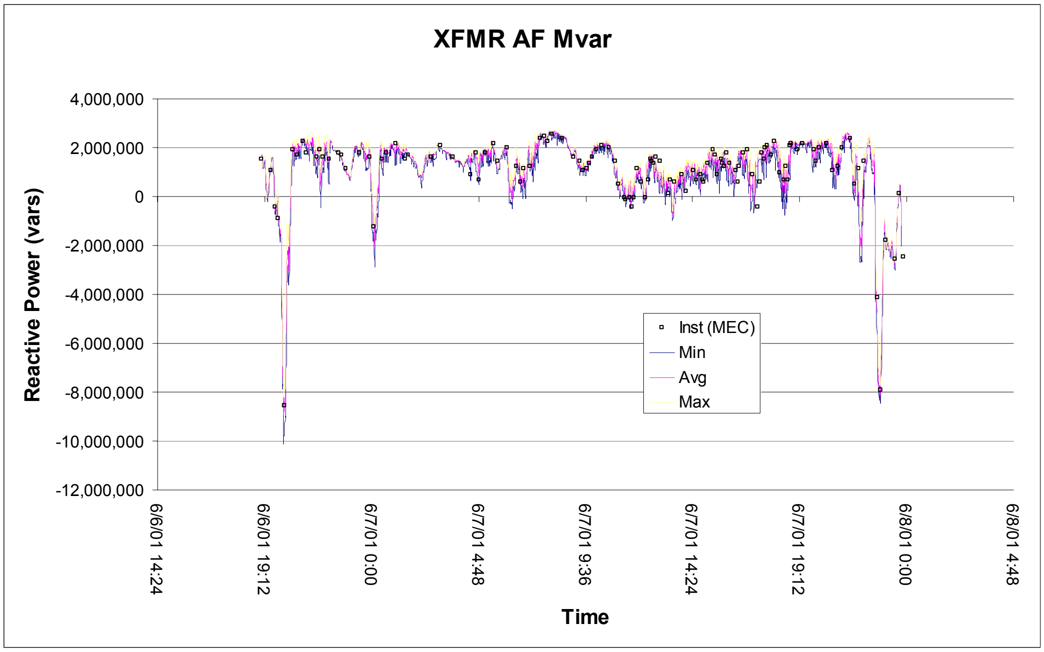


Figure 9. Comparison with MEC-collected data at Buena Vista Substation (reactive power)

3.2.2 Meteorological Monitoring

Enron Wind allowed the installation of the Met One weather station and associated transducers on one of their existing met towers. The Storm Lake I wind farm has a total of 4 met towers (two lattice towers, and two monopole towers). Because of the ease of installing the transducers on the lattice tower, Enron Wind preferred us to use one with this construction. Using the latitude/longitude coordinates for the two lattice towers and the substation, the TopoUSA program was used to check for line of sight between each tower and the substation (a line of sight is required between the met tower and the substation to use the radios on each end). A line of sight was obtainable between met tower 101 and the substation.

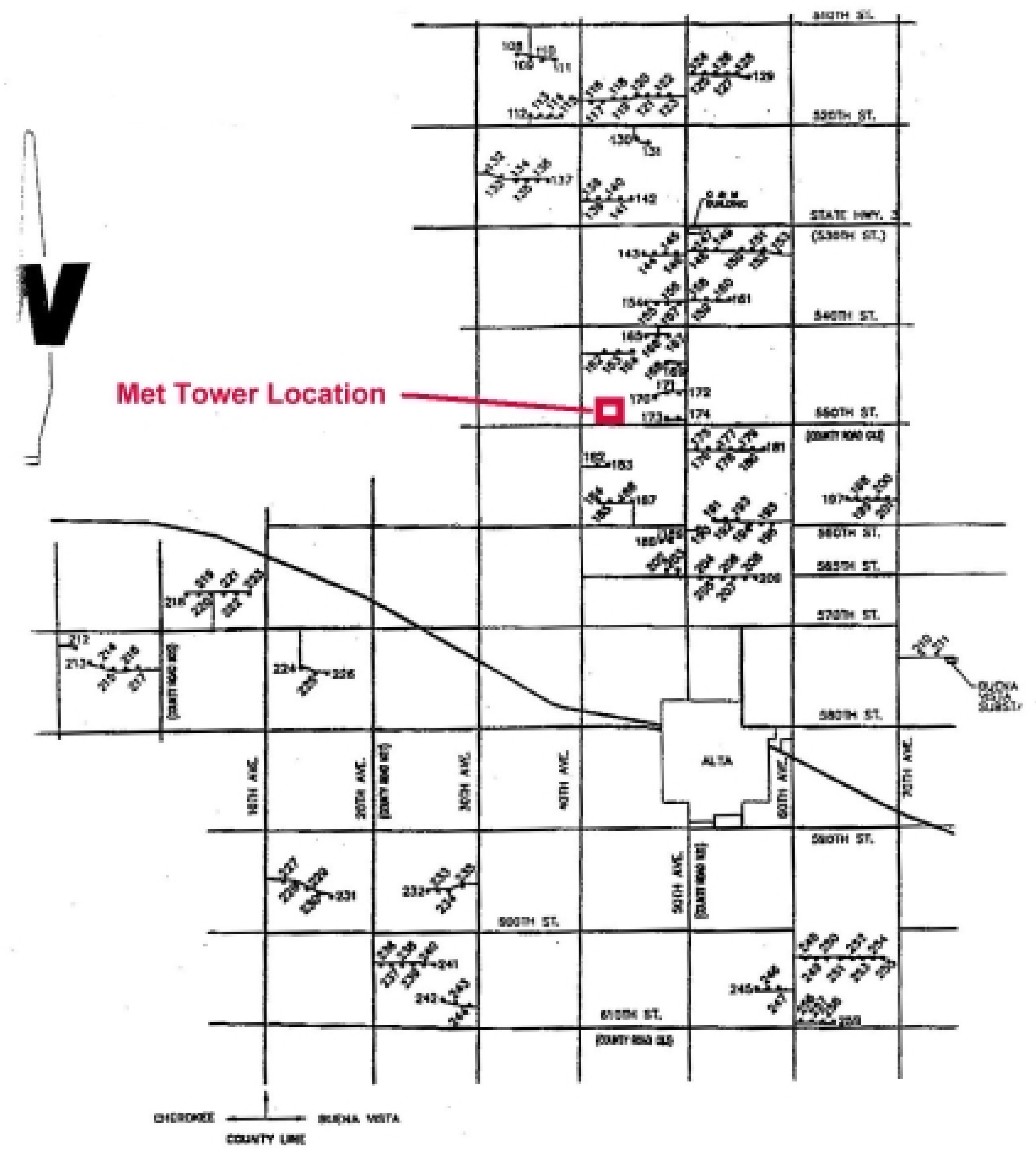


Figure 10. Met tower locations

The antenna installed at the Buena Vista Substation for collecting the met data from tower 101 is shown in Figure 11. In this photo, Mike Holton from MidAmerican Energy is installing the antenna approximately 3 m above the substation building on an existing repeater tower. The Met One logger installed at tower 101 is shown in Figure 12, and Figure 13 shows the tower with the logger and transducers installed. The transducers were installed in February 2001 by the Enron Anemometry crew, which placed them at approximately 58 m (190 ft) (the tower height is 61 m (200 ft)). The heated, heavy-duty sensors will be installed before the winter of 2002.

Figure 11. Substation antenna for collecting met data

Figure 12. Met One logger installed at tower 101

Figure 13. Tower 101 with Met One logger and transducers

4 Lake Benton Wind Farm

4.1 Wind Farm Overview

The Lake Benton site is located in southwestern Minnesota, northwest of the town of Lake Benton, along a topographic feature known as Buffalo Ridge. This is the premier wind resource area in the State of Minnesota. The wind resource arises from storm-driven winds, which occur as a result of the passage of low-pressure systems throughout the year. The resource is better in winter and early spring as the low-pressure centers are more intense and numerous during that time of the year. There are several wind plants in this region, with most of this energy being collected at Xcel Energy's (formerly Northern States Power) Buffalo Ridge Substation. Total wind generation capacity (nameplate rating) is 230 MW connected to Buffalo Ridge, with an additional 50 MW connected to another local substation. The substation connects to the 115 kV bulk transmission system. Monitoring at this collection point will thus provide an aggregate of multiple smaller wind farms and would be indicative of the characteristics of a single, large, geographically or topographically diverse wind plant.

The majority of the wind generation connected to the Buffalo Ridge Substation consists of the Zond Z-750 wind turbines (similar to the Storm Lake I site). Each turbine sits atop a 51.2 m (168 ft) lattice tower, with each blade spanning approximately 24 m (79 ft). The actual rotor diameter is 50 m (164 ft), giving a swept area of 1,966 sq. m (21,124 sq. ft).

A single-line diagram of the Buffalo Ridge Substation is shown in Figure 14. Note that the Fox and Golf projects are no longer fed into the Buffalo Ridge Substation, but into the Chanarambie Substation.

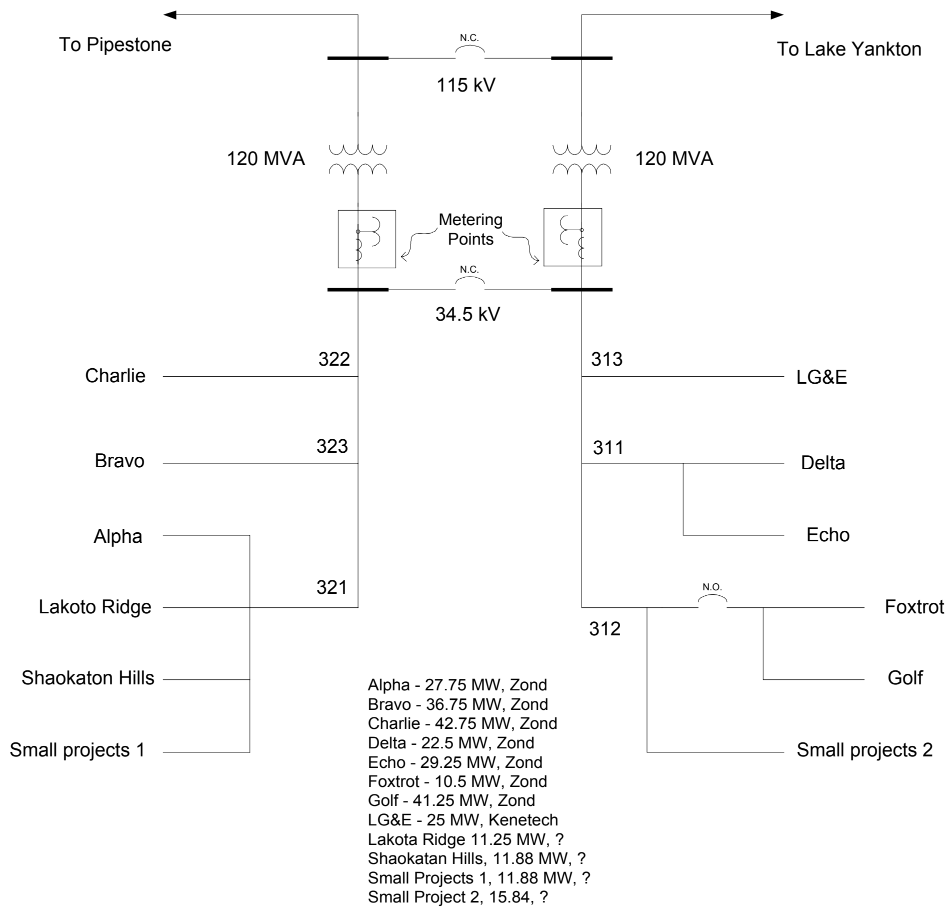


Figure 14. One-line diagram of Buffalo Ridge Substation

4.2 Monitoring System

Unlike the Storm Lake site, only the power monitoring equipment is located at the Buffalo Ridge Substation. Due to the topography of the land, a line of sight was not obtainable between the substation and one of the met towers (again Enron Wind allowed us access to one of their towers for installing our equipment). To alleviate this problem, other alternatives were investigated for gathering the necessary met data. After weighing various options, it was decided that the most efficient and cost-effective approach would be to install a second InfoNode at one of the interconnect buildings and use the existing phone line to remotely access the data. After taking the latitude/longitude coordinates of all the interconnect buildings for the wind farm, along with those for the two Enron met towers of lattice-type configuration, the Golf interconnect building was found to have a line of sight with one of the towers. A simplified diagram of the monitoring equipment is shown in Figure 15.

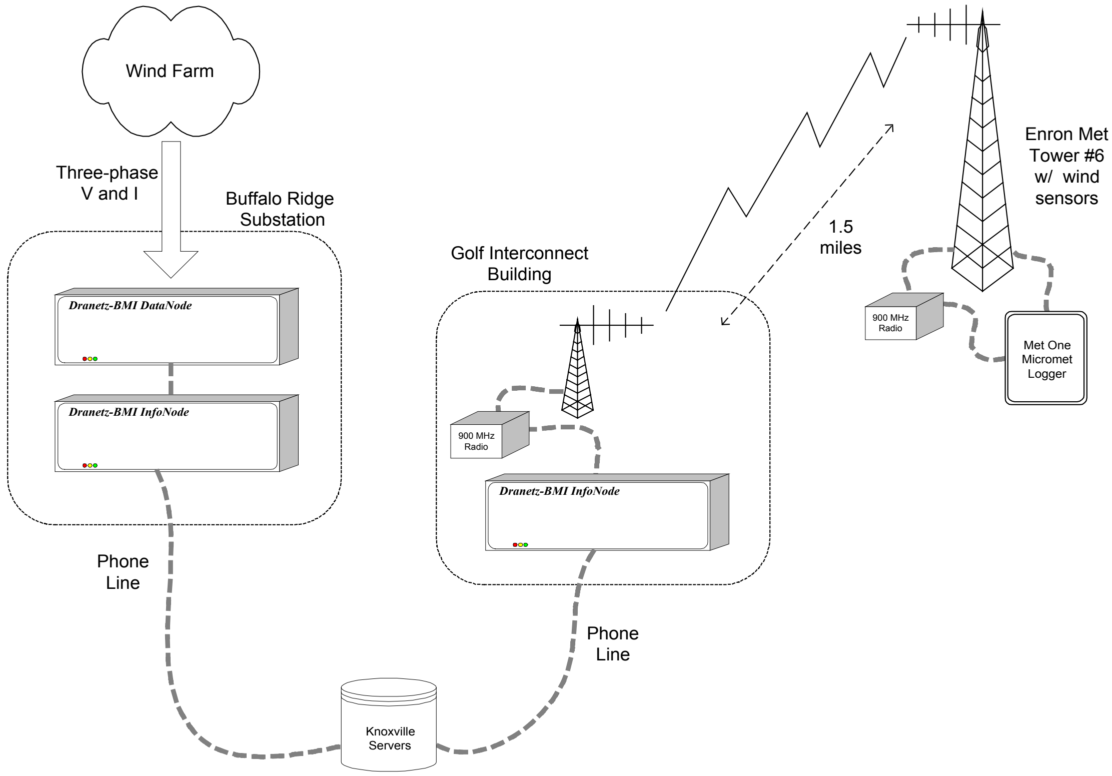


Figure 15. Diagram of Lake Benton monitoring equipment

A list of the equipment utilized for the Lake Benton wind farm includes:

- (2) Dranetz-BMI 5504 InfoNode w/ GPS antenna and receiver
- (1) Dranetz-BMI 5530 DataNode and associated voltage/current transducers
- (2) FreeWave 900 MHz transceivers
- (2) 10 dB antennas
- (1) Met One Micromet logger
- (1) Met One 020C wind direction sensor
- (1) Met One 010C wind speed sensor
- (1) Met One 023 wind direction sensor (heavy duty w/ heater)
- (1) Met One 013 wind speed sensor (heavy duty w/ heater)
- (1) Met One 064 temperature sensor
- (1) Met One 090D barometer.

4.2.1 Power Monitoring

As shown in Figure 14, the entire wind plant is fed into two 120 MVA transformers. Because the two transformers are in parallel, a single DataNode was used to monitor the aggregate current flowing through each transformer (each phase of the current transformers has a single wire corresponding to a single phase of each of the two transformers). Both the current and potential transformers are located on the 34.5kV side of the transformer. As with the Buena Vista Substation, a 5504 InfoNode stores the data locally until downloaded to a local server. Xcel Energy installed the power monitoring equipment in January 2001.

Images of the Buffalo Ridge installation are not available at this time.

4.2.2 Meteorological Monitoring

Enron Wind allowed the installation of the Met One weather station and associated transducers on one of their existing met towers. The Lake Benton wind farm has a total of two met towers of lattice-type configuration (see Figure 16). A line of sight was obtainable between met tower 6 and the Golf interconnect building.

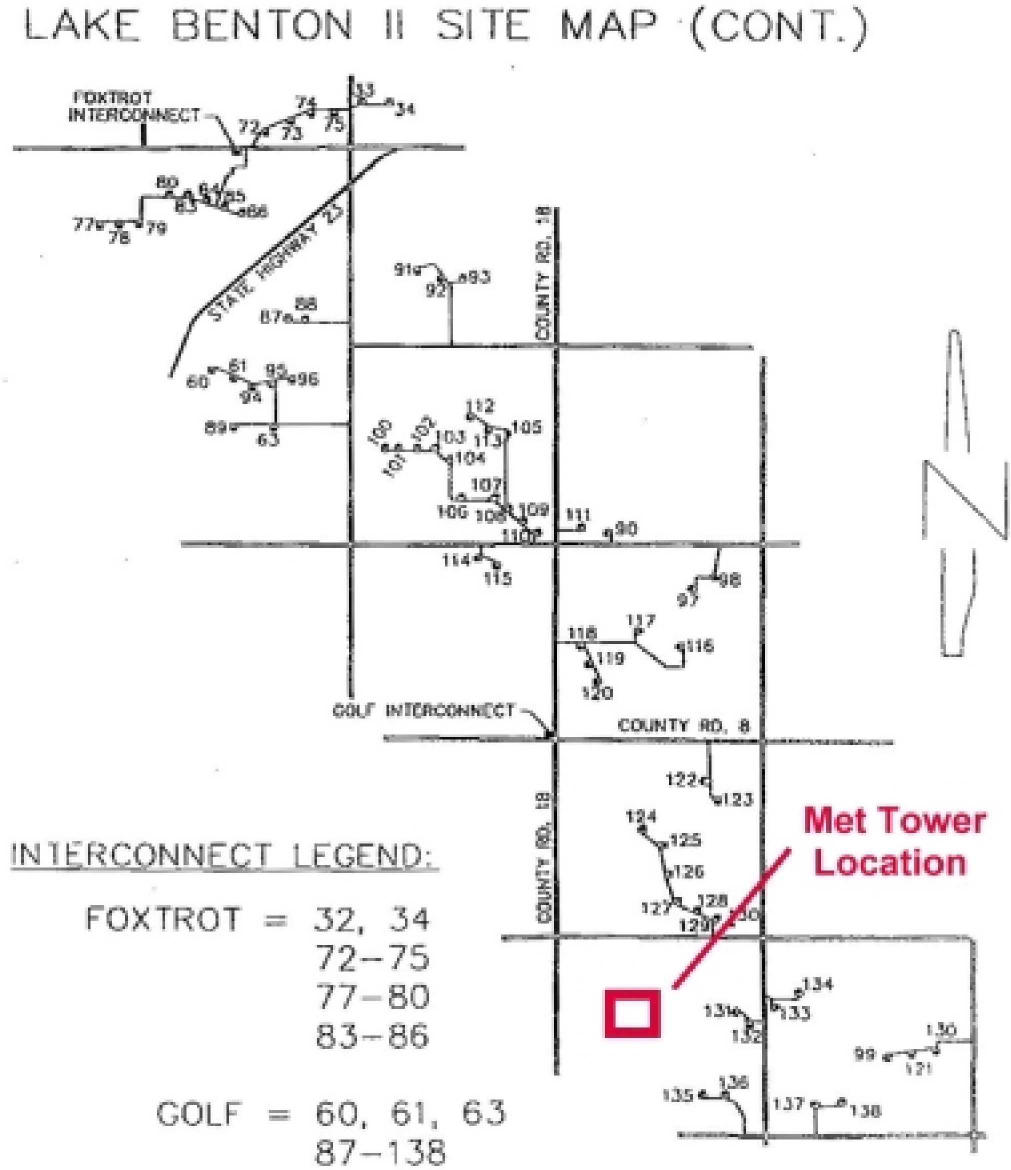


Figure 16. Met tower locations

The InfoNode installed at the Golf interconnect building is shown in Figure 17. The antenna installed at the Golf interconnect building for collecting the met data from tower 6 is shown in Figure 18. The Met One logger installed at tower 6 is shown in Figure 19 (lower enclosure), with Figure 20 shows the tower with the logger and transducers installed. The transducers were installed in June 2001 by the Enron Anemometry crew, which placed them at approximately 49 m (160 ft) (turbine hub height is 51.8 m (170 ft)). The heated, heavy-duty sensors will be installed before the winter of 2001.

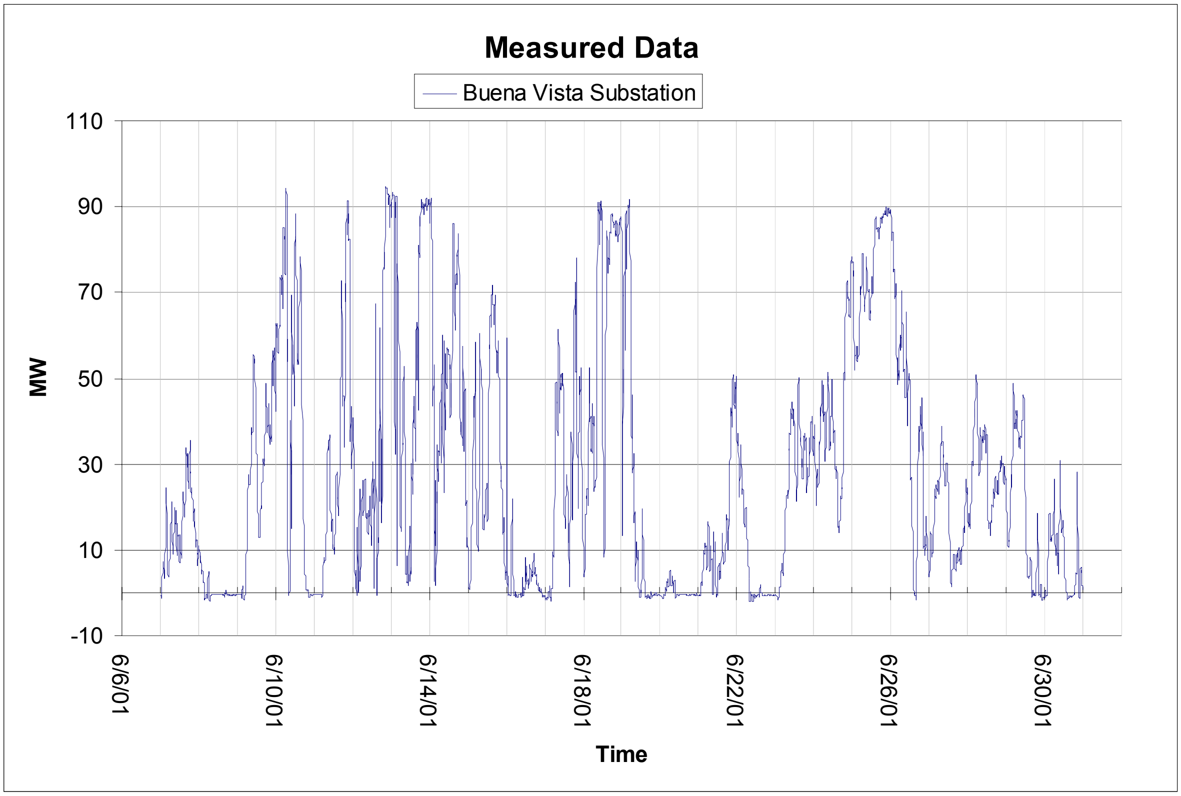
Figure 17. InfoNode installation at Golf interconnect building

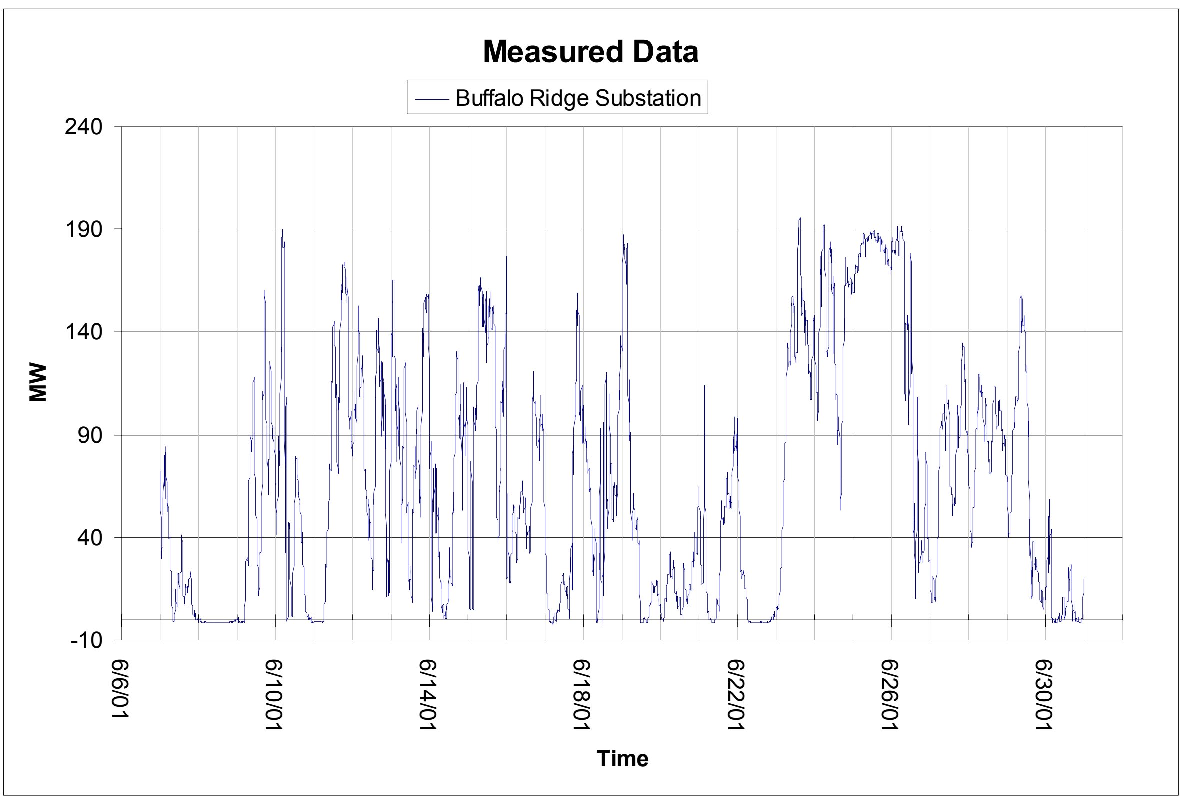
Figure 18. Golf interconnect building

Figure 19. Met One logger installed at tower 6

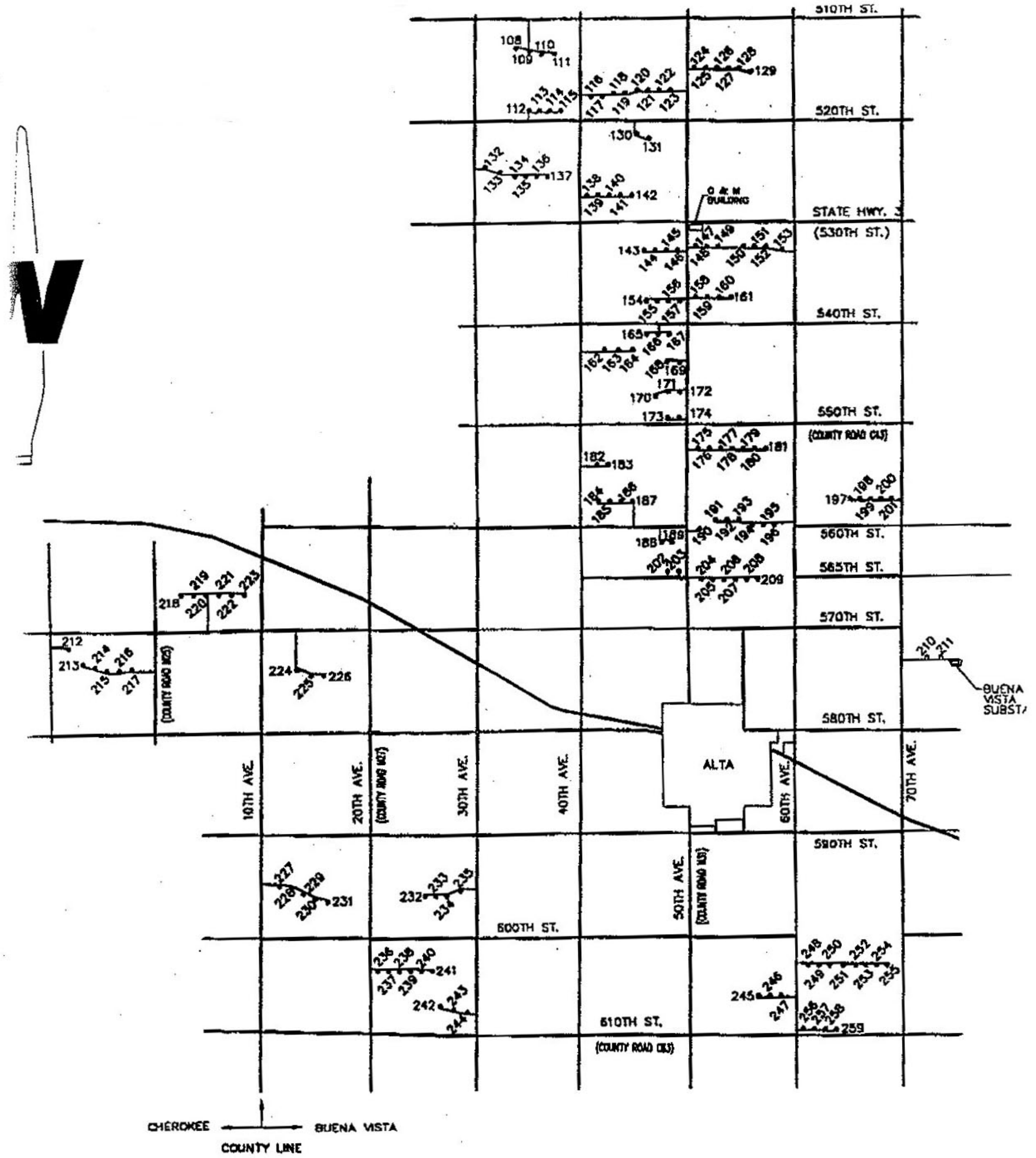
Figure 20. Tower 6 with Met One logger and transducers

Appendix A: Sample Data

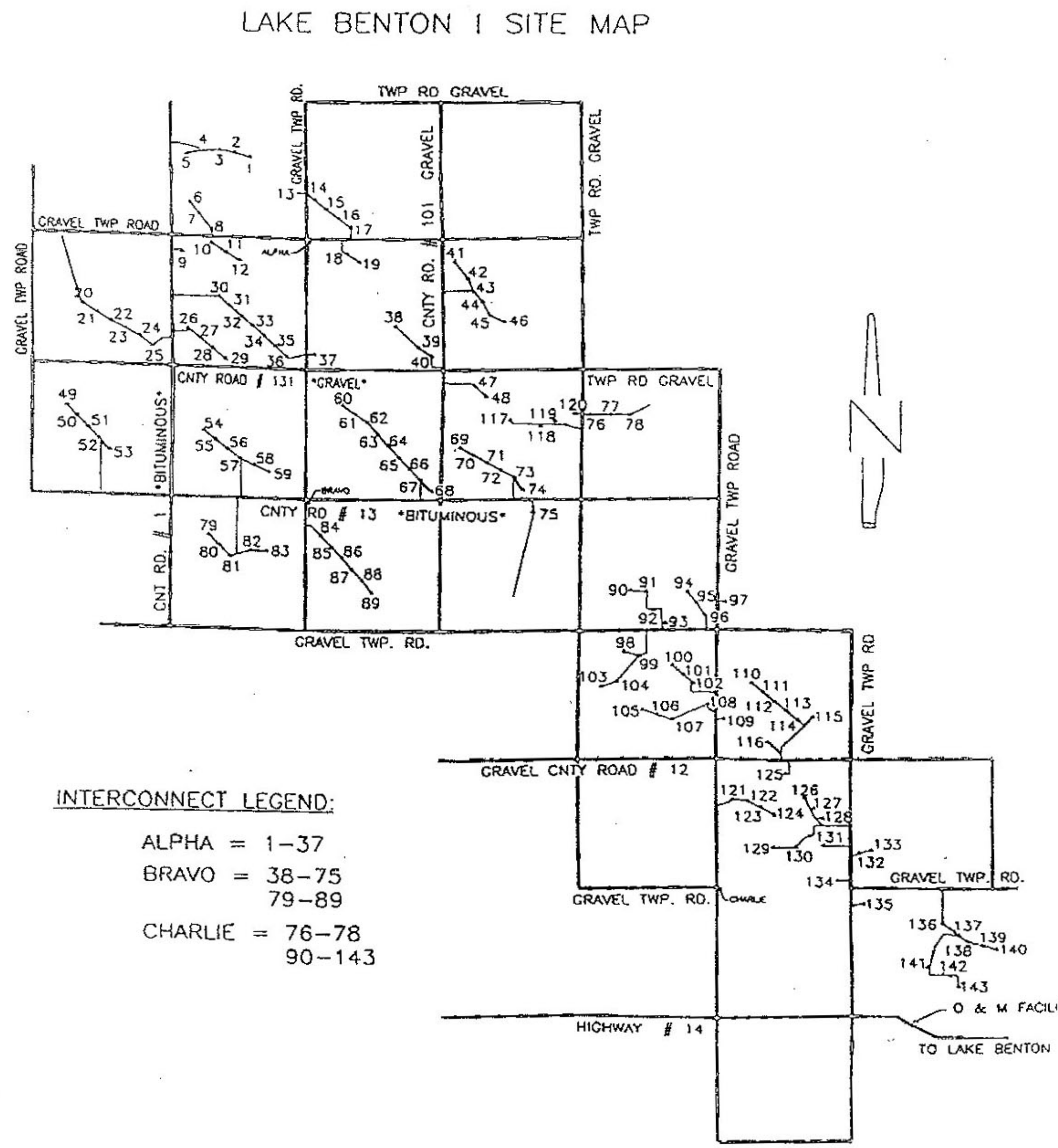




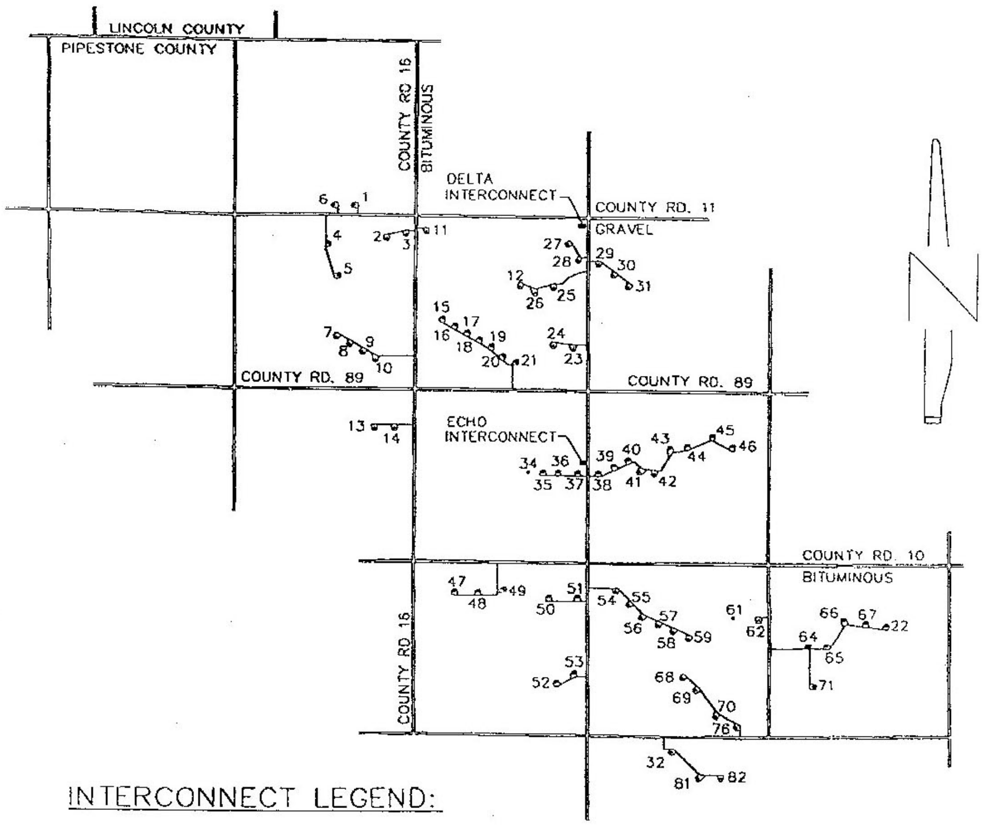
Appendix B: Geographical Representation of Storm Lake I Wind Turbines



Appendix C: Geographical Representation of Lake Benton Wind Turbines



LAKE BENTON II SITE MAP

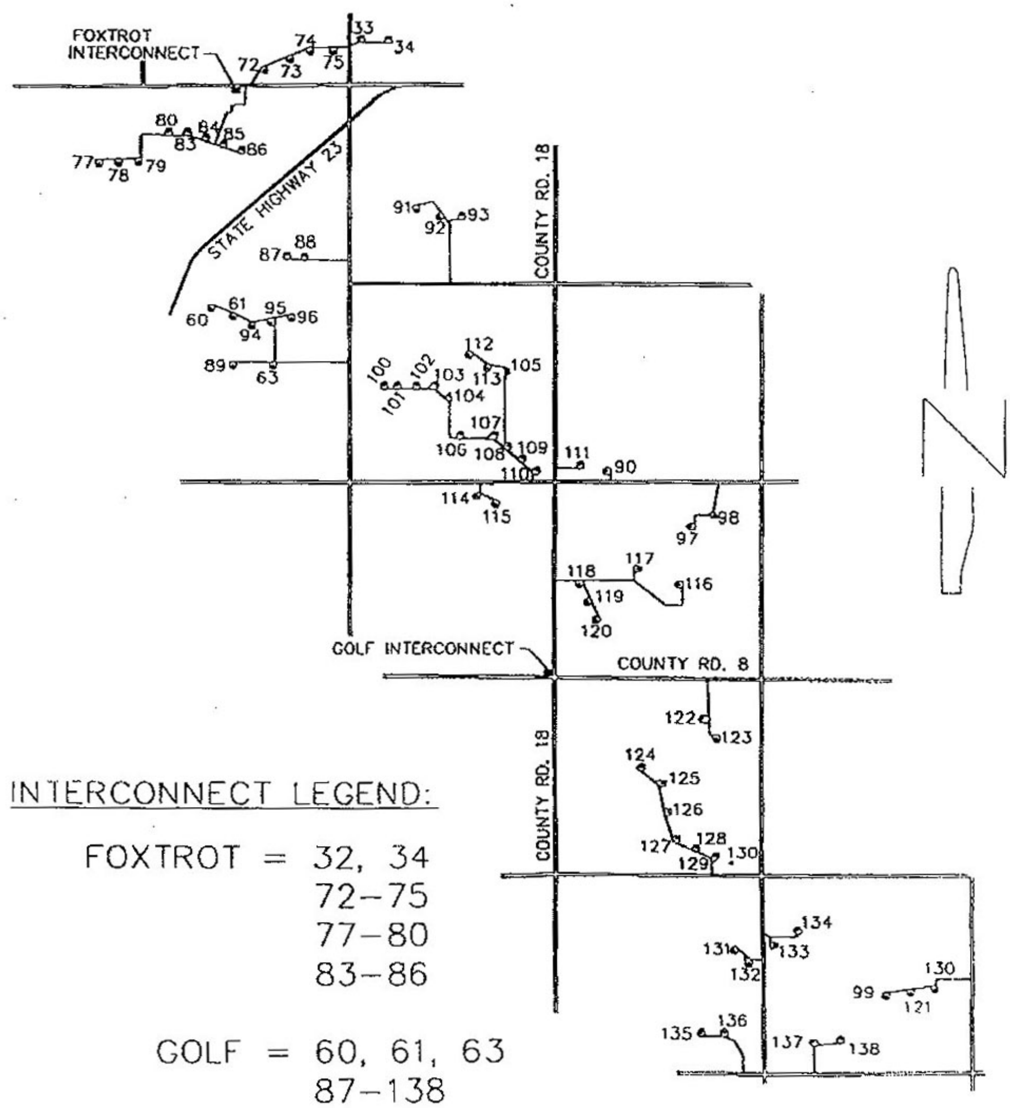


INTERCONNECT LEGEND:

DELTA = 1–21
23–31

ECHO = 22, 32
35–59
62
64–71
76, 81–82

LAKE BENTON II SITE MAP (CONT.)



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The Wind Program and the wind power industry currently do not have the ability to accurately assess ancillary service burdens or benefits of wind-powered electricity. This evaluation can help in determining if efforts should be expended in beginning to examine possible mitigation strategies by including detailed data analysis from two wind farm facilities.

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