Wisconsin Wind Resource Assessment Program

Final Report

1997 - 2001

Prepared for:

Dairyland Power Cooperative
Madison Gas and Electric
National Renewable Energy Laboratory
Northern States Power
Public Service Commission of Wisconsin
Superior Water, Light, and Power
Wisconsin Electric Power Company
Wisconsin Energy Bureau
Wisconsin Power and Light Company
and
Wisconsin Public Service Company

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INTRODUCTION

A consortium of utilities in the State of Wisconsin is conducting a statewide wind resource assessment study in conjunction with the Wisconsin Energy Bureau (WEB), the Public Service Commission of Wisconsin, and the National Renewable Energy Laboratory (NREL). The utility consortium includes Wisconsin Public Service Company; Superior Water, Light and Power; Madison Gas and Electric; Wisconsin Electric Power Company; Northern States Power; Wisconsin Power and Light Company; and Dairyland Power Cooperative. The purpose of the Wisconsin Wind Resource Assessment Program (WRAP) is to identify potential areas for wind energy project development and to obtain wind data from a geographically diverse sample of the state of Wisconsin. The consortium retained the services of Global Energy Concepts, LLC (GEC), an engineering consulting firm, to conduct this study.

Thirteen sites were selected for wind monitoring. Wind resource assessment data were collected for three years. The first six monitoring stations were installed in November 1997. The next six stations were installed during the summer of 1998. In November 1999, Site 410 was installed to conduct a wind shear study at the Low Wind Speed Turbine Project in Glenmore, Wisconsin.[1] In April 2000, Site 403 was decommissioned and in October the equipment was installed at Site 414 in southern Wisconsin on Empire Prairie. Eleven of the monitoring sites have reached the end of the three years of data collection and have been decommissioned. GEC continues to collect data from the two remaining stations, Sites 410 and 414. Details on the methodology involved in selecting these sites are provided in a separate report prepared by GEC entitled *Wisconsin Wind Resource Assessment Program Monitoring Plan.*[2]

The study has included six semi-annual data reports and this final report. Each semi-annual report provides a general summary of the data collected during that reporting period. This final report provides a three-year summary for the monitoring sites that have completed three years of data collection as well a summary of the data collected from Sites 403, 410, and 414.

MONITORING STATION OVERVIEW

Table 1 lists the site number, name, elevation, location and data collection period for each monitoring station. The locations and tower types of the fourteen monitoring stations are provided in Figure 1.

[1] The Low Wind Speed Turbine Project is a 1.2 MW wind energy project funded by the Eastern Wisconsin Utilities and the Electric Power Research Institute (EPRI). Additional information on this project can be found in the *Wisconsin Low Wind Speed Turbine Project Development* report published by EPRI (reference TR-111438).

[2] All data and reports produced for the Wisconsin WRAP are funded in part by the Wisconsin Department of Administration, Division of Energy and Intergovernmental Relations, through the Wisconsin Energy Bureau (WEB). All data and reports are available through the WEB (energy@mail.state.wi.us; phone 608/266-8234).

Table 1. Monitoring Station Demographics

Site #	Site Name	Elevation	Latitude	Longitude	Data Collection Period
401	Spring Valley	370 m (1215 ft)	44º53' N	92º14' W	11/09/97 – 1/31/01
402	Abbotsford	450 m (1475 ft)	44º59' N	90º18' W	11/10/97 – 1/31/01
403	Rib Lake	500 m (1640 ft)	45º17' N	90º15' W	11/12/97 – 4/11/00
404	Cornucopia	310 m (1015 ft)	46º49' N	91º06' W	11/13/97 – 1/31/01
405	Sturgeon Bay	250 m (820 ft)	42º36' N	89º54' W	11/20/97 – 1/31/01
406	Montfort	340 m (1115 ft)	42º57' N	90º26' W	11/14/97 – 1/31/01
407	Rock River	285 m (930 ft)	43º26' N	88º18' W	08/13/98 – 9/12/01
408	Eden	400 m (1320 ft)	43º43' N	88º17' W	07/09/98 – 7/11/01
409	Honeymoon Hill	330 m (1080 ft)	43º58' N	88º05' W	06/12/98 – 6/27/01
410	Wind Shear Study	299 m (981 ft)	44º20' N	87º95' W	11/09/99 – 9/30/01
411	Clay Banks	255 m (835 ft)	44º44' N	87º20' W	07/08/98 – 7/12/01
412	Tomah	445 m (1460 ft)	43º53' N	90º35' W	06/26/98 – 7/12/01
413	Hurley	555 m (1825 ft)	46º25' N	90º14' W	07/24/98 – 10/2/01
414	DeForest	323 m (1060 ft)	44º22' N	87º59' W	10/05/00 – 9/30/01

NOTES: Site 403 was moved to Site 414. sites 410 and 414 are continue to collect data, but the data is not being validated or corrected, pending funding.

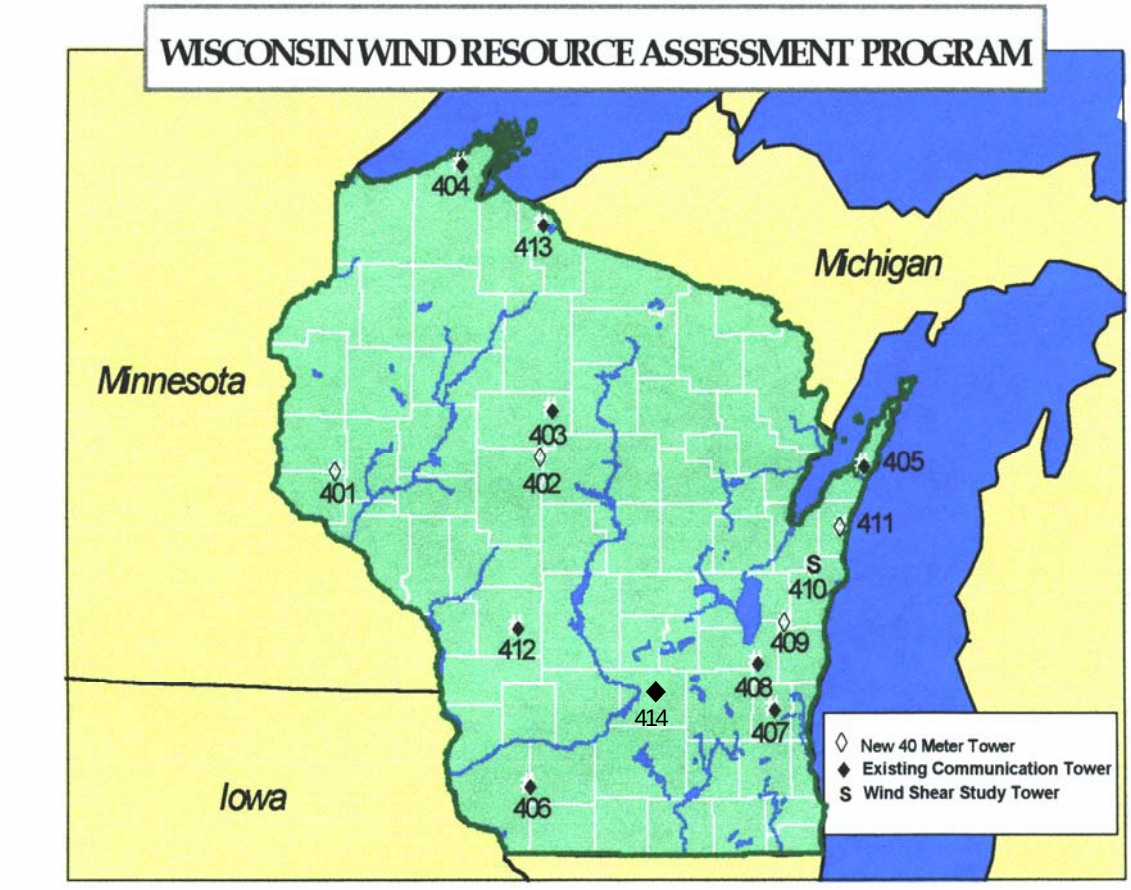

Figure 1. Location of Wisconsin Wind Monitoring Stations

MONITORING EQUIPMENT

GEC installed the monitoring stations with the assistance of Lake Michigan Wind and Sun (LMWS) of Sturgeon Bay, Wisconsin, and NRG Systems based in Burlington, Vermont. LMWS has provided ongoing maintenance for this monitoring network. All monitoring equipment was purchased from NRG Systems.

Each monitoring station was equipped with four or five calibrated wind speed sensors, two wind direction sensors, a temperature sensor, and a cellular data logger with a solar panel for battery recharging. All of the stations were initially configured to measure wind speed at 10, 25, and 40 meters. When possible, existing communication towers were used to collect data at an additional height of 60 meters. The 10-meter anemometers were moved to 60 meters on the eight communication towers during November 1999 through April 2000. The redundant 60-meter anemometer was installed on the opposite side of the tower to evaluate tower shadow. In addition, a second vane was added at the 60-meter level. The wind speed and wind direction measurement levels for each site are provided in Table 2. Site 410, the wind shear tower, is uniquely equipped with wind speed sensors at 37, 60, 83, 103, and 123 meters and wind direction sensors at 37, 83, and 123 meters. Details on the equipment configurations for each site are provided in the *Wisconsin Wind Resource Assessment Program Monitoring Plan*.

Table 2. Monitoring Station Measurement Heights

	Measurement Heights			
SITE #	**10m**	**25m**	**40m**	**60m**
401	WS	WS/DIR	WS/DIR	
402	WS	WS/DIR	WS/DIR	
404	WS	WS/DIR	WS	WS/DIR
405	WS	WS/DIR	WS	WS/DIR
406	WS	WS/DIR	WS	WS/DIR
407	WS	WS/DIR	WS	WS/DIR
408	WS	WS/DIR	WS	WS/DIR
409	WS	WS/DIR	WS/DIR	
411	WS	WS/DIR	WS/DIR	
412	WS	WS/DIR	WS	WS/DIR
413	WS	WS/DIR	WS	WS/DIR
414	WS	WS/DIR	WS	WS/DIR

WS = wind speed DIR = wind direction

Note: 10m anemometers moved to 60m level on communication towers during November 1999 through April 2000.

	Measurement Heights				
SITE #	**37m**	**60m**	**83m**	**103m**	**123m**
410	WS/DIR	WS	WS/DIR	WS	WS/DIR

SITE DESCRIPTIONS

Following is a description of the unique characteristics of each monitoring site.

Site 401 – Spring Valley. This station is located in western Wisconsin approximately three miles north of Spring Valley in St. Croix County. The site is on a gently sloping terrain feature with good exposure in all directions.

Site 402 – Abbotsford. This station is located in central Wisconsin approximately two miles north of Abbotsfort in Marathon County. The site is on flat terrain and is well exposed on all sites.

Site 403 – Rib Lake. This station is located in central Wisconsin just east of Rib Lake in Greenwood County. The site is in a flat clearing on forested terrain.

Site 404 – Cornucopia. This station is located in northern Wisconsin approximately two and a half miles south of Cornucopia in Bayfield County. The site is in a well-exposed clearing on the forested terrain of the Bayfield Peninsula.

Site 405 – Sturgeon Bay. This station is located in eastern Wisconsin on the Door County Peninsula approximately four miles north of Sturgeon Bay. This site is on relatively flat terrain with low-lying trees to the north and northwest.

Site 406 – Montfort. This station is located in southern Wisconsin approximately two mile south of Montfort in Grant County. The site is on rolling grassland terrain and is well exposed on all sides.

Site 407 – Rock River. This station is located in southeastern Wisconsin approximately two miles northeast of Allenton in Washington County. The site is on a geologic uplift feature called the Niagara Escarpment that runs along the eastern edge of the state. There is good exposure in all directions.

Site 408 – Eden. This station is located in southeastern Wisconsin approximately seven and a half miles southeast of Fond du Lac in Fond du Lac County. The site is on hilly terrain with good exposure in all directions.

Site 409 – Honeymoon Hill. This station is located in southeastern Wisconsin approximately one mile north of New Holstein in Calumet County. The site is on a geologic uplift feature called the Niagara Escarpment that runs along the eastern edge of the state. There is good exposure in all directions.

Site 410 – Wind Shear Study. This site is located near the town of Glenmore, Wisconsin, in Brown County approximately ten miles south of Green Bay. The site stands along a geologic uplift feature called the Niagara Escarpment that runs along the eastern edge of the state. There is good exposure in all directions.

Site 411 – Clay Banks. This station is located in eastern Wisconsin on the Door County Peninsula approximately two miles north of Clay Banks. This site is on slightly hilly terrain not far from the shores of Lake Michigan.

Site 412 – Tomah. This station is located in central Wisconsin approximately six miles southwest of Tomah in Monroe County. This site is on slightly hilly terrain with more prominent hills to the west.

Site 413 – Hurley. This station is located in north Wisconsin near the Michigan boarder approximately four miles southwest of Hurley in Iron County. The site is on hilly, forested terrain.

Site 414 – DeForest. This station is located is south-central Wisconsin approximately four miles north of DeForest in Columbia County. This site is on flat terrain with homes directly to the north and west.

DATA ANALYSIS

Data are downloaded by cellular phone and quality-controlled by GEC on a weekly basis. In July 1998, the data-averaging interval was changed from hourly to 10-minute averages based on a request from NREL. For reporting and analysis purposes, GEC converts the data to hourly averages. All data are reviewed for accuracy and invalid data are removed to create a validated data set. Data are considered invalid if they do not represent the actual wind conditions at the site. Typical causes of invalid data include sensor icing, tower shadow, and equipment damage due to lightning, electrostatic discharge, failed components, or vandalism.

DATA REPLACEMENT METHODS

Missing and erroneous wind speed data at the highest measurement level are replaced when possible to create a corrected data set. Data are replaced using the following methods in the order presented. In the case where only a few hours are missing, the average of the hour before and the hour after the outage is used to replace the invalid data. When a longer period of data is affected and another wind speed sensor is operating at the site, the data are filled in based on a correlation between the sensors. When all sensors are affected by the outage, a correlation is developed to a nearby reference site that has data concurrent with the affected hours. If no reference site data are available, the missing data are replaced with the average diurnal values of valid data from the same site during a representative period. The data replacement methods used for each section of invalid data are provided in the semi-annual reports.

If there were an insufficient number of data points available to provide for accurate data replacement when semi-annual data reports were prepared, the removed or missing data were replaced during preparation of this final report. The majority of missing or invalid data were replaced on a semi-annual basis. The data replacement methods for this final report are summarized in the appendix. The appendix includes a list of data replacement methods for each section of invalid data.

DATA RECOVERY

For Tables 3 and 4, all hours and percentages are based on the time periods given in Table 1.

Table 3 provides the recovery rates for wind speed data collected at each measurement level. The overall recovery rate at all measurement levels for the duration of the program was 94.4% for all fourteen sites. The recovery rate at the highest measurement level for all sites is 94.5%. This second recovery rate is of primary importance because it represents the percentage of data obtained from the monitoring level nearest the hub height of commercially available wind turbines. The data recovery rate represents the percentage of data remaining after erroneous data have been removed. Therefore, the recovery rate for actual data collected is higher. Table 3 also provides the total number of hourly data points which were either missing or removed during the data validation process at each monitoring height.

Table 3. Wind Speed Data Recovery Rates

Site Number	Site Name	Period Hours	Hours Lost 10m	25m	40m	60m	Recovery Rates All Heights	Highest Level
401	Spring Valley	28,320	702	702	424	N/A	97.8%	98.5%
402	Abbotsford	28,296	395	547	1,065	N/A	97.6%	96.2%
403	Rib Lake	21,168	1,082	1,271	1,472	1,666	93.5%	92.1%
404	Cornucopia	28,224	193	2,011	2,093	2,071	94.4%	92.7%
405	Sturgeon Bay	28,056	1,467	1,679	1,756	1,698	94.1%	93.9%
406	Montfort	28,200	1,882	2,841	3,770	4,311	88.6%	84.7%
407	Rock River	27,029	283	1,200	1,360	519	96.9%	98.1%
408	Eden	26,333	105	454	727	529	98.3%	98.0%
409	Honeymoon Hill	26,671	2,388	2,443	2,419	N/A	90.9%	90.9%
410	Wind Shear Study*	16,596	N/A	N/A	213	444	98.0%	98.7%
411	Clay Banks	26,405	136	163	172	N/A	99.4%	99.3%
412	Tomah	26,694	340	571	3,307	711	95.4%	97.3%
413	Hurley	27,960	2,719	4,422	5,369	3,304	85.9%	88.2%
414	DeForest	8,664	N/A	160	197	132	98.1%	98.5%
		348,616	11,692	18,464	24,344	15,385	94.4%	94.5%

*40m wind speed actually measured at 37m. All Heights Recovery Rate is based on 40 and 60m anemometers. Highest Level Recovery Rate is based on the 60m anemometer.

Site Number	Site Name	Period Hours	Hours Lost 83m	103m	123m	Recovery Rate Upper Levels
410	Wind Shear Study	16,596	1,162	1,954	4,322	85.1%

Of the total missing and removed data, 61% was due to equipment malfunction. Icing events at all sites accounted for 22% of the removed data, tower shadow accounted for 11%, and missing data for unknown reasons accounted for the remaining 5%. Table 4 provides a breakdown of the specific causes of missing and removed data for each site.

Table 4. Causes of Wind Speed Data Loss for All Levels

Site Number	Site Name	Icing hrs	Icing %	Malfunction hrs	Malfunction %	Maintenance hrs	Maintenance %	Tower Shadow hrs	Tower Shadow %	Unknown hrs	Unknown %
401	Spring Valley	1,016	56%	722	39%	0	0.0%	0	0%	90	5%
402	Abbotsford	2,007	100%	0	0%	0	0.0%	0	0%	0	0%
403	Rib Lake	1,561	28%	3,768	69%	0	0.0%	162	3%	0	0%
404	Cornucopia	1,219	19%	5,076	80%	0	0.0%	70	1%	3	0%
405	Sturgeon Bay	1,301	20%	5,072	77%	0	0.0%	2	0%	225	3%
406	Montfort	1,554	12%	9,236	72%	0	0.0%	1,833	14%	181	1%
407	Rock River	956	28%	197	6%	0	0.0%	1,529	45%	680	20%
408	Eden	966	53%	69	4%	117	6.4%	663	37%	0	0%
409	Honeymoon Hill	698	10%	4,872	67%	0	0.0%	0	0%	1,680	23%
410	Wind Shear Study	2,034	0%	2,397	0%	0	0.0%	3,579	0%	85	0%
411	Clay Banks	417	89%	0	0%	0	0.0%	0	0%	54	11%
412	Tomah	1,746	35%	2,350	48%	50	1.0%	417	8%	366	7%
413	Hurley	1,510	10%	13,792	87%	0	0.0%	227	1%	285	2%
414	DeForest	406	83%	0	0%	0	0.0%	35	7%	48	10%
		17,391	22%	47,551	61%	167	0.2%	8,517	11%	3,697	5%

RESULTS

This report provides a three-year summary of the data collected at each site, with the exception of Sites 403, 410, and 414. Only two years of data are summarized for Rib Lake, Site 403, which was moved before three years of data had been collected. Sites 410 and 414 have not yet completed three years of data collection. This report summarizes one year and eleven months of data collected from the Wind Shear Study, Site 410, and one year of data collected at DeForest, Site 414. As shown in Table 5, the annual data summary periods for all fourteen sites do not coincide, however full twelve-month periods were used when possible to provide comparative annual reporting.

Table 5. Annual Data Summary Periods

Site #	Site Name	Annual Data Summary Periods	Years
401	Spring Valley	Jan-Dec 1998, 1999, 2000	3
402	Abbotsford	Jan-Dec 1998, 1999, 2000	3
403	Rib Lake	Jan-Dec 1998 & 1999	2
404	Cornucopia	Jan-Dec 1998, 1999, 2000	3
405	Sturgeon Bay	Jan-Dec 1998, 1999, 2000	3
406	Montfort	Jan-Dec 1998, 1999, 2000	3
407	Rock River	Sep-Aug 98-99, 99-00, 00-01	3
408	Eden	Jul-Jun 98-99, 99-00, 00-01	3
409	Honeymoon Hill	Jul-Jun 98-99, 99-00, 00-01	3
410	Wind Shear Study	Nov-Sep 99-00 & Oct-Sep 00-01	1.9
411	Clay Banks	Jul-Jun 98-99, 99-00, 00-01	3
412	Tomah	Jul-Jun 98-99, 99-00, 00-01	3
413	Hurley	Jul-Jun 98-99, 99-00, 00-01	3
414	DeForest	Oct-Sep 00-01	1

WIND SPEED

Classes of wind power density at 10 m and 50 meters[(a)]

Wind Power Class	10 m (33 ft)				50 m (164 ft)			
	Power Density, Watts per square meter		Speed[(b)], meters per second (miles per hour)		Power Density, Watts per square meter		Speed[(b)], meters per second (miles per hour)	
	lower limit	upper limit	lower limit	upper limit	lower limit	upper limit	lower limit	upper limit
1	0	100	0	4.4 (9.8)	0	200	0	5.6 (12.5)
2	100	150	4.4 (9.8)	5.1 (11.5)	200	300	5.6 (12.5)	6.4 (14.3)
3	150	200	5.1 (11.5)	5.6 (12.5)	300	400	6.4 (14.3)	7.0 (15.7)
4	200	250	5.6 (12.5)	6.0 (13.4)	400	500	7.0 (15.7)	7.5 (16.8)
5	250	300	6.0 (13.4)	6.4 (14.3)	500	600	7.5 (16.8)	8.0 (17.9)
6	300	400	6.4 (14.3)	7.0 (15.7)	600	800	8.0 (17.9)	8.8 (19.7)
7	400	1000	7.0 (15.7)	9.4 (21.1)	800	2000	8.8 (19.7)	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law: (mean wind speed at desired height) = (known mean wind speed at other height) x [(desired height ÷ known height)^(1/7)]

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3%/1000 m (5%/5000 ft) elevation.

Table 6 summarizes the annual average wind speeds at all measurement levels for each station based on the time periods listed in Table 5. The averages for the highest measurement level at each site are based on the corrected hourly data set. The averages for the remaining measurement levels are based on the validated hourly data set (invalid data were removed but not replaced).

Table 6. Annual Average Wind Speed

		10m		25m		40m		60m	
Site #	**Site Name**	**m/s**	**mph**	**m/s**	**mph**	**m/s**	**mph**	**m/s**	**mph**
401	Spring Valley	4.1	(9.1)	4.8	(10.7)	5.5	(12.3)	N/A	
402	Abbotsford	4.3	(9.6)	5.2	(11.7)	5.9	(13.3)	N/A	
403	Rib Lake	3.0	(6.7)	3.7	(8.3)	4.5	(10.1)	5.3	(11.8)
404	Cornucopia	3.9	(7.7)	4.2	(9.5)	4.7	(10.5)	5.4	(12.0)
405	Sturgeon Bay	3.5	(9.6)	4.6	(10.3)	5.7	(12.8)	6.6	(14.7)
406	Montfort	4.3	(8.5)	5.2	(11.6)	5.7	(12.8)	6.3	(14.2)
407	Rock River	3.8	(8.5)	5.0	(11.1)	5.8	(13.0)	6.5	(14.4)
408	Eden	4.8	(10.7)	5.8	(13.0)	6.5	(14.6)	6.9	(15.4)
409	Honeymoon Hill	5.2	(11.7)	5.9	(13.2)	6.7	(14.9)	N/A	
410	Wind Shear Study*	N/A		N/A		5.6	(12.6)	6.4	(14.4)
411	Clay Banks	4.7	(10.4)	5.4	(12.1)	6.3	(14.0)	N/A	
412	Tomah	3.7	(8.3)	4.9	(11.0)	5.4	(12.2)	6.2	(13.9)
413	Hurley	2.9	(6.6)	5.2	(11.6)	5.9	(13.2)	6.7	(15.0)
414	DeForest	N/A		5.0	(11.1)	5.7	(12.8)	6.1	(13.7)

*40m wind speed actually measured at 37m

NOTE: N/A indicates data not collected at this level

		83m		103m		123m	
Site #	**Site Name**	**m/s**	**mph**	**m/s**	**mph**	**m/s**	**mph**
410	Wind Shear Study	7.2	(16.1)	7.6	(17.0)	8.0	(17.9)

Figures 2 and 3 provide a comparison of the 40-meter wind speed averages at all sites. The annual average wind speeds at 40 meters ranged from 4.5 to 6.7 m/s (10.1 to 14.9 mph) at the 14 monitoring sites. As shown in Figure 2, Site 408, Eden, and Site 409, Honeymoon Hill, had the highest 40-meter annual wind speeds. Site 408 and 409 are located in eastern Wisconsin along a terrain feature known as the Niagara Escarpment. All illustrated in Figure 3, the seasonal patterns are similar at all 14 sites. The winds are generally highest during the winter and spring, decrease in during the summer months, June through August, and increase again in the autumn.

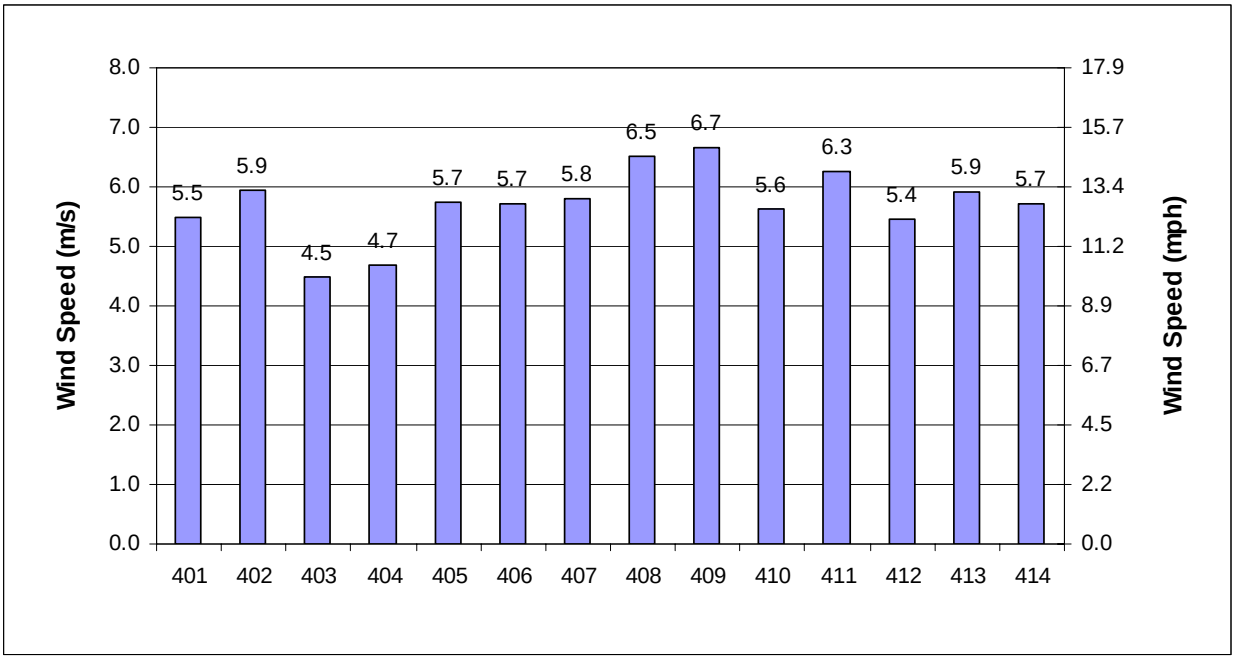

Figure 2. 40-Meter Annual Average Wind Speed

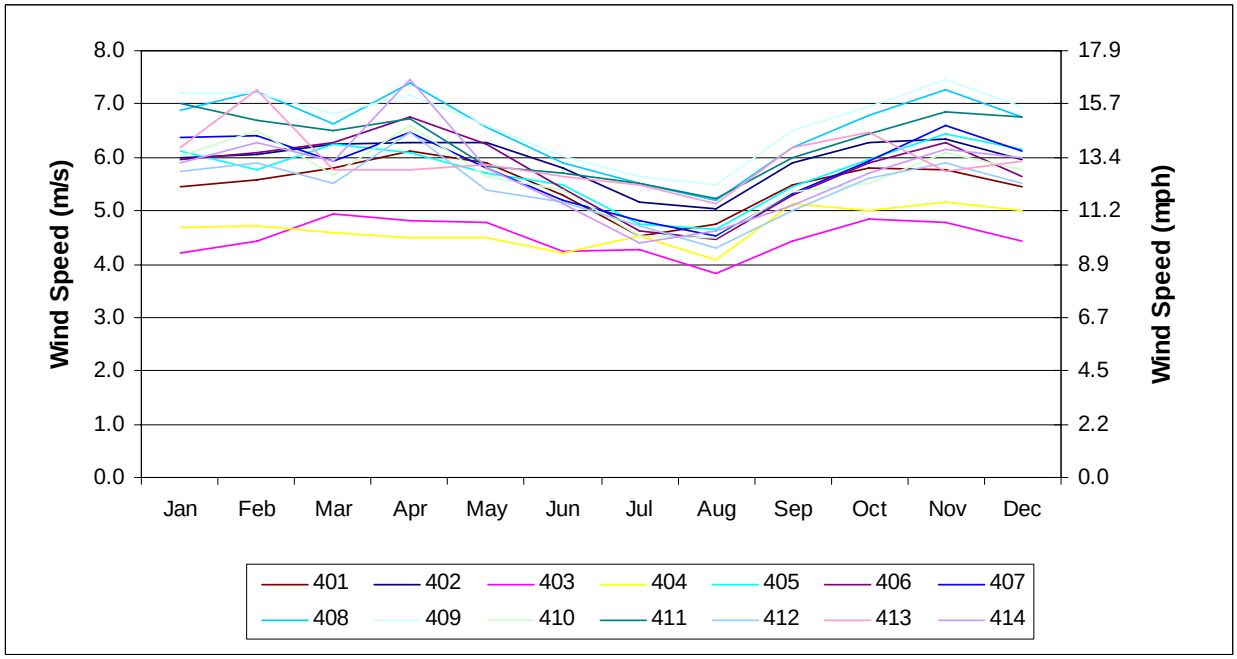

Figure 3. 40-Meter Average Monthly Wind Speed

Figure 4 illustrates the diurnal wind speed patterns at the 40-meter level for all sites. As shown in the figure, the diurnal wind speed patterns are similar at all 14 sites. The wind speeds are highest at midday and again late at night to early morning.

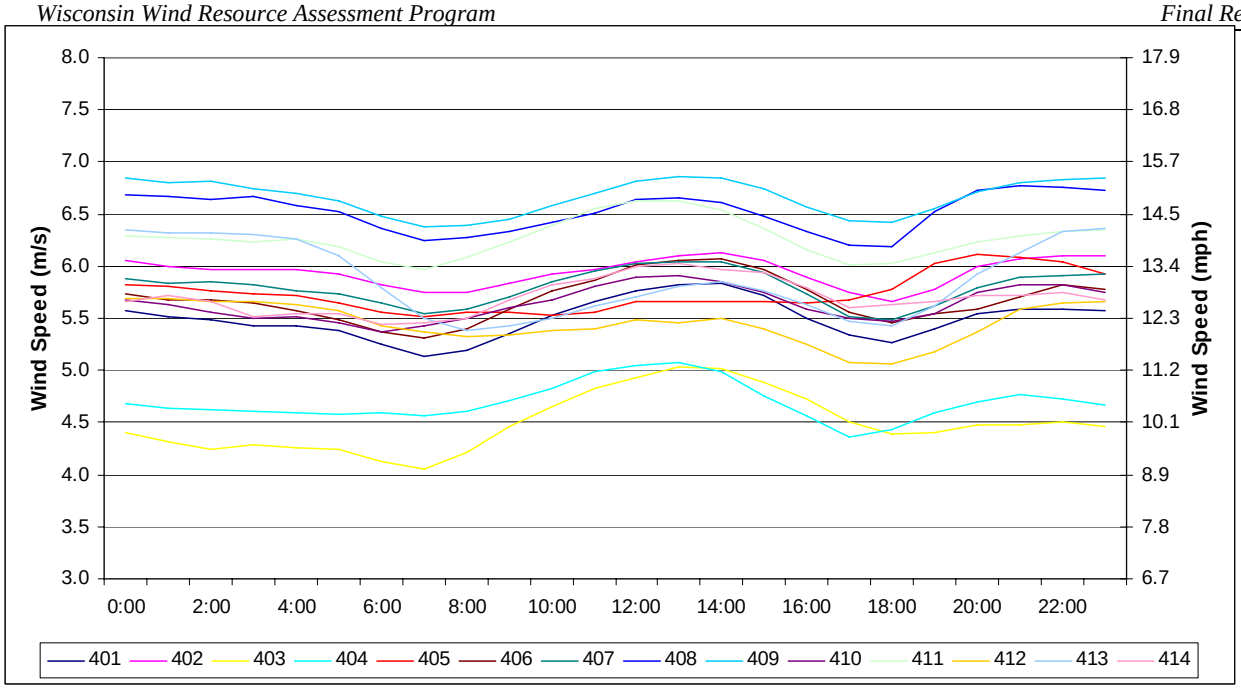

Figure 4. 40-Meter Diurnal Wind Speed Patterns

WIND DIRECTION

Figures 5 through 18 provide a summary of the annual wind direction at each monitoring site. These wind rose graphs illustrate the percent time and percent energy in each direction sector. The wide, outlined bars represent the percent of total energy and the narrower, shaded bars illustrate the percent of total time in each of the sixteen direction sectors. Monthly wind rose graphs are provided in the appendices of the semi-annual reports and give a seasonal view of the wind direction at each of the sites.

There is significant variation between the sites in terms of the wind direction characteristics, but similarities can be seen by region. Sites 407, 408, 409, 410 and 411 in eastern Wisconsin along the Niagara Escarpment and Site 414 just to the west experienced predominantly west and south-westerly winds. Site 405, to the north on the Door Peninsula, also experienced west-southwesterly winds but with some south-southeasterly influence.

Site 406, in the southwest corner of the state, experienced predominantly southwesterly winds with some west-northwesterly and easterly influence. Site 412, just north of Site 406, experienced southwesterly and northwesterly winds.

Site 401 on the western border of Wisconsin has a multi-directional pattern with winds from the northwest as well as from the south and the east. The centrally located sites, Sites 402 and 403, also have multi-directional patterns, experiencing winds from all direction.

Site 404 in the far north of the state experienced predominantly westerly winds and Site 413, also in the north, experienced predominantly southerly winds.

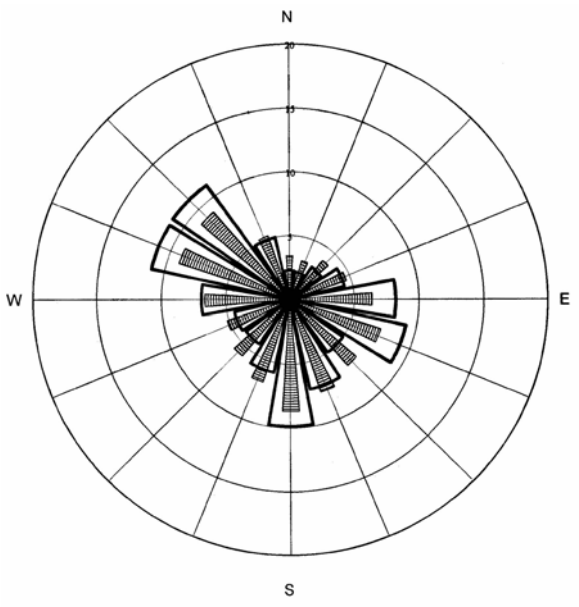

Figure 5. 401 – Spring Valley

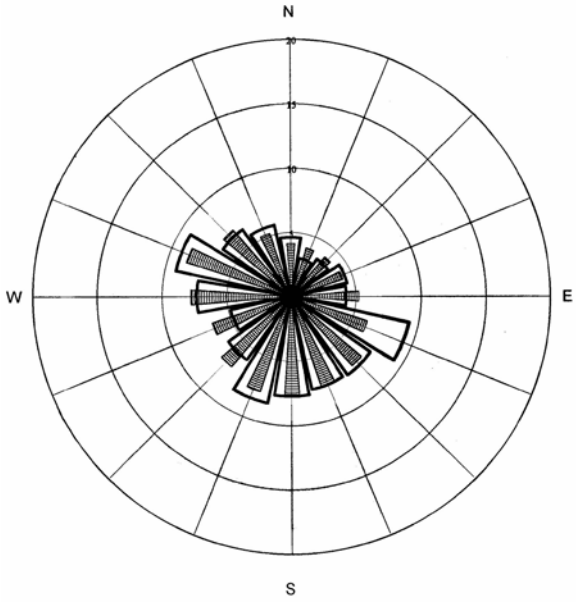

Figure 6. 402 – Abbotsford

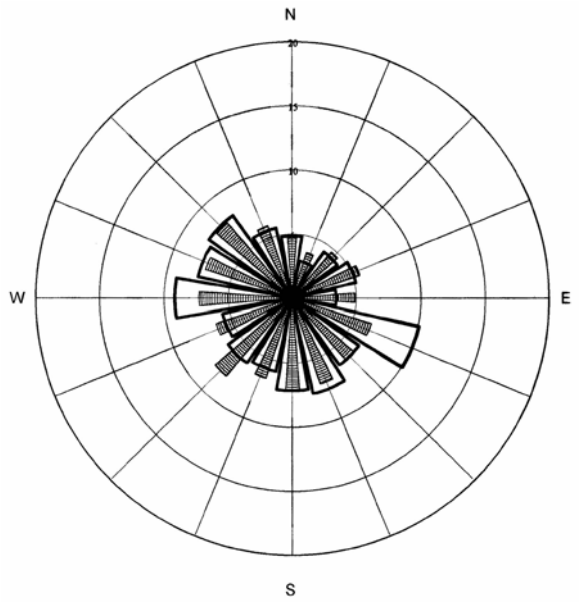

Figure 7. 403 – Rib Lake

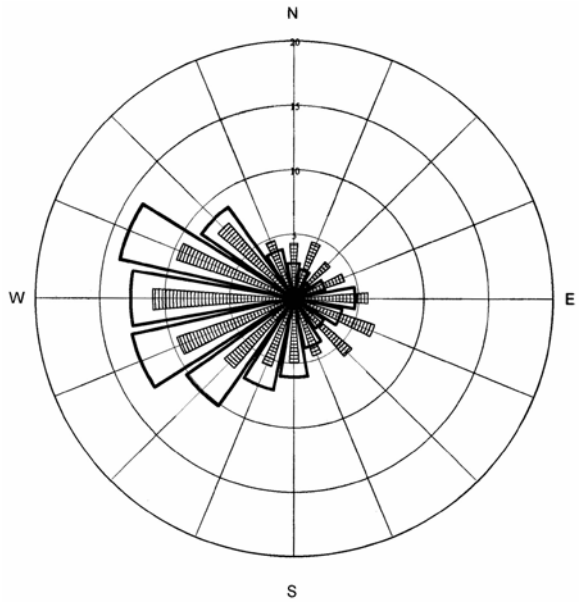

Figure 8. 404 – Cornucopia

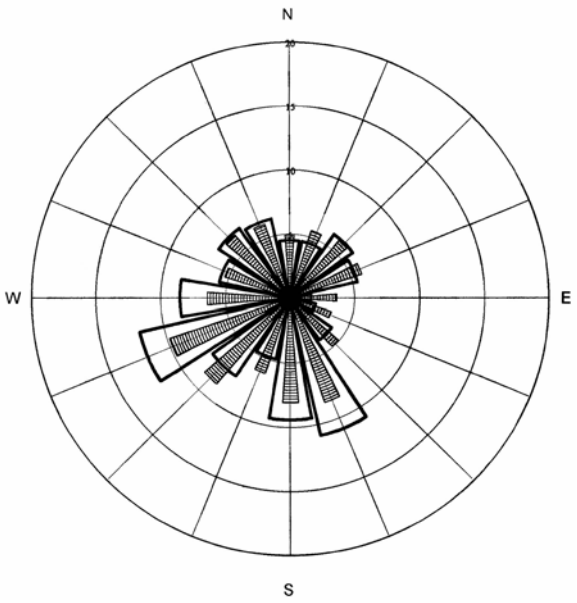

Figure 9. 405 – Sturgeon Bay

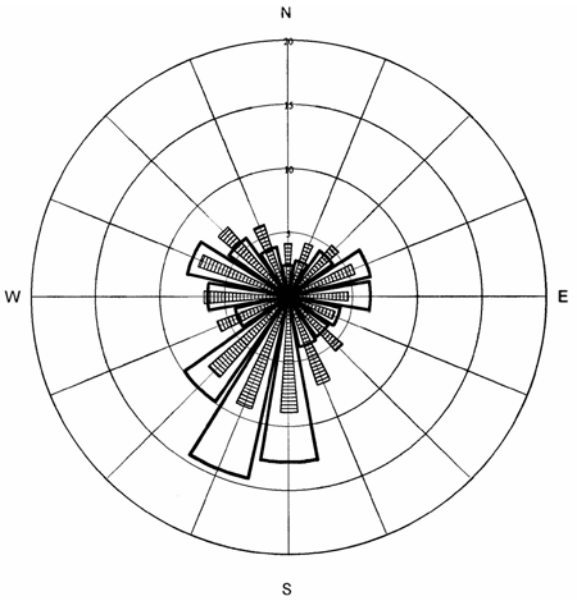

Figure 10. 406 – Montfort

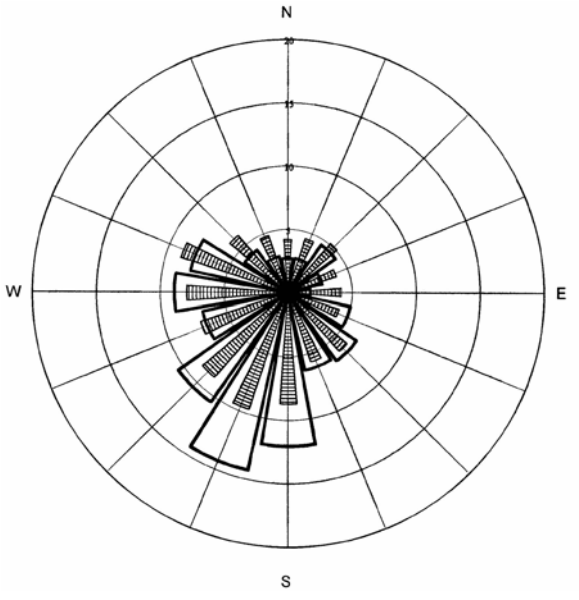

Figure 11. 407 – Rock River

Figure 12. 408 – Eden

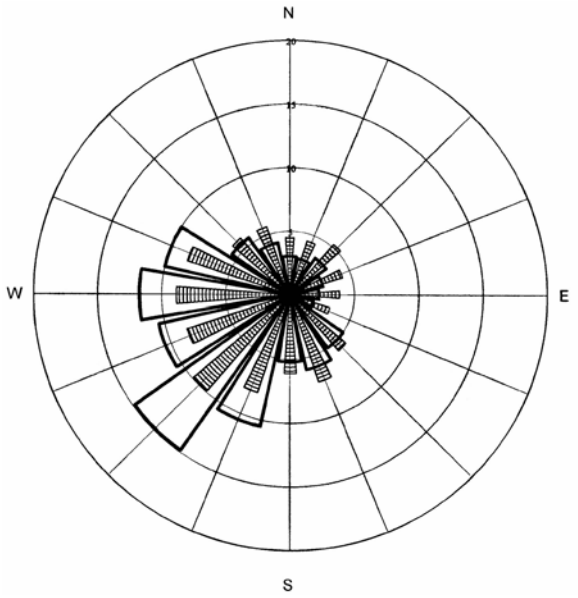

Figure 13. 409 – Honeymoon Hill

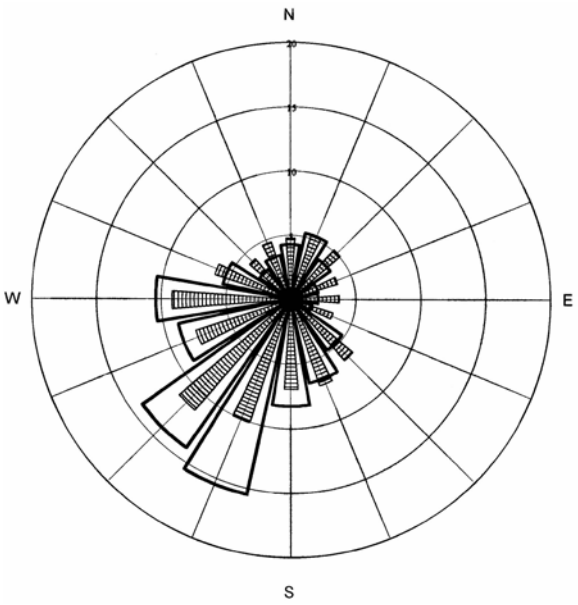

Figure 14. 410 – Wind Shear Study

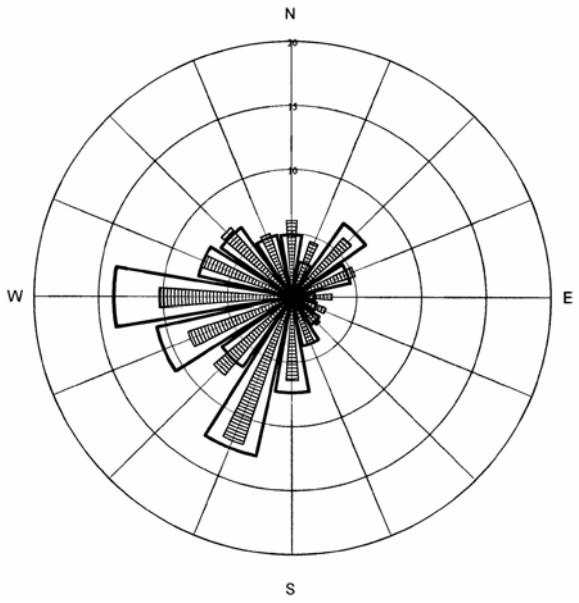

Figure 15. 411 – Clay Banks

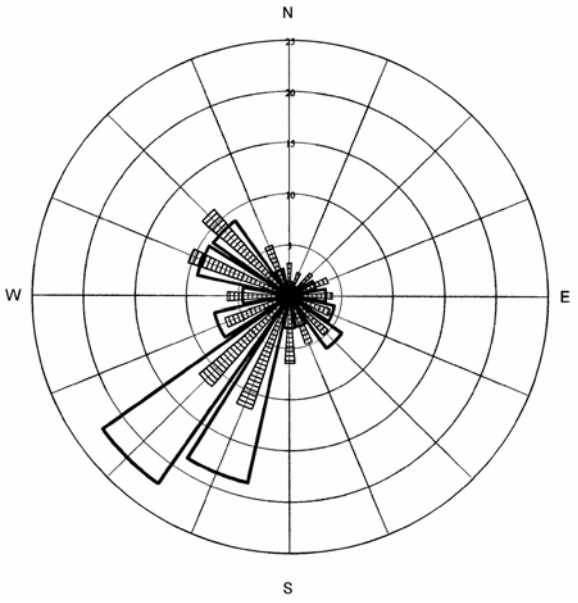

Figure 16. 412 – Tomah

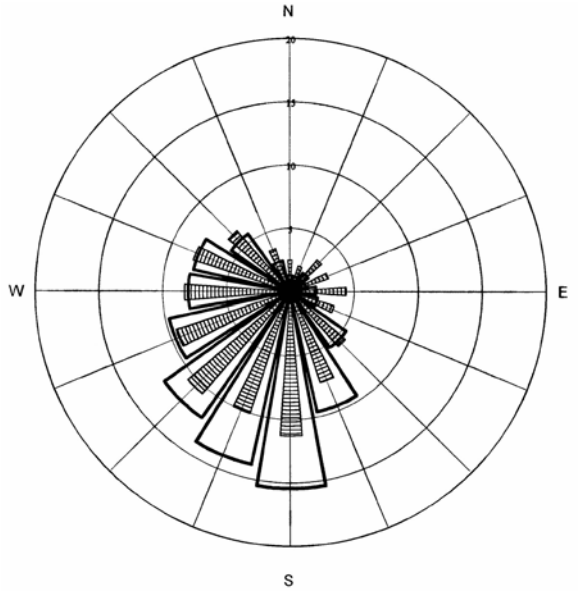

Figure 17. 413 – Hurley

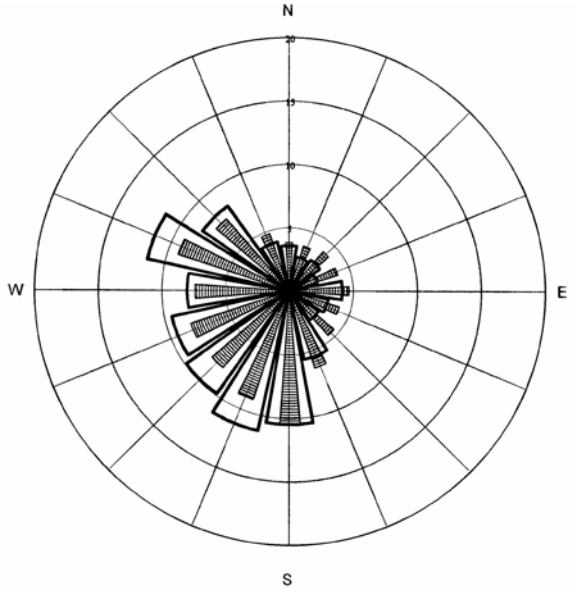

Figure 18. 414 – DeForest

WIND SHEAR

Wind shear is calculated based on the power law formula where wind speed is assumed to change exponentially with respect to height[3]. The theoretically derived value for wind shear over smooth, flat terrain is 0.14. The wind shear exponents at all fourteen of the Wisconsin sites are higher than this theoretical value. Table 7 provides a summary of the calculated wind shear exponent for all sites. For the purpose of this report, the wind shear exponent is calculated based on operable wind speeds greater than 4 m/s. With the exception of Site 410, the wind shear exponent is calculated between 25 and 40 meters for all sites, and between 25 and 60 meters when possible. At Site 410, the wind shear has been calculated for three height intervals between 60 meters and 123 meters. This information is valuable during wind project development in determining an optimal wind turbine hub height.

TURBULENCE INTENSITY

Turbulence intensity (TI) is a relative indicator of turbulence and not an absolute value. According to the American Wind Energy Association, a relatively low turbulence intensity is 0.10 or less, moderate turbulence intensity is indicated by values between 0.10 and 0.25, with high turbulence levels indicated by values above 0.25.

Turbulence intensity is calculated as the standard deviation of the wind speed divided by the average wind speed. As shown in Table 7, the average TI values from the predominant wind direction range from 0.10 to 0.17 for each site. The TI values are at the low end of the moderate range, indicating no significant concerns for wind energy development at any of the Wisconsin

[3] For wind speed (v_1 and v_2) at respective heights (h_1 and h_2), $v_2/v_1=(h_2/h_1)^{\alpha}$ where α is the wind shear exponent.

monitoring locations. TI values for all direction sectors are provided in the wind rose graphs included in the appendices of the semi-annual reports.

Table 7. Wind Shear and Turbulence Intensity

Site #	Site Name	Average TI (Predominant Direction)	Average Wind Shear Exponent 25m - 40m	Average Wind Shear Exponent 25m - 60m
401	Spring Valley	0.15	0.29	N/A
402	Abbotsford	0.13	0.27	N/A
403	Rib Lake	0.17	0.33	0.32
404	Cornucopia	0.17	0.20	0.23
405	Sturgeon Bay	0.13	0.44	0.39
406	Montfort	0.10	0.19	0.20
407	Rock River	0.11	0.32	0.29
408	Eden	0.11	0.23	0.19
409	Honeymoon Hill	0.11	0.19	N/A
410	Wind Shear Study*	0.11	N/A	0.27
411	Clay Banks	0.13	0.27	N/A
412	Tomah	0.13	0.20	0.23
413	Hurley	0.13	0.28	0.29
414	DeForest	0.10	0.29	0.23

*Shear Exponent actually measured between 37m-60m

Site #	Site Name	Average Wind Shear Exponent 60m - 83m	83m - 103m	103m - 123m
410	Wind Shear Study	0.31	0.18	0.21

APPENDIX

DATA REPLACEMENT TABLE