SUSTAINABLE AUTOMATION

WCROC Wind Resource Assessment August 2003 to July 2004

Final Report

1/7/2005

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Rev. 0

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Executive Summary

The West Central Research and Outreach Center has a long-term goal of building a renewable energy and research center comprising a variety of power generation, energy storage, and end use components. The first major component of the center will be a 1.65 MW wind turbine to be installed in March 2005. To be able to accurately project the performance of this wind turbine, and to more fully understand the characteristics of their local wind resource, in Spring 2003 WCROC contracted with Sustainable Automation LLC to conduct a year long wind resource assessment at the site. Sustainable Automation installed a meteorological tower and wind data logger in July 2003 and subsequently processed the logged data each month to generate a series of monthly reports. The present report is a summary of the data and conclusions from this year-long wind assessment.

Wind speed was measured at 30, 40, and 50 meters. By calculating a best-fit wind shear exponent of 0.244, the annual average wind speed at 70m (the proposed wind turbine hub height) was determined to be 7.35 m/s. The average 70m wind speed at the WCROC site is 5-7% higher than the measured wind speed at Alberta (15 miles to the west) and somewhat higher than is predicted by the Minnesota wind map published by the Minnesota Department of Commerce. The wind speed probability distribution was found to fit a Weibull curve with a shape factor k=2.33 and a scale factor c=8.28 m/s. Most months showed little or no average diurnal variation in wind speed. However, the wind was found to be highly directional, with NW and SE directions dominating.

Based on the measured characteristics, we calculated the energy output that would be achieved by various turbines installed at this site. The Vestas V82 turbine purchased by WCROC is expected to produce approximately 5,700 MWh per year, which will generate annual revenue to WCROC of about $228,000, assuming an energy sales price of $0.04/kWh.

1 Introduction

The West Central Research and Outreach Center has a long-term goal of building a renewable energy and research center comprising a variety of power generation, energy storage, and end use components. The first major component of the center will be a 1.65 MW wind turbine to be installed in March 2005. To be able to accurately project the performance of this wind turbine, and to more fully understand the characteristics of their local wind resource, in Spring 2003 WCROC contracted with Sustainable Automation LLC to conduct a year long wind resource assessment at the site. Sustainable Automation installed a meteorological tower and wind data logger in July 2003 and subsequently processed the logged data each month to generate a series of monthly reports. The present report is a summary of the data and conclusions from this year long wind assessment.

2 Wind Data Logging Equipment

2.1 *Tower*

WCROC purchased an NRG 60-meter Tall Tower (Figure 1) for this project. Subsequently, the manufacturer advised that in severe icing conditions, which are rare but not unheard of in west central Minnesota, the 60-meter tower could suffer structural failure and therefore recommended to leave off the top 10 meters of the tower.

Even at 50 meters, the tower is a tall and heavy structure. An accident while raising or lowering the tower could result in severe damage to the equipment and/or personnel. Sustainable Automation recommends that any future lower and/or raising of the tower be done (or at least supervised) by experienced tower installers with the proper equipment. We found the tower installation kit supplied by NRG to be inadequate to the task.

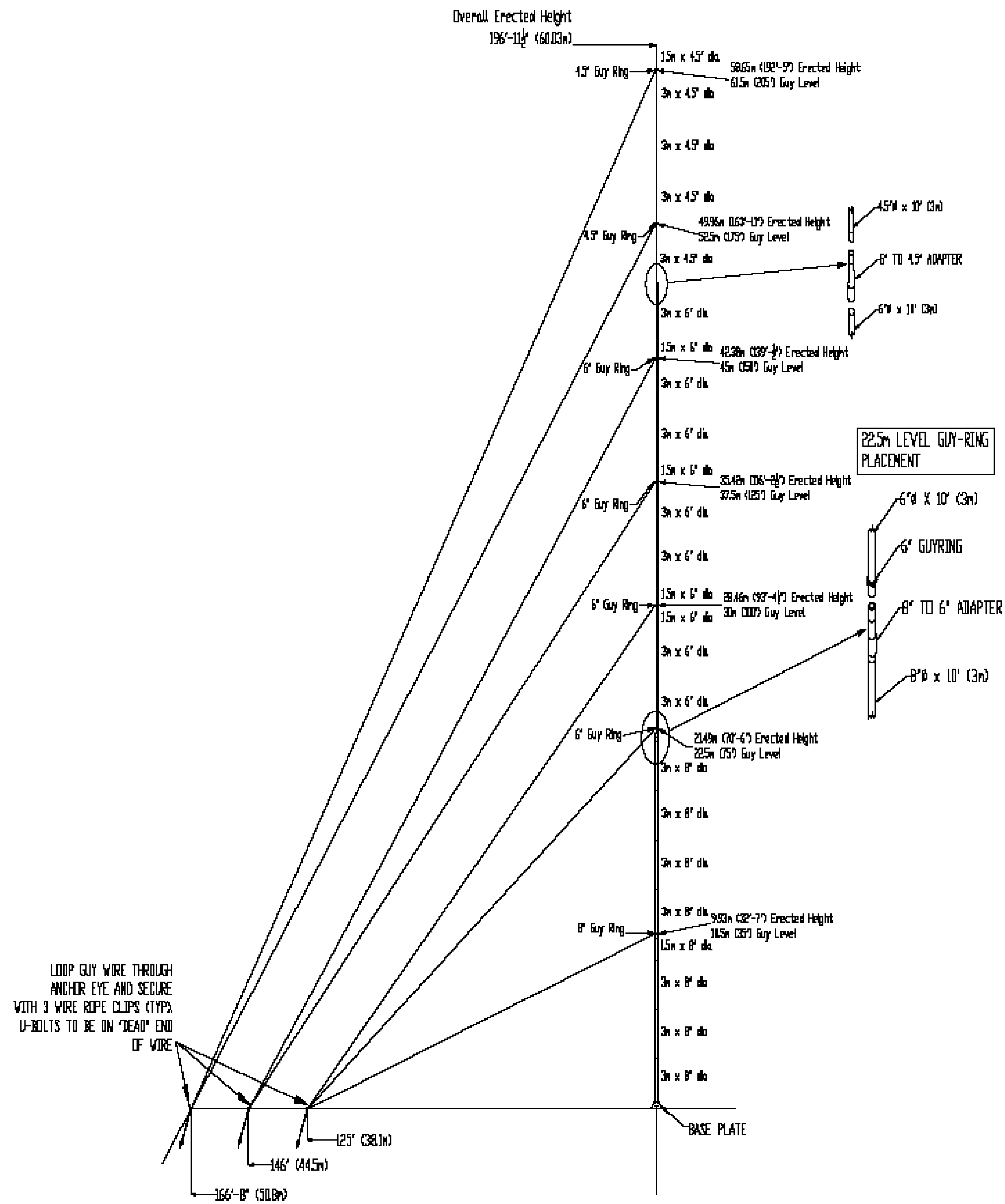


Figure 1 NRG 60m Tall Tower

2.2 *Instrumentation*

Ten different sensors are installed on the meteorological tower at WCROC. Their function and locations are shown in the table below.

Channel Number	**Elevation (m)**	**Measured Quantity**	**Sensor NRG Part Number**
1	50	Wind Speed	#40
2	50	Wind Speed	#40
3	40	Wind Speed	#40
4	40	Wind Speed	#40
5	30	Wind Speed	#40
6	30	Wind Speed	#40
7	50	Wind Direction	#200P
8	40	Wind Direction	#200P
9	2-3	Ambient Temperature	#110S
10	2-3	Atmospheric Pressure	#BP20

At each wind measurement level, there are two or three instrumentation booms that hold the sensors out away from the tower, one sensor per boom. The tower tilt plane is oriented in the 135/315 direction. At each level, on boom is oriented in the tower tilt plane, the other two (or one, in the case of the 30m level) are mounted perpendicular to this boom. The sensor boom orientation is as follows:

Channel Number	Elevation (m)	Sensor Type	Boom Heading (degrees)
1	50	Wind Speed	315 (NW)
2	50	Wind Speed	225 (SW)
3	40	Wind Speed	315 (NW)
4	40	Wind Speed	225 (SW)
5	30	Wind Speed	315 (NW)
6	30	Wind Speed	225 (SW)
7	50	Wind Direction	45 (NE)
8	40	Wind Direction	45 (NE)

2.3 *Data Logger*

All of the sensors are connected to a NRG Symphonie Data Logger, equipped with an iPack analog cellular communication module. At 10-minute intervals, the data logger records the average, standard deviation, maximum, and minimum value of each data channel for the preceding 10-minute period. The data is stored on a small plug-in memory card. Once a week the data logger places a cellular telephone call to a local ISP access number. Once the phone connection is made, the data logger automatically logs onto its ISP account and emails data files, one per 24-hour period, to the email addresses specified in the data logger setup file.

Detailed information on the cellular and Internet service accounts is provided in the following sections.

2.4 *Cellular Service*

Parameter	Value
Symphonie Data Logger Serial Number	30901080
Cellular Service Provider	Cellular 2000 http://www.rccwireless.com/zone40/ Customer Service: 800-450-8255 Morris Electronics (Agent) 511 Atlantic Ave, Morris, MN 56267 320-589-1781
ESN (found on AMPS iPack label	214-00289646
MIN (supplied by cellular service provider)	320-287-0520
SID (supplied by cellular service provider)	01370
System Preference (supplied by cellular service provider)	System B
Antenna Location	West of Cyrus along Rte. 28

2.5 *Internet Service Provider*

Parameter	Value
Internet Service Provider	ISP West http://www.ispwest.com/ 866-477-9378
Service Prepaid Through	7/16/2005
Username	wcroc
Password	morris
Mailbox Name	wcroc@ispwest.com
Mailbox Password	morris
Primary ISP Dialup Phone Number	320-231-0125
Primary DNS Number	4.2.2.1
Secondary DNS Number	4.2.2.2
Authentication Method	PAP
SMTP Server Name	smtp.ispwest.com
POP3 Server Name	Pop3.ispwest.com
Symphonie Patch Password	revision

3 Wind Resource Characteristics

3.1 *Wind Direction*

A wind rose is a polar plot that represents the percentage of time that the wind direction falls within each sector of the compass. Figure 2 shows a wind rose for each month of the year as measured during the period 8/2003 – 7/2004. These wind roses are based on the wind vane measurements at 50m, which should closely match the wind direction profile at 70m.

Note that for most months of the year, the wind direction distribution is strongly bipolar in that the wind is from the NW or the SE nearly all of the time. This is not of great significance at a single turbine site with relative flat and unobstructed terrain, but if additional turbines were to be added in the future, it would be important to lay out the turbine row perpendicular the prevailing wind directions.

3.1 *Wind Speed*

Wind speed is the most important aspect of the wind resource, because there is a direct relationship between wind speed and wind turbine power output. At the time this wind resource assessment, it was not known which wind turbine(s) would ultimately be installed at WCROC, but it was anticipated that the individual turbines would be of less than 1 MW capacity with a hub height of around 50 meters. Therefore, measuring wind speeds at various levels up to 50 m seemed appropriate. Additionally, it becomes considerably more expensive to install very tall met towers allowing measurements at 70 m and higher. Ultimately, however, a turbine with a 70 m hub height was selected, so now we are primarily interested at the wind resource at 70 m. The first step then is to intelligently extrapolate the wind speed data collected at the lower heights. The next section describes this procedure.

3.1.1 Vertical Wind Shear

This variation of wind speed with height is called *wind shear*. Wind energy engineers typically model wind shear using one of two mathematical models, the logarithmic profile or the power law profile. The latter is used in our analysis.

The power law profile assumes that the ratio of wind speeds at different heights is given by the following equation:

$$\frac{v(z_{hub})}{v(z_{anem})} = \left(\frac{z_{hub}}{z_{anem}}\right)^{\alpha}$$

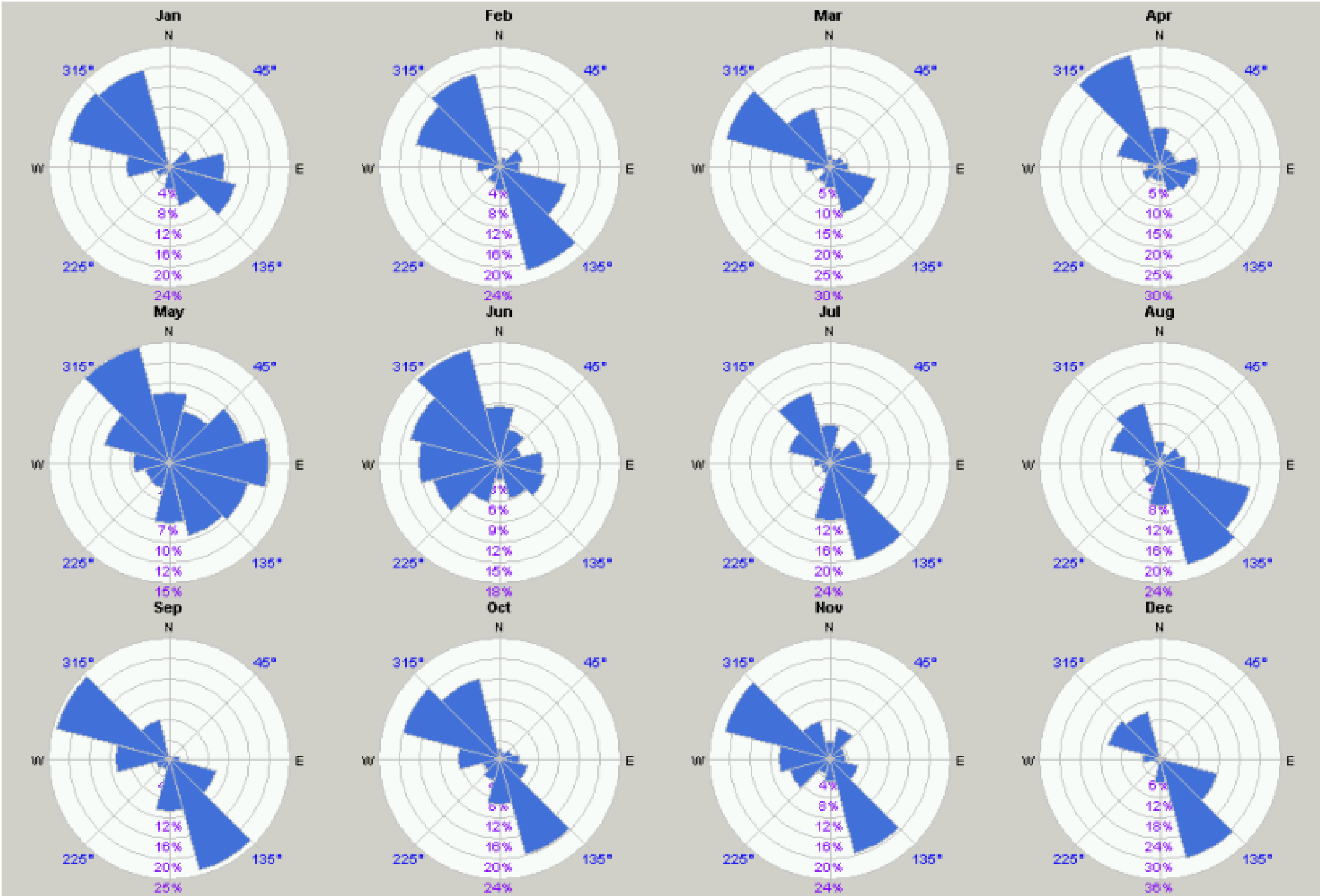


Figure 2 Monthly Wind Roses at WCROC Site (8/2003 - 7/2004)

where:

z_{hub} = the hub height of the wind turbine [m]
z_{anem} = the anemometer height [m]
α = the power law exponent
$v(z_{hub})$= wind speed at the hub height of the wind turbine [m/s]
$v(z_{anem})$= wind speed at anemometer height [m/s]

The power law exponent is a dimensionless parameter and is equal to 1/7 for turbulent flow over a flat plate. Wind speed researchers, however, have found that in practice the power law exponent depends on temperature, season, terrain roughness, and several other factors. To determine the most appropriate value for the WCROC site, we computed the wind shear exponent to fit the 40 and 50-meter data for each 10-minute logging interval and then averaged them. We also computed the 70-meter average wind speed using the shear exponent determined for each 10-minute period. Whether one computes the annual average 70-meter wind speed by averaging the extrapolated wind speeds for each data logging interval or by extrapolating the 50-meter annual average using the annual average shear exponent, the results are very nearly the same.

Figure 3 shows the results of this analysis. The data points indicated by little squares represent the actual measured annual average wind speed at 30, 40, and 50 meters respectively. The best-fit wind shear exponent between the 40 and 50-meter data was found to be 0.244. This agrees well with the Minnesota Dept. of Commerce data from the Alberta, MN met tower (Alberta is 15 miles west of Morris), which showed that the average wind shear exponent between 50 and 70 meters was 0.22 for the period 1995-98, with the annual averages varying between 0.21 and 0.26.

3.1.2 Average Wind Speed

The monthly and annual average wind speeds at 30, 40, 50, and 70 meters are shown in Table 2.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
30m	6.54	6.07	7.02	6.55	6.63	5.03	4.16	4.73	5.90	5.79	6.43	6.76	5.97
40m	6.91	6.47	7.49	7.00	7.08	5.47	4.60	5.18	6.41	6.32	7.05	7.24	6.43
50m	7.16	6.85	7.84	7.32	7.33	5.70	4.86	5.55	6.85	6.77	7.49	7.59	6.77
70m*	7.77	7.44	8.51	7.95	7.96	6.19	5.28	6.02	7.44	7.35	8.13	8.24	7.35

*Calculated using shear exponent.

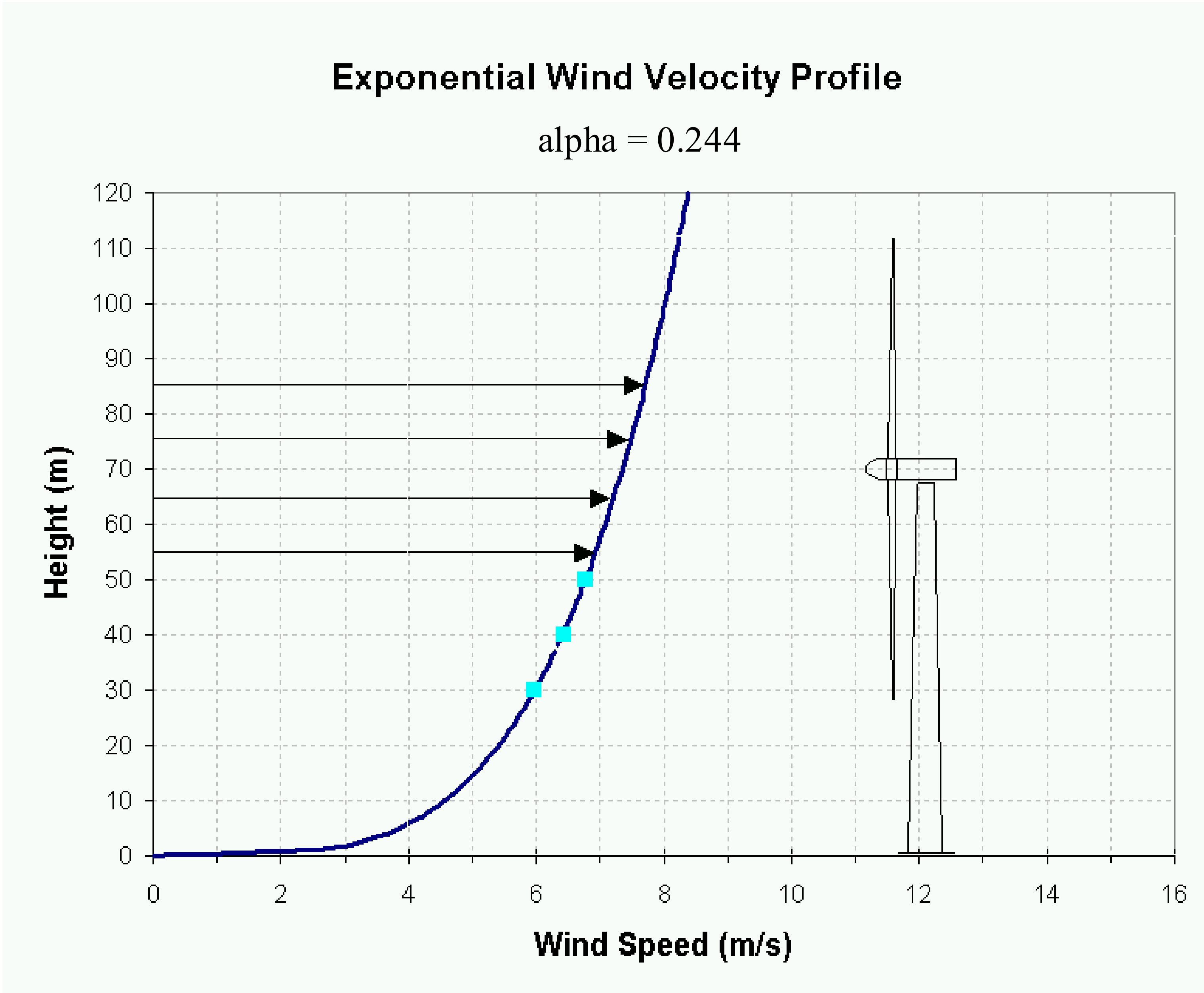


Figure 3 Annual Average Wind Shear at WCROC Site

Figure 4 shows the monthly and annual average wind speed along with the maximum and minimum daily averages and maximum and minimum instantaneous wind speeds for each month. The graph shows that the minute-to-minute and even day-to-day variation in wind speed throughout the year is greater than the variation in the monthly averages. Even though occasionally the wind is completely calm, the indicated wind speed never drops below 0.4 m/s due to a required offset in the anemometer calibration.

3.1.3 Wind Speed Distribution

As one can see in Figure 5, the wind speed at the WCROC site is highly variable throughout the year. It is useful to plot the wind speed probability distribution function (the percentage of time that the wind spends at each speed) to understand the character of this seemingly random variation.

The two-parameter Weibull distribution is often used to characterize wind regimes because it has been found to provide a good fit with measured wind data. The probability density function is given by the following equation:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$

where *v* is the wind speed, *k* is a dimensionless shape factor, and *c* is a scale parameter with the same units as *v*. The cumulative distribution function is given by the following equation:

The two parameters c and *k* are related to the average wind speed by the following expression:

$$\bar{v} = c\Gamma\left(\frac{1}{k} + 1\right)$$

where Γ is the gamma function.

Any Weibull distribution can therefore be described by the average wind speed and the Weibull *k* value. The Weibull *k* value is an indication of the breadth of the distribution of wind speeds. In Figure 6, three Weibull distributions are plotted, all with the same average wind speed of 6 m/s. It can be seen in this graph that lower *k* values correspond to broader distributions. There is

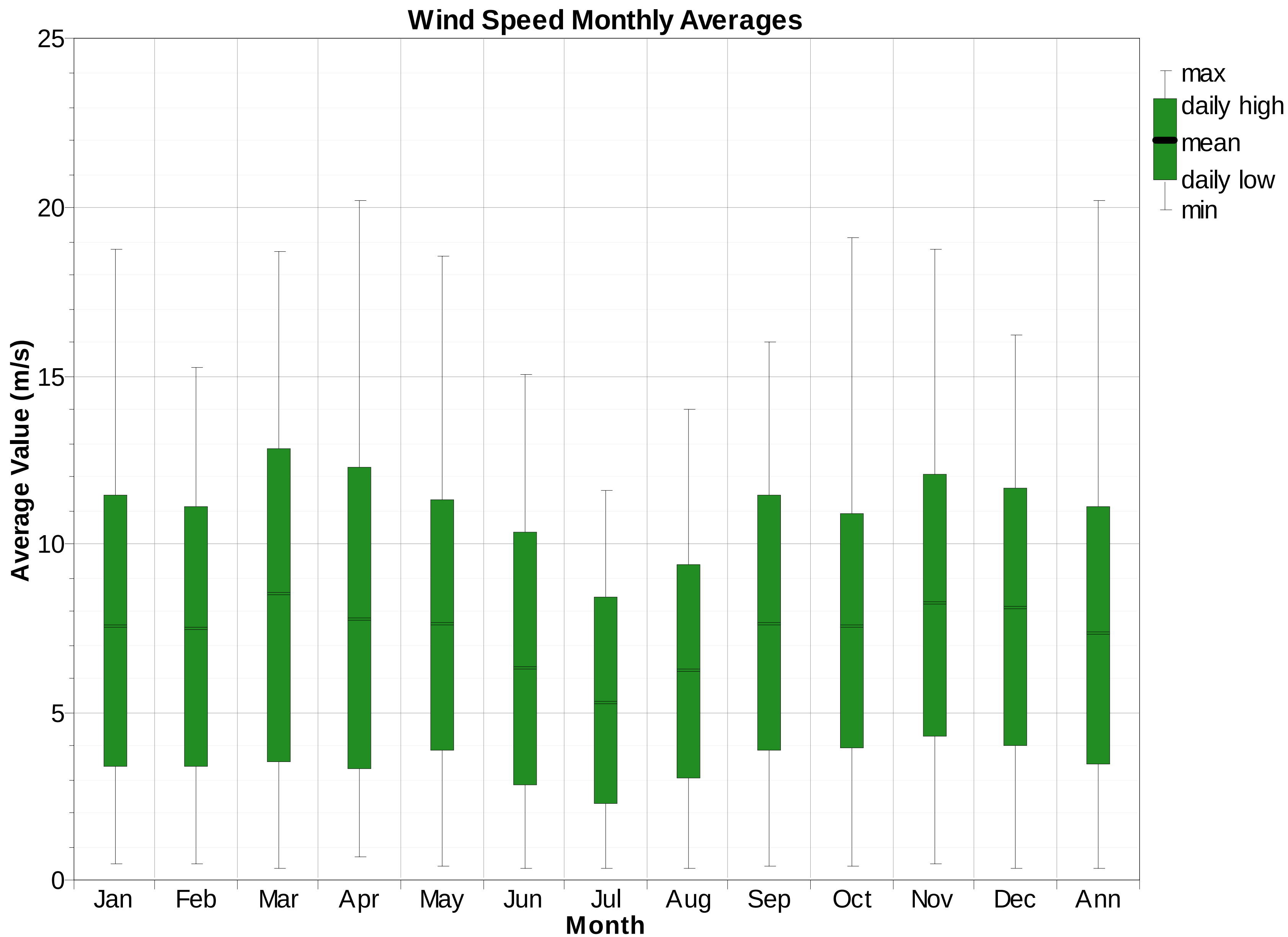


Figure 4 Monthly Max, Min, and Average Wind Speeds at 70 Meter

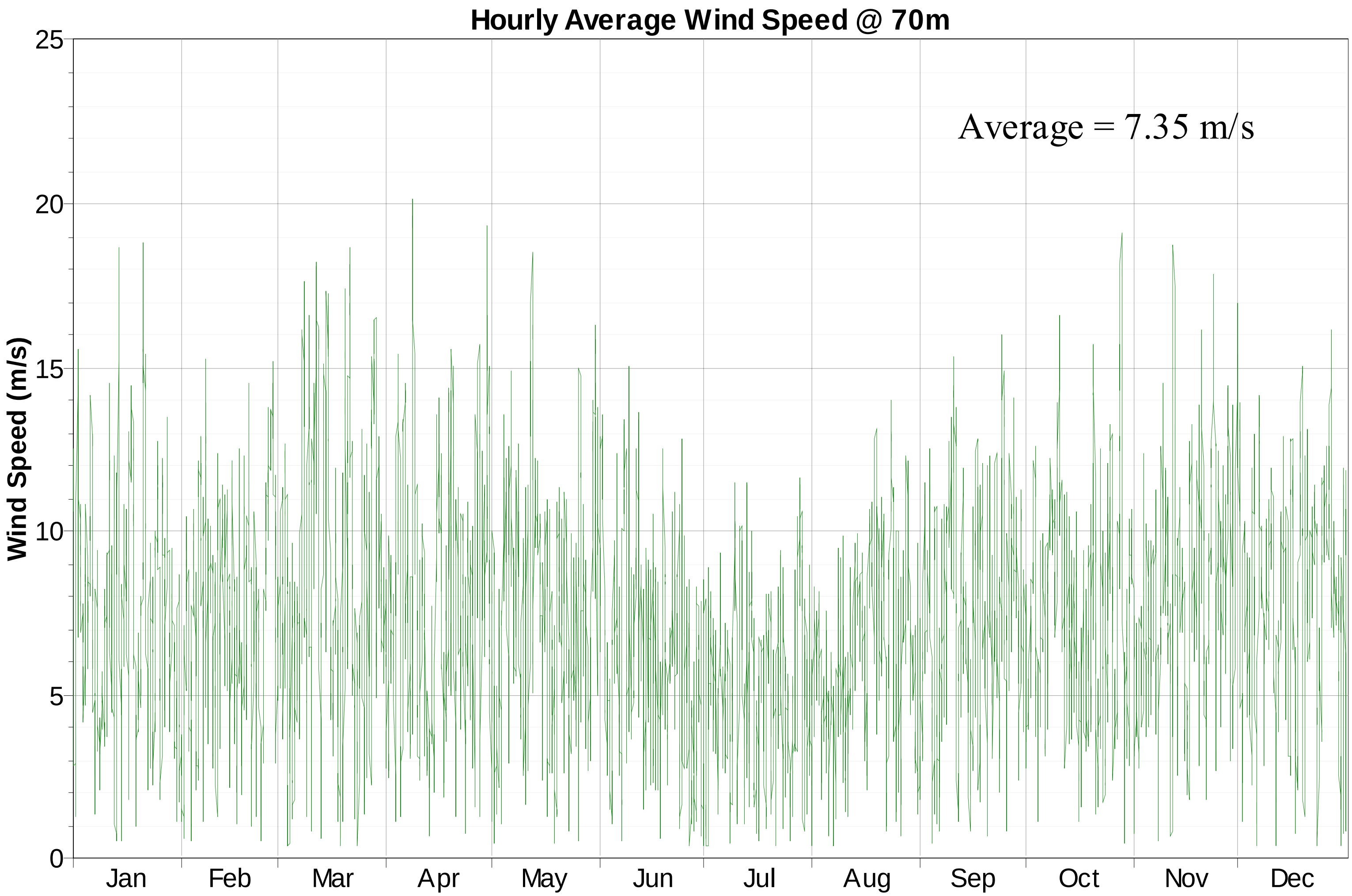


Figure 5 Hourly Average WCROC Wind Speed During the Study Period

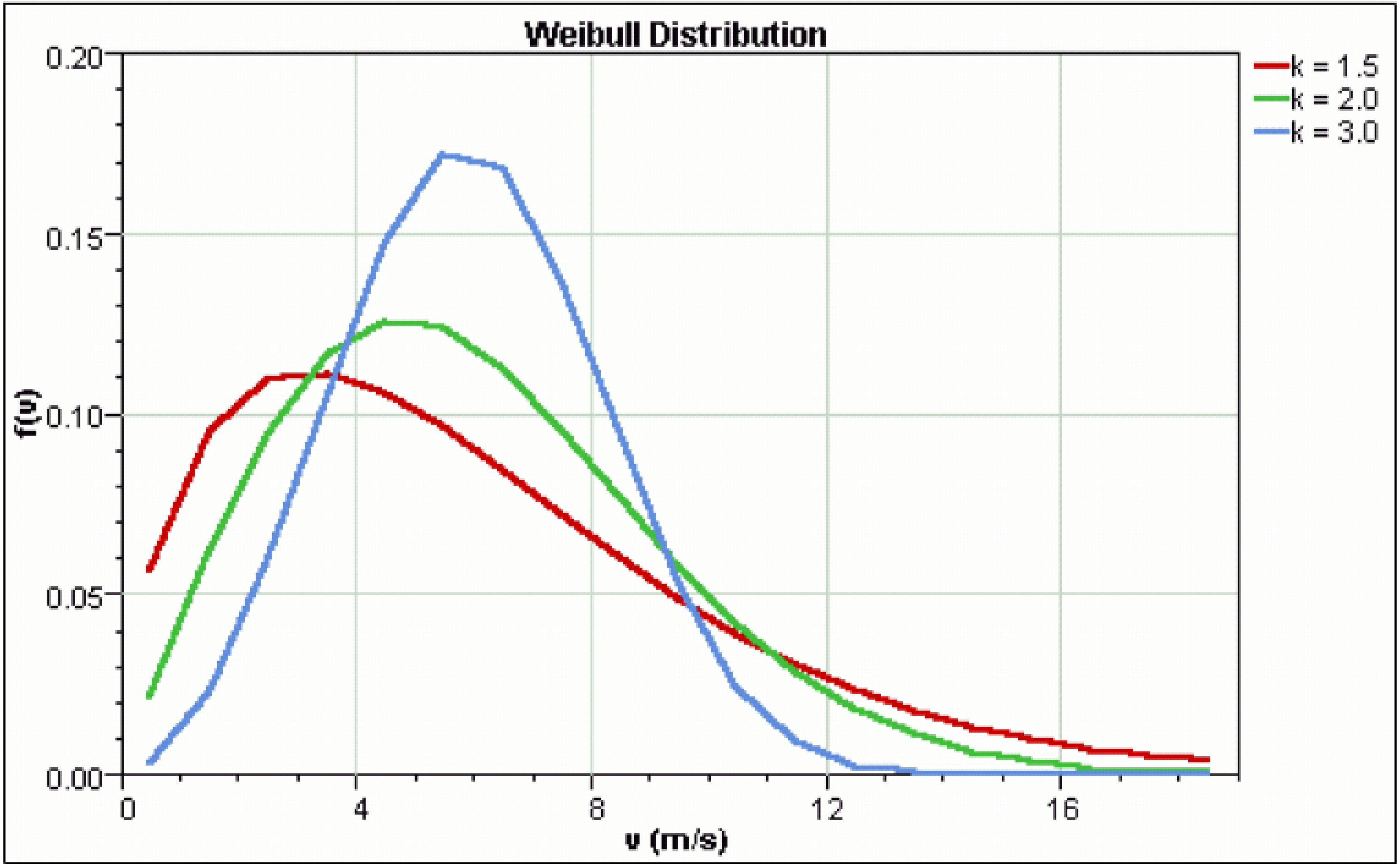


Figure 6 Effect of k Factor on Weibull Distributions

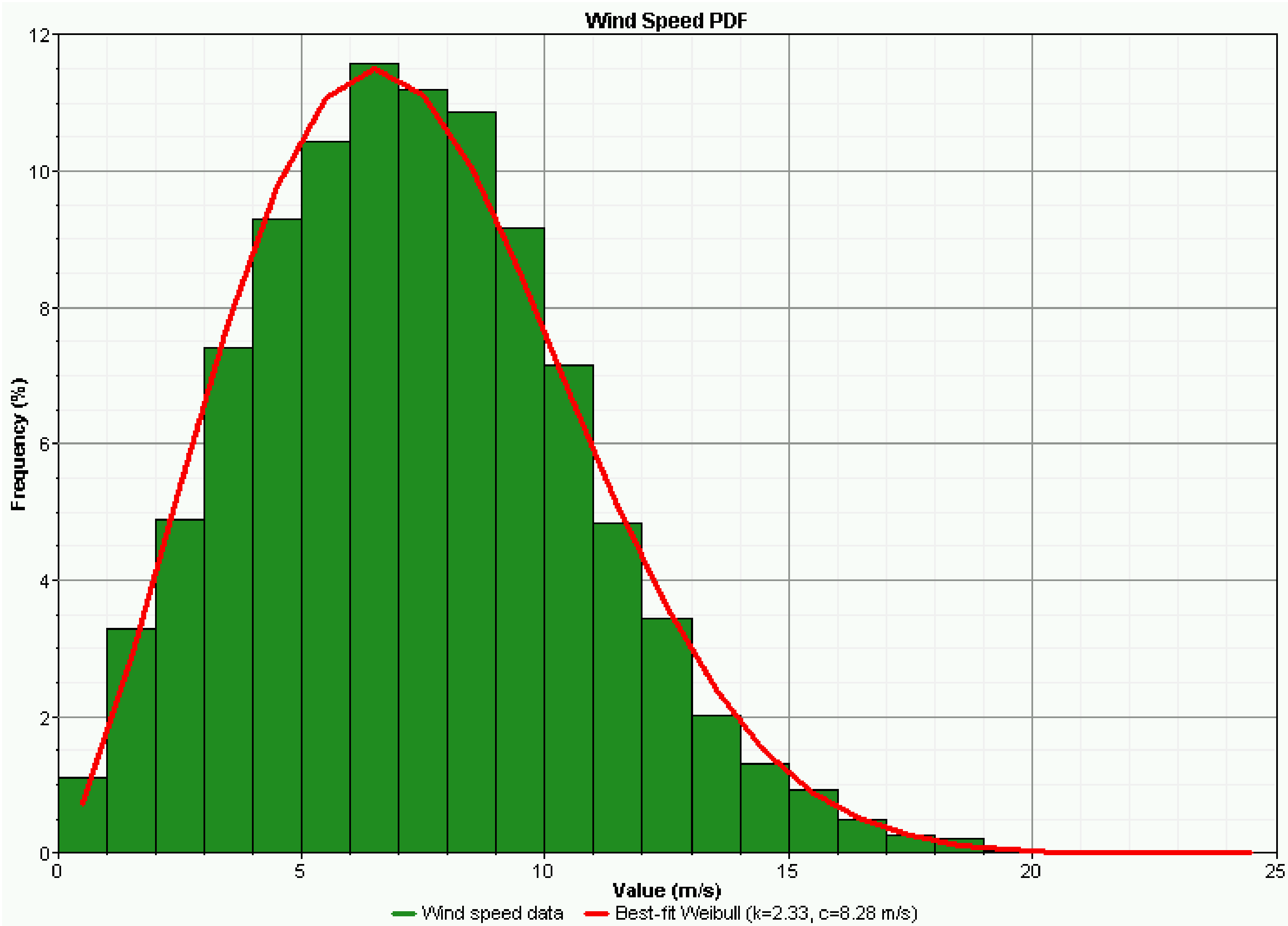


Figure 7 Wind Speed Probability Distribution

some correlation between the Weibull *k* value and the average wind speed. In general, lower average wind speeds correspond to lower Weibull *k* values, and vice versa.

Figure 7 shows the probability distribution of the extrapolated 70m wind speed data for the WCROC site and the resulting best fit Weibull distribution. The Weibull parameters were found to be k=2.33 and c=8.28 m/s. Knowing these parameters for a site makes it easy to estimate the wind energy production of a particular turbine without needing hourly wind data for a whole year.

We did not observe a strong diurnal profile (wind speed versus time of day) at the WCROC site, other than that during June through October, the average wind speed was slightly lower during the morning from about 8:00 AM to noon.

3.1.4 Turbulence Intensity

Turbulence intensity is defined as the standard deviation of wind speed divided by the average wind speed for a particular measurement period. The average 10-minute turbulence intensity for the WCROC was measured to be as follows:

Anemometer Height	Turbulence Intensity
30m	.15
40m	.13
50m	.13

These are relatively low turbulence intensity numbers and of no great concern. As one would expect at a plains site, the wind becomes less turbulent as one moves away from the ground and is therefore further from the influence of surface roughness and obstructions. It is expected that the turbulence intensity at 70 meters is as low or lower than that at 50 meters. Also, a review of the monthly data shows that the turbulence intensity during the winter high wind months (0.11 – 0.12 at 50 meters) is less than during the less windy summer months (0.15 – 0.16 at 50 meters). This is probably explained by the reduced turbulence due to thermal convection during the winter months.

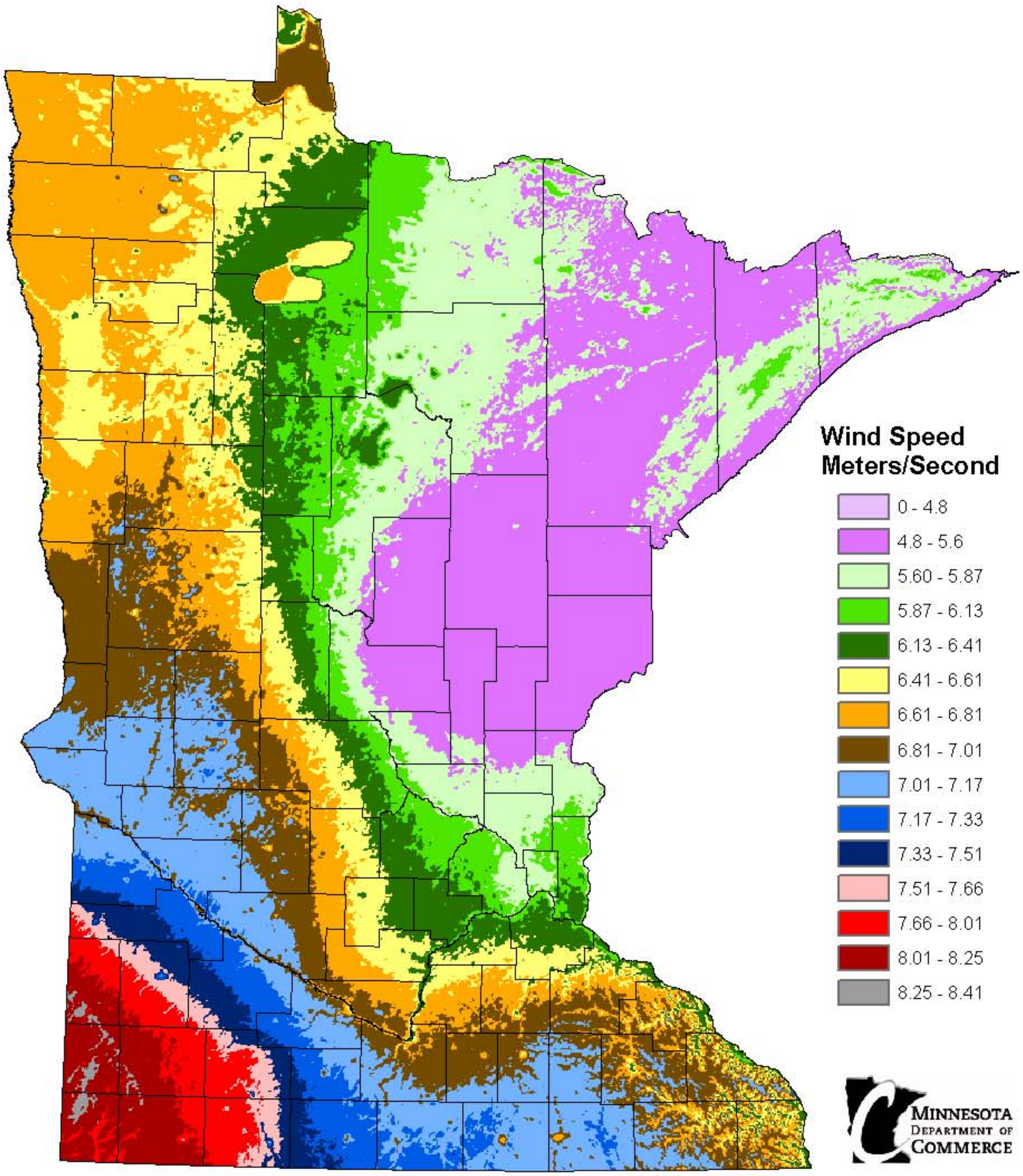
3.2 *Comparison with Data from Alberta, MN*

The Minnesota Department of Commerce has been collecting wind data at various locations around the state for about the last 10 years. One of these sites is in Alberta, MN, about 15 miles to the west of Morris (where WCROC is located). According to the "Wind Resource Analysis Program Report – 2002" published by the Department of Commerce, the average 70m wind speed at Alberta for the period 1995-2001 was 7.0 m/s, with a minimum annual average of 5.9 and a maximum annual average of 7.3. We have found many errors and gaps in the raw data we have seen from the Alberta site, and we do not know how much quality control was performed on the data before determining annual averages. Assuming the Alberta numbers are correct, if we compare the long-term average wind speed at Alberta with the WCROC average over our study period, we find that the WCROC average is 5% higher (7.35/7.0 = 1.05). However, our study period may have been an unusually windy year for the region, so from this data alone, we cannot claim that the WCROC site has a significantly better resource. We need to compare the sites for the same time period. We were able to obtain the Alberta data for our study period of 8/2003 to 7/2004. There are many errors and gaps in this data, but by considering the good data (7718 hours out of a possible 8760), we were able to compute approximate monthly averages for the 70m wind speed at Alberta. These are shown in the table below. One can see that over the same measurement period, the WCROC wind speed is significantly higher in most months. The annual average is 7% better at the Morris site (7.35/6.87 = 1.07).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Alberta	7.86	7.34	7.26	5.81	4.77	5.26	7.31	7.12	7.79	7.71	7.86	7.34	6.87
WCROC	7.77	7.44	8.51	7.95	7.96	6.19	5.28	6.02	7.44	7.35	8.13	8.24	7.35

Figure 8 shows the Minnesota Department of Commerce Map of Wind Speed at 70 meters for the entire state. Alberta and Morris are in Stevens County in the light blue band, which signifies an average wind speed between 7.01 and 7.17 meters per second. While Alberta appears to be generally at the low end of this range, the present study indicates that Morris is higher than this range. If 8/2003 – 7/2004 was a less windy year than average than normal, as suggested by the Alberta average of 6.87 m/s, then the true long term average at Morris may be approximately 7.5 m/s ((7.0/6.87) x 7.35 = 7.51). Thus, the current state wind map appears to underestimate the wind resource at least for certain sites in West Central Minnesota.

Minnesota's Wind Resource by Wind Speed at 70 Meters



The Department of Commerce prepared this map using the WindMap program, which takes into account wind data, topography, and land use characteristics. Data is averaged over a cell area 750 meters square, and within any one cell there could easily be features that could increase or decrease the results shown on this map. Regions with the greatest concentrations of monitoring sites show the most accurate results. This map shows the general variation of Minnesota's wind resource and should not be used to determine the performance of specific projects.

June 2002

Figure 8

4 Wind Turbine Productivity

In the context of wind energy production, what is of greatest interest is how the wind characteristics are reflected in the actual performance of a particular wind turbine. There is not a simple or obvious mathematical relationship between the energy contained in the wind and the amount of energy a given wind turbine will produce. In each case, it depends on the shape of the wind turbine's power curve (the amount of electric power the turbine produces at each wind speed). In this section, we examine the productivity of several different wind turbines if installed at the WCROC site or any site with a similar wind regime.

4.1 *Vestas V82-1.65MW*

The turbine selected for the WCROC renewable energy demonstration center is the Vestas V82, with a rated capacity of 1.65 MW. The power curve for this turbine is shown in Figure 9. When modeled using the hourly wind speed collected in the WCROC wind resource assessment, the project daily average output over the course of a year is as shown in Figure 10. While this power versus time graph looks similar to the wind speed versus time graph, its probability distribution does not at all resemble a Weibull distribution. As shown in Figure 11, there is a large spike at 1650 kW, reflecting the fact that the wind turbine spends a substantial amount of time at rated power.

Another way of depicting the amount of time the wind turbine spends at various output levels is by the so-called wind power duration curve, as shown in Figure 12. Each point on the curve represents the number of hours that the wind turbine output is equal to or greater than a certain level. The figure shows that for approximately 10% of the year, or 900 hours, the turbine is operating at rated power. It also indicates that the turbine is producing at least some power about 90%ofthetime.

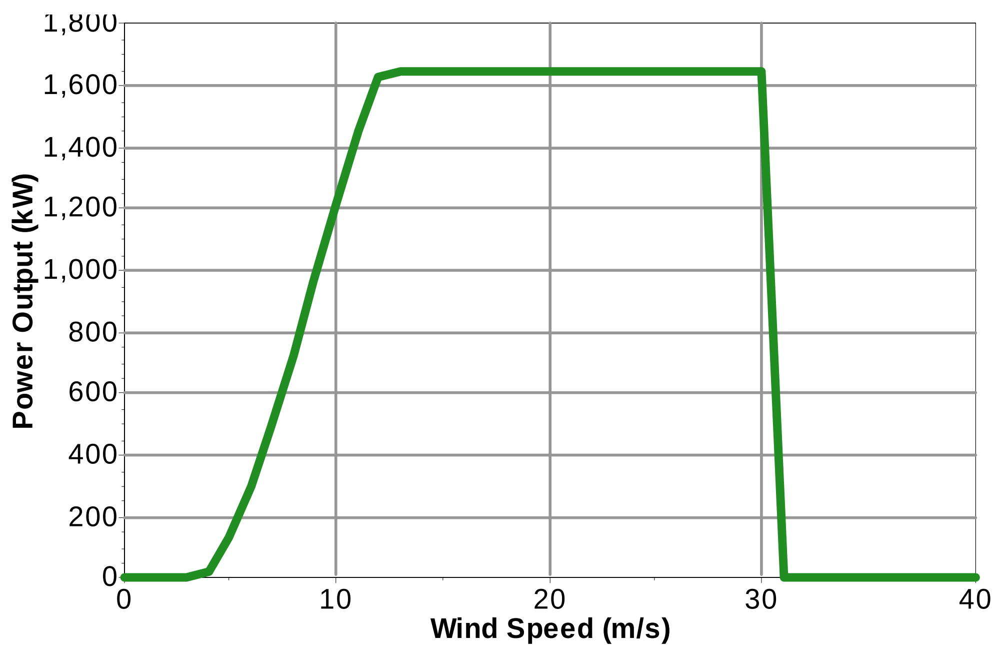


Figure 9 Power Curve for Vestas V82 - 1.65MW

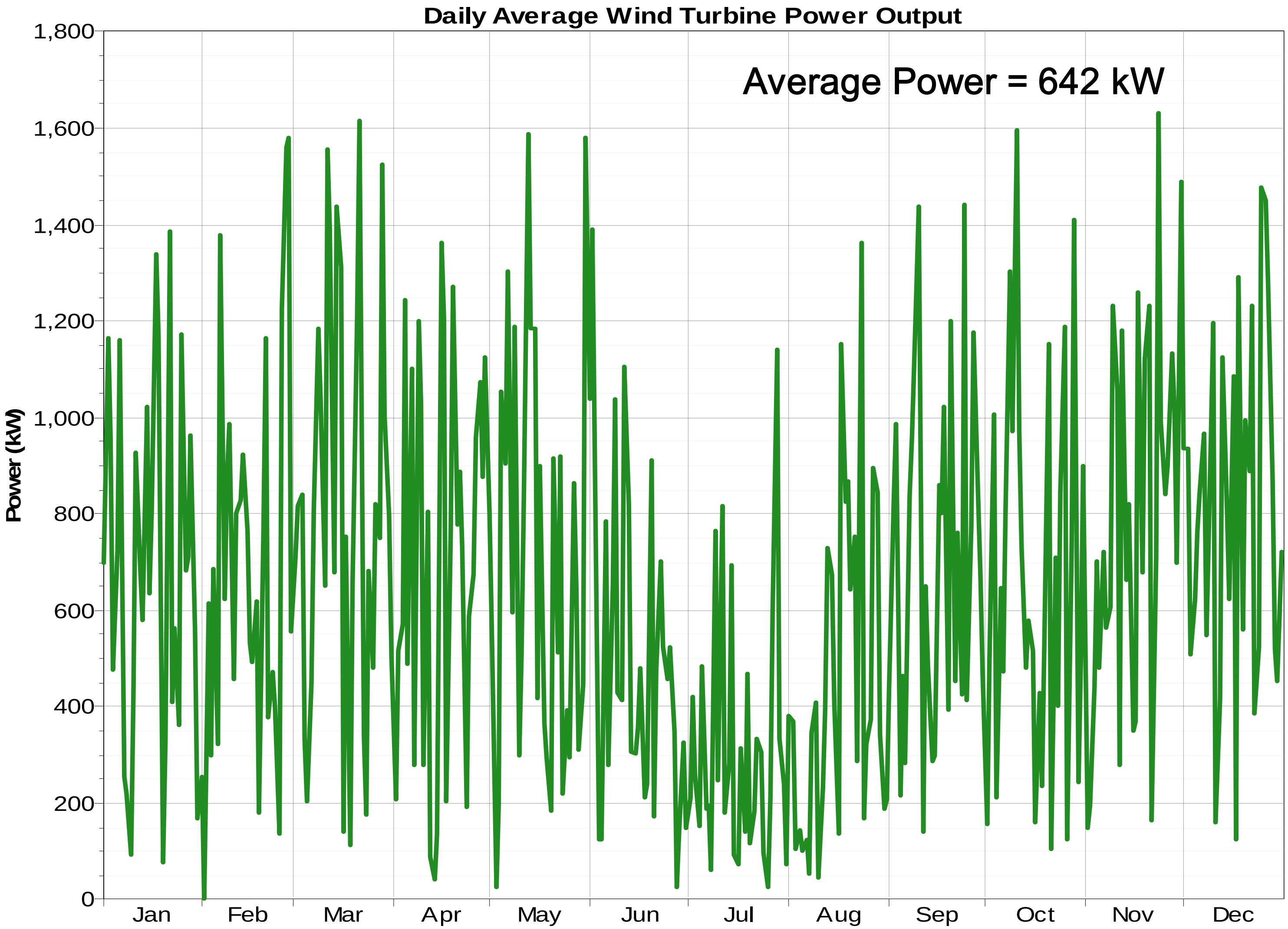

Daily Average Wind Turbine Power Output
Average Power = 642 kW
Power (kW)
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 10

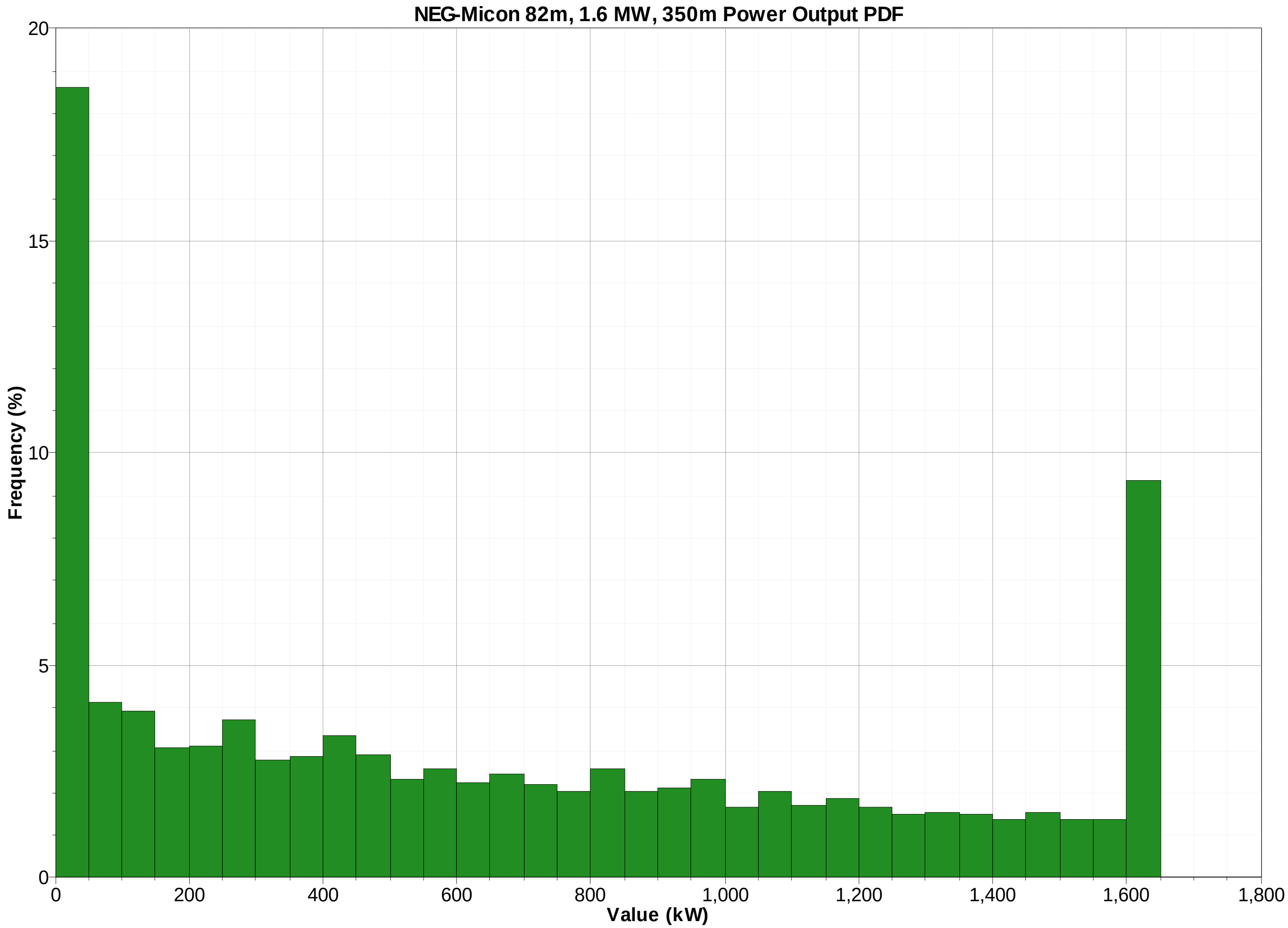

NEG-Micon 82m, 1.6 MW, 350m Power Output PDF
Frequency (%)
20
15
10
5
0
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
Value (kW)

Figure 11

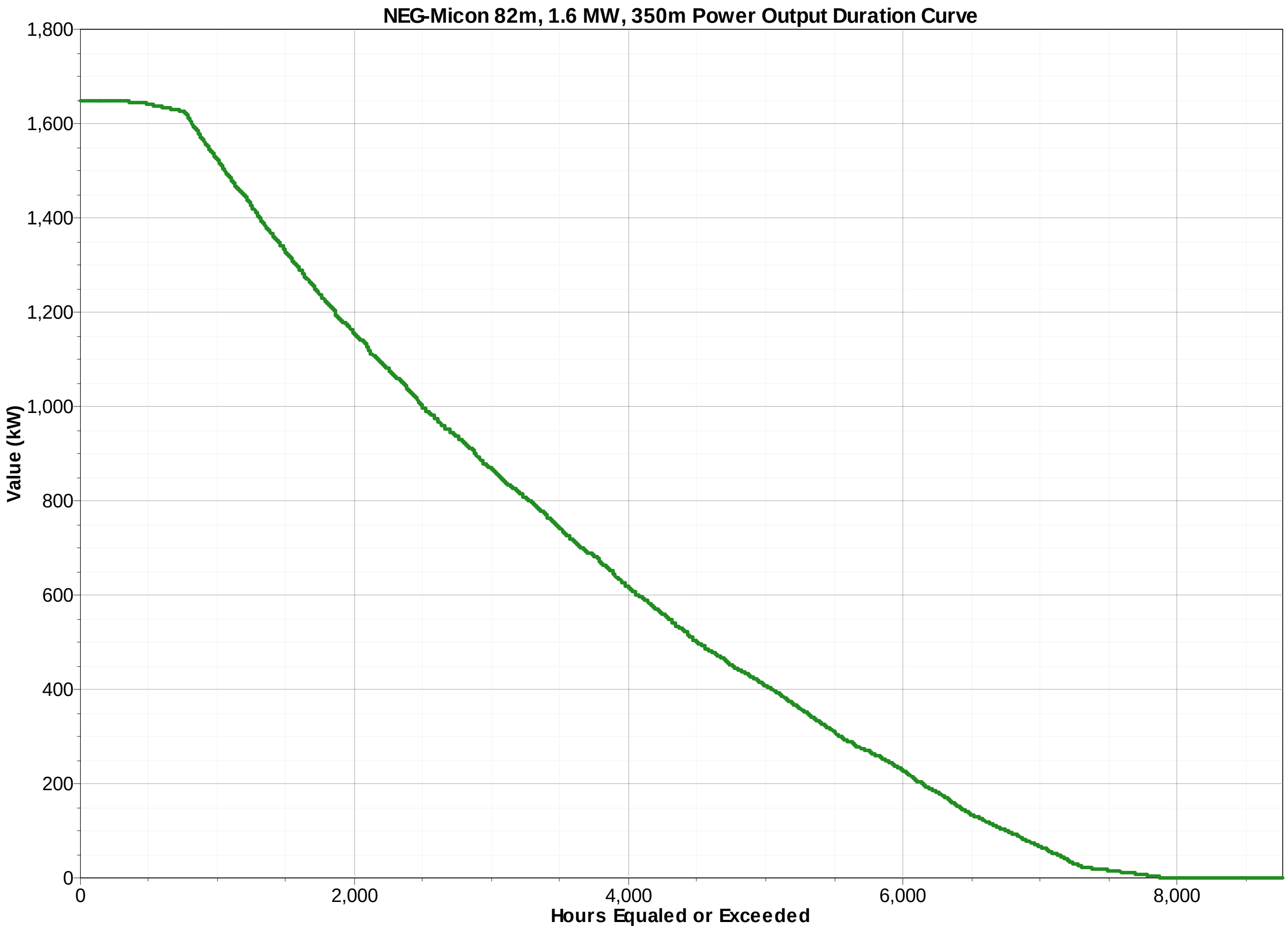

NEG-Micon 82m, 1.6 MW, 350m Power Output Duration Curve
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Value (kW)
0
2,000
4,000
6,000
8,000
Hours Equaled or Exceeded

Figure 12

The table below shows the estimated wind turbine monthly revenue based on an electric energy sales price of $0.04/kWh.

Month	Energy Sold	Revenue
	(kWh)	($)
Jan	503,815	20,153
Feb	471,204	18,848
Mar	599,599	23,984
Apr	515,898	20,636
May	521,202	20,848
Jun	344,203	13,768
Jul	233,056	9,322
Aug	333,291	13,332
Sep	510,541	20,422
Oct	495,058	19,802
Nov	568,706	22,748
Dec	606,968	24,279
Annual	5,703,541	$228,142

Electric Energy Sales Price = $0.04/kWh

The table below shows the projected reduction in emissions of the major atmospheric pollutants associated with electrical power production that the wind turbine will provide when operated at the WCROC site.

Emissions Reductions

Pollutant	Emissions (kg/yr)
Carbon dioxide	-3,604,638
Sulfur dioxide	-15,628
Nitrogen oxides	-7,643

4.2 *Comparison of Different Available Wind Turbines*

The following table shows the relative performance of several available turbines that might be considered for a Minnesota distributed generation application. We have chosen a wide range of turbine power ratings to fit a variety of possible applications.

Manufacturer	**Rated Power (kw)**	**Rotor Diameter (m)**	**Tower Height (m)**	**Annual Energy Output (kWh)**
Vestas	1,650	82	70	5,703,541
Fuhrlander	600	50	75	2,216,134
Fuhrlander	600	50	50	2,036,626
Fuhrlander	250	29.5	50	668,334
Fuhrlander	100	21	35	298,400

5 Data File Summary

Accompanying this report is a CD-ROM containing the setup data for the NRG data logger and both the raw and processed data files for all data collected to date. The files are organized into the following folders:

Raw Data

This folder contains all the raw data files as emailed by the Symphonie data logger. The raw data files span the period 7/23/03 to 1/9/05. The files are in binary format and have the filename extension *rwd*. These files have already been imported into the master database for the WCROC site.

Scaled Data

This folder contains the ASCII text file equivalent of the raw data files. There is a separate text file for each 24-hour period. These are spreadsheet readable tab delimited files.

Filtered Data

These files are similar to the "scaled data" files, except that there is a full month of 10-minute data stored in each file. Also, any necessary data filters (to eliminate bad data caused by loose wires, icing, or other cause) have been applied before saving the data.

Reports

This folder contains the individual Windows metafiles as generated by the Symphonie Data Retriever software. There is one file per table or graph. These are the graphics that were compiled to make the month reports that Sustainable Automation delivered to WCROC.

Monthly Reports

This folder contains all the monthly reports, in both Word and Acrobat format, that were sent to WCROC by Sustainable Automation.

Site Files

This folder contains the master database and the iPack configuration file.