# Wind Resource Analysis and Wind Turbine Performance Report

Prepared for:

**Bad River Band of Lake Superior Tribe of Chippewa Indians**

Submitted by:

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## Project Overview and Executive Summary

### OBJECTIVE

Seventh Generation Energy Systems was commissioned by the Bad River Band of Lake Superior Tribe of Chippewa Indians to conduct a wind resource monitoring study. Analysis of the wind resource will be used to evaluate the feasibility of installing a range of different sized wind turbines on the Bad River Reservation. This report provides the results of the wind speed monitoring program and discusses its implications for the success of a Band-owned wind energy project.

### INTRODUCTION

To gather information about the Band's wind resource, SGES installed four 50-meter (164-foot) tall tilt-up meteorological towers (met towers) with wind monitoring instruments. The Bad River met towers were each equipped with four anemometers, two wind vanes, a temperature sensor and a multi-channel data logger at test sites jointly selected by the Band and SGES. Three of the met towers were installed and began operating in January 2005 and the fourth was installed in June 2005. At the time this report was written, one of the towers had been decommissioned and three of the towers were still in operation.

### KEY RESULTS AND CONCLUSIONS

The quality of the wind resource on Bad River lands as measured during the study period is a class 1 with a mean wind speed of between 10 and 11 miles per hour at 50 meters. At 30 meters, the measured wind speed is between 7.7 and 8.6 mph. At 80 meters the measured wind speed is projected to be between 12.5 and 14 mph.

Given this annual wind resource, the economics of a project are challenged for several reasons. These include the relatively low wind resource, a lack of available incentives to help fund the cost of a wind project, the moderate energy rates that a Band turbine would receive, and the current high cost of wind turbine equipment.

Despite these financial challenges, the installation of a wind energy system can offer value that is difficult to measure in upfront costs or simple economic payback. These

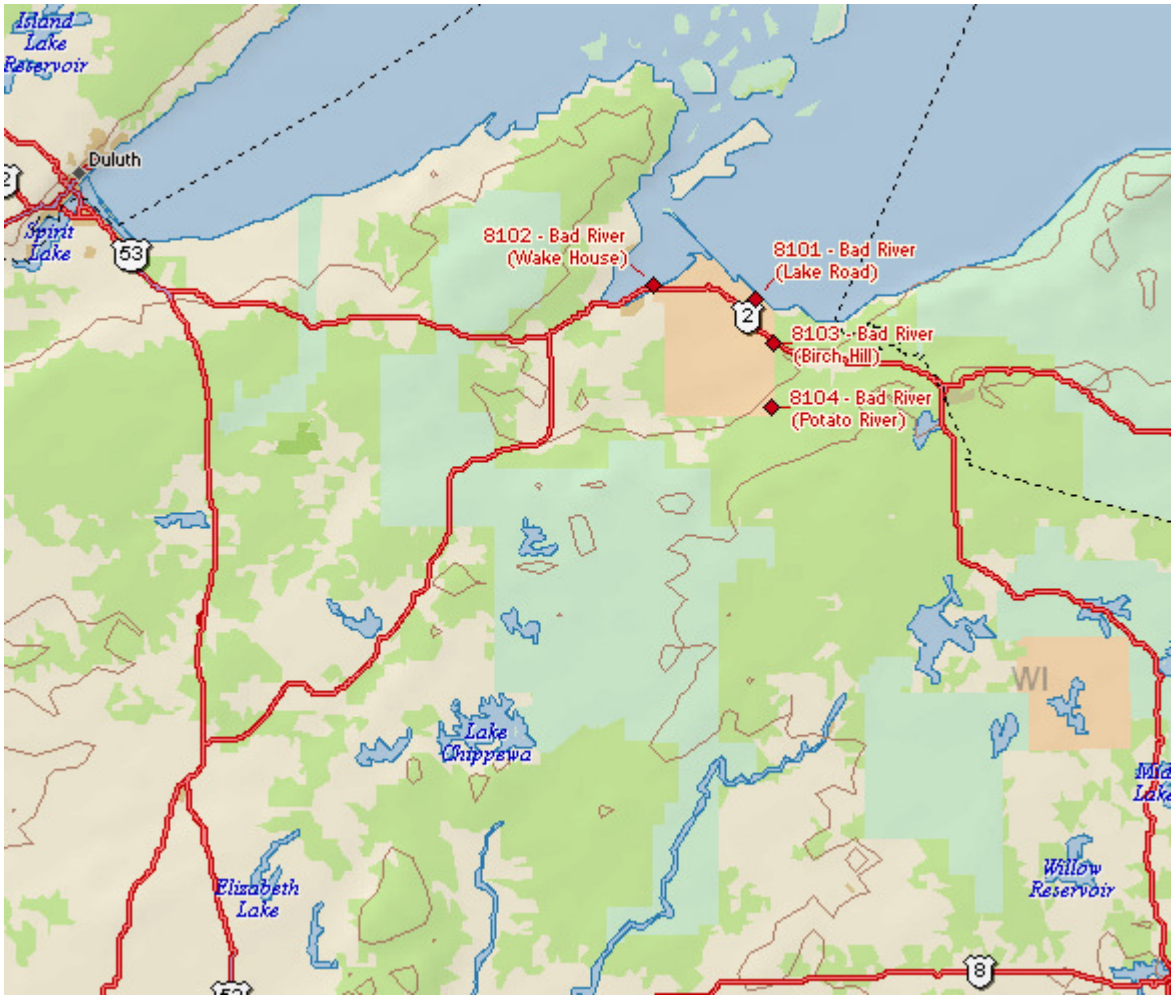
benefits include educational and marketing opportunities and a cleaner environment. As such, we recommend that the Band give consideration to the installation of a wind energy system if their objectives are beyond simple economic returns. If the Band was to move forward with a wind turbine installation, we recommend that the Lake Road or Birch Hill sites be looked at first. Turbines at either of these locations are estimated to produce 15 to 30 percent more energy than at the Wake House and Potato River sites.

Additional recommendations, more detailed discussion about the key conclusions summarized above, and recommended “next steps” are presented at the end of this report.

## Site Location and Description

The Bad River wind speed monitoring sites are located in northern Wisconsin on the Bad River Reservation. The Reservation encompasses 125,000 plus acres and is characterized by an abundance of forests and wetlands.

The wind speed monitoring equipment and met towers were installed at four locations (Lake Road, Wake House, Birch Hill and Potato River) as shown in Figure 1 and Figure 2.



Land use in the area is predominantly forested and characterized as generally flat land with gently rolling hills. The elevation at the northern boundary of the reservation is 610 feet along the Lake Superior shoreline. The elevation slowly increases to between 700 and 800 feet towards the southern boundary. One area of higher elevation lies along the southeast boundary at levels nearly 1200 feet. These elevation differences are presented in Table 3.

**Figure 2. Bad River Met Tower Sites with Land Features**

**Figure 3. Bad River Met Tower Sites with Elevation**

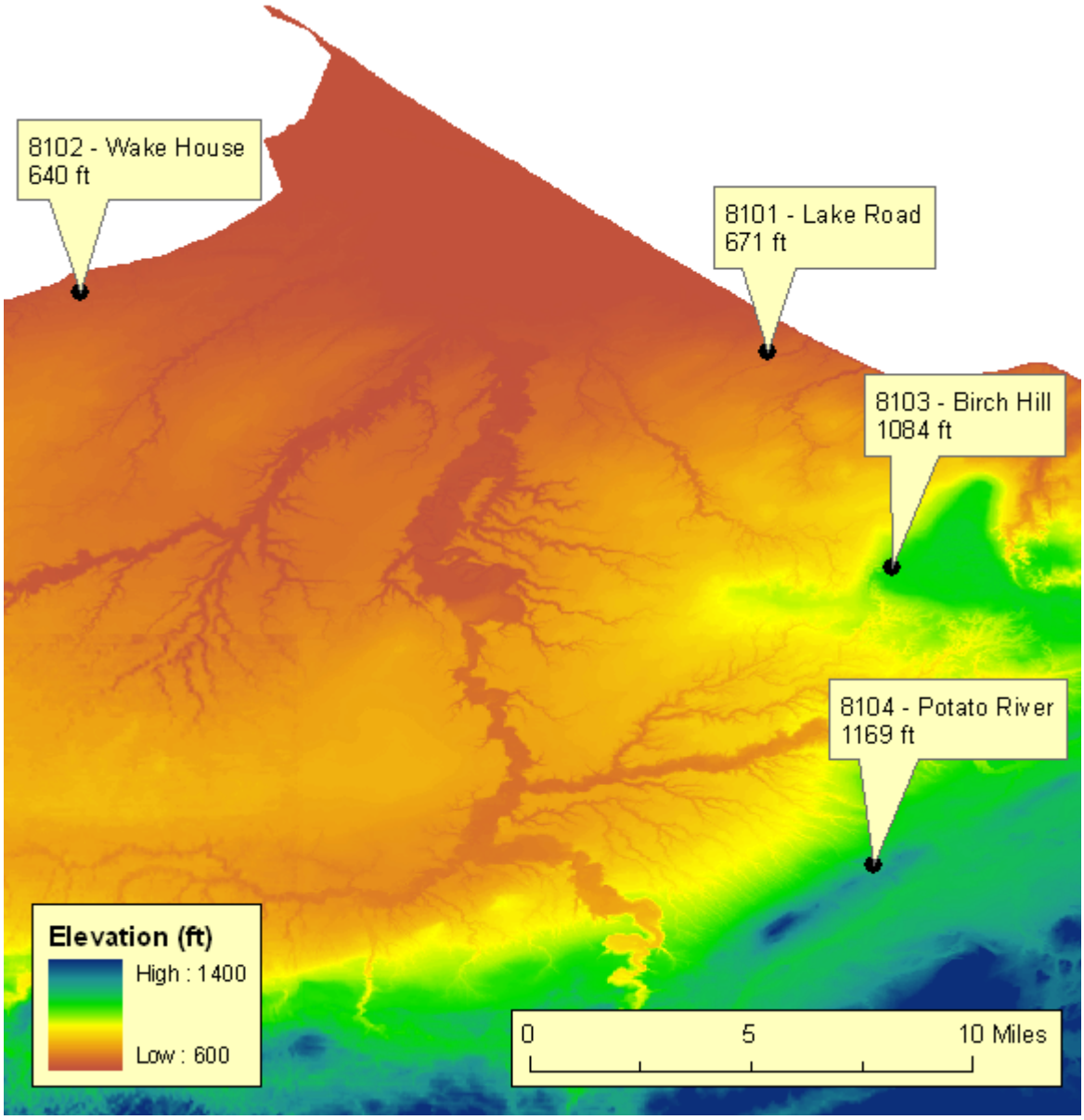


Figure 4 through Figure 7, below, show the groundcover, nearly all forested, within a mile of the met tower sites. This forested terrain, with the exception of a few small fields, is representative of almost all developable land within the Reservation. The mature tree canopy is around 20 meters in height.

**Figure 4. Lake Road Met Tower Location**

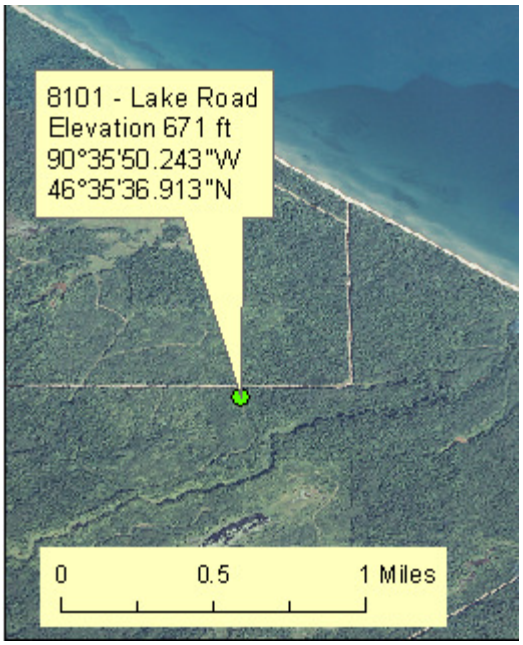



**Figure 5. Wake House Met Tower Location**

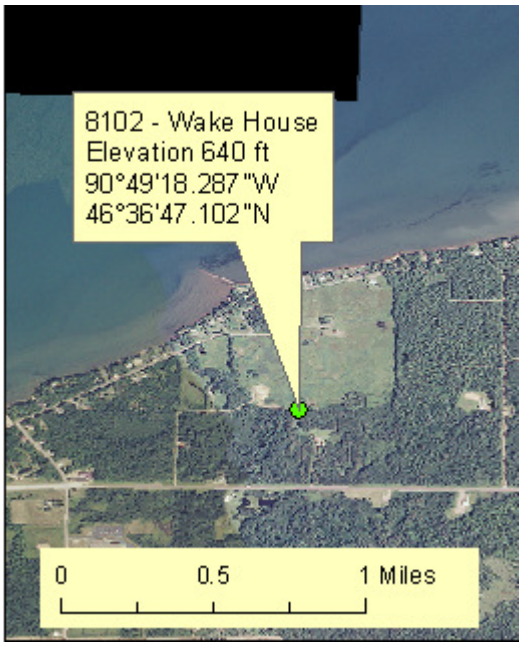



**Figure 6. Birch Hill Met Tower Location**

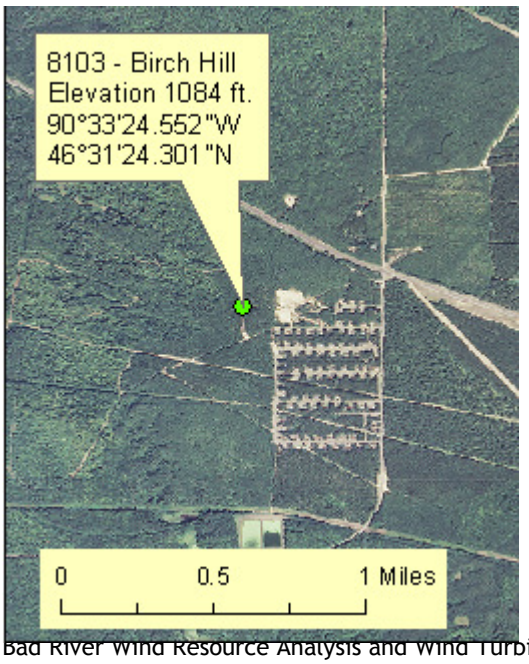
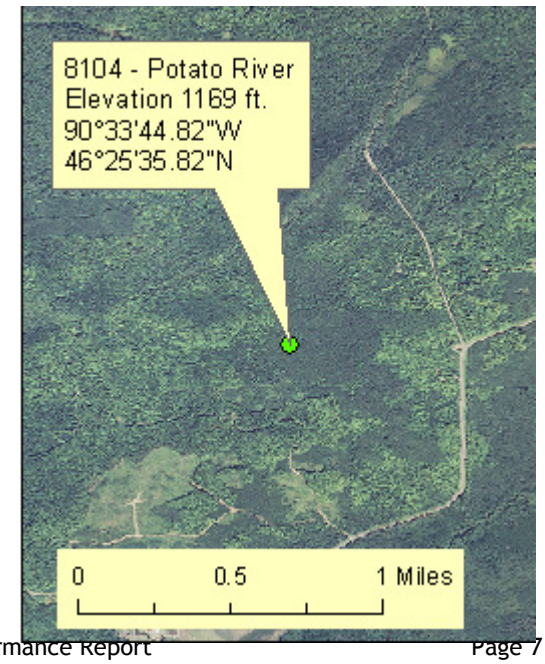



**Figure 7. Potato River Met Tower Location**



## Tower and Sensor Description

Wind resource monitoring was performed using NRG Systems 50-meter (164-feet) NOW measurement systems. NRG is one of the world's leading suppliers of professional-grade wind resource monitoring equipment. Each tower is a standard 6-inch diameter tilt-up tower secured with four sets of guy-cables attached to eight earth anchors set in the ground. Four standard #40 NRG anemometers and two #200P wind vanes were configured at heights and orientations as summarized in Table 1 below. Each sensor was installed on a 43-inch side mount boom providing an IEC compliant tower diameter to boom length ratio of 7:1. Complete sensor orientation and configuration details are found in each met tower's corresponding Site Commissioning Form.

**Table 1. Bad River Tower Sensor Configurations**

| | **Lake Road** | | **Wake House** | | **Birch Hill** | | **Potato River** | |
|---|---|---|---|---|---|---|---|---|
| Sensors | Height | Orientation to MAG North | Height | Orientation to MAG North | Height | Orientation to MAG North | Height | Orientation to MAG North |
| #40 Anemometer | 50m | 270° | 50m | 290° | 50m | 275° | 50m | 270° |
| #40 Anemometer | 50m | 80° | 50m | 82° | 50m | 83° | 50m | 180° |
| #200P Wind Vane | 50m | 0° | 50m | 0° | 50m | 358° | 50m | 90° |
| #40 Anemometer | 40m | 270° | 40m | 290° | 40m | 275° | 42m | 270° |
| #200P Wind Vane | 40m | 0° | 40m | 290° | 40m | 358° | 40m | 0° |
| #40 Anemometer | 25m | 270° | 25m | 0° | 25m | 275° | 30m | 270° |
| Temperature Sensor | 3m | | 3m | | 3m | | 3m | |

## Data Logger Description

An NRG Symphonie Data Recorder (SDR) was used to log the site wind speed data. SDR measures actual wind speed every two-seconds and then calculates and stores a 10-minute average wind speed and standard deviation value along with temperature and wind direction. The data from the SDR was retrieved manually by Band staff and sent in raw form to SGES. Detailed logger information is included in each met tower's corresponding Site Commissioning Form.

**Figure 8. NRG Symphonie Data Logger (typical)**

**Figure 9. Met Tower Sensors (typical)**

## Monitoring Period

Three met towers (Lake Road, Wake House, Birch Hill) were erected in January, 2005 and one met tower (Potato River) was erected in June, 2005. The Wake House tower was decommissioned in October 2008. The other three towers were in operation at the time that this report was written.

Data used in this report covers a two year period from August 1, 2005 through July 31, 2007. However, due to a data logging problem attributed to faulty sensor cables on the Wake House met tower, data after October 2006 for this tower was erroneous and could not be used. For the Wake House tower, a one-year data set is used: from August 1, 2005 through July 31, 2006.

## Data Quality

Aside from the erroneous data gathered from the Wake House met tower from October 2006 to October 2007, overall data recovery from each site was perfect with a 100 percent recovery rate.

The data was processed to remove invalid readings due to winter icing events. For most sensors these invalid readings amounted to 0.5% to 1.5% of the data and this data was removed from the data set. Interestingly, the Lake Road met tower did not show any indication of icing.

## Data Confidence and Correlation

Although the data that this report is based on spans two full years, it is important to note that these data sets do not provide a long-term statistical model of the wind resource that is 100% accurate. Wind speeds vary from year to year and even a three-year study only provides a 95% certainty level. If greater certainty is required, a long-term correlation study could be performed. Such a study would compare wind speeds from the data set used in this report to long-term wind resource records. Wind speed estimates at the Bad River site would then be increased or decreased based on this comparison.

## Results Summary

The four met tower sites demonstrated an average 50-meter wind speed of between 10 and 11 miles per hour with a prevailing southwesterly orientation. These winds are considered a Class 1 or "low" wind resource with an average power density of around 100 watts per meter$^2$ and a mean energy content of approximately 1,000 kWh per meter$^2$. The highest recorded wind gust was 51.8 mph on November 13, 2005.

The calculated wind shear coefficient, which indicates how the wind speed changes with increasing height, is near 0.5 at each site. This is an extremely high value and we suggest using a slightly modified wind shear which is produced by ignoring all wind speeds less than 8.96 mph (4 m/s). By ignoring these low wind speeds which would not result in any energy generation we get a more practical wind shear coefficient, in this case 0.4. This adjusted shear coefficient is still quite high which indicates relatively rough ground and suggests that there will be significant wind speed increases with increasing tower height.

The recorded turbulence intensity at 50 meters at each site was around 20 percent. This is a high turbulence level which means that the wind speed varied considerably during each measurement period.

The wind resource exhibited a distribution shape factor (Weibull) of between and K= 1.98 and 2.42. A normal wind speed distribution with K = 2 is the basis for estimating energy production from standard wind turbine power curves. The sites with higher K values mean strong winds are less available than a site with a "normal" distribution.

Table 2 below shows the summary results at the 50 meter level from each Bad River met tower. The most relevant information is highlighted as bold text. A summary of wind characteristics at each anemometer level for each tower is presented in Appendix A.

**Table 2. Bad River Met Tower Summary Results**

| **Met Tower** | **Lake Road** | ***Wake House** | **Birch Hill** | **Potato River** |
|---|---|---|---|---|
| Anemometer | Speed 50m A | Speed 50m A | Speed 50m A | Speed 50m A |
| **Height above ground (m)** | **50** | **50** | **50** | **50** |
| **Mean wind speed (mph)** | **10.81** | **9.87** | **11.2** | **10.21** |
| Median wind speed (mph) | 10.5 | 9.4 | 11 | 9.9 |
| Min wind speed (mph) | 1 | 0.9 | 0.9 | 1.1 |
| Max wind speed (mph) | 40 | 51.8 | 38.9 | 35 |
| **Mean power density (W/m²)** | **121** | **103** | **121** | **96** |
| Mean energy content (kWh/m²/yr) | 1,057 | 905 | 1,063 | 839 |
| Energy pattern factor | 1.734 | 1.951 | 1.598 | 1.671 |
| **Weibull k** | **2.214** | **1.984** | **2.423** | **2.314** |
| Weibull c (mph) | 12.2 | 11.12 | 12.6 | 11.51 |
| 1-hr autocorrelation coefficient | 0.866 | 0.845 | 0.862 | 0.851 |
| Diurnal pattern strength | 0.019 | 0.067 | 0.021 | 0.029 |
| Hour of peak wind speed | 4 | 15 | 24 | 4 |
| **Mean turbulence intensity** | **0.183** | **0.177** | **0.189** | **0.211** |
| **Adjusted turbulence intensity** | **0.166** | **0.154** | **0.170** | **0.195** |
| **Wind Shear** | **0.502** | **0.487** | **0.495** | **0.529** |
| **Adjusted Wind Shear** | **0.389** | **0.368** | **0.438** | **0.458** |
| Frequency of calms (%) | 0 | 0 | 0.67 | 0 |
| Possible records | 105,121 | 52,561 | 105,121 | 105,121 |
| Valid records | 105,121 | 52,480 | 103,875 | 103,642 |
| Missing records | 0 | 81 | 1,246 | 1,479 |
| Data recovery rate (%) | 100 | 99.8 | 98.8 | 98.6 |

* Data from the Wake House met tower only covers a one-year (2005-2006) time period, whereas the other three met towers have a 2-year long dataset (2005-2007). We estimate that the Wake House met tower would show slightly higher wind speeds (a 2 to 3% increase) if valid 2006-2007 data was available.
* The values in the table above are produced from analyzing all valid wind data. A more practical value for mean turbulence intensity and wind shear can be calculated by analyzing only wind speeds greater than 8.96 mph (4 m/s) as this wind speed is commonly the threshold at which turbines are able to start producing energy. As shown, the “adjusted” wind shear and turbulence intensity both decrease once low wind speeds are removed from the calculation.

## Detailed Results

### MONTHLY WIND SPEEDS

Table 3 below and Figure 10 through Figure 13 show how the wind speed varies by month throughout the monitoring period. As is typical in Wisconsin, the summer months show the lowest average wind speeds and the strongest winds are present in cooler winter months.

**Table 3. Monthly Wind Speed Data (from primary 50m anemometer)**

| Tower | Lake Road | Wake House | Birch Hill | Potato River |
|---|---|---|---|---|
| Month | Mean (MPH) | Mean (MPH) | Mean (MPH) | Mean (MPH) |
| Jan | 11.81 | 10.46 | 11.61 | 10.76 |
| Feb | 11.56 | 10.89 | 11.23 | 9.93 |
| Mar | 11.12 | 8.94 | 11.60 | 10.57 |
| Apr | 10.04 | 9.55 | 11.41 | 10.21 |
| May | 10.47 | 9.54 | 11.79 | 10.81 |
| Jun | 9.41 | 8.34 | 10.59 | 9.86 |
| Jul | 9.98 | 9.66 | 10.66 | 9.89 |
| Aug | 9.80 | 8.81 | 10.04 | 9.28 |
| Sep | 11.30 | 10.36 | 11.51 | 10.58 |
| Oct | 11.54 | 10.42 | 11.48 | 10.34 |
| Nov | 11.74 | 11.80 | 11.55 | 10.63 |
| Dec | 11.04 | 9.75 | 10.95 | 9.67 |
| All data | 10.82 | 9.88 | 11.20 | 10.21 |

**Figure 10. Monthly Average Wind Speeds - Lake Road**

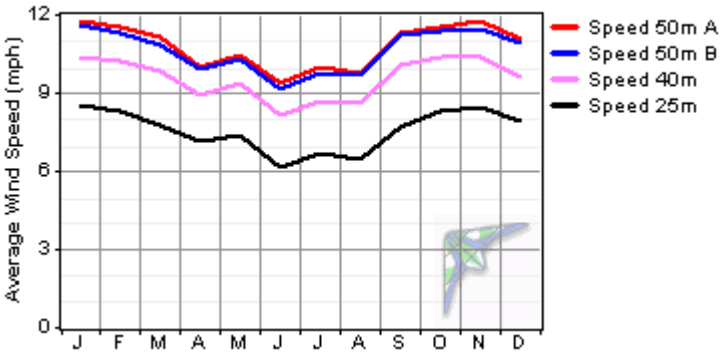



**Figure 11. Monthly Average Wind Speeds - Wake House**

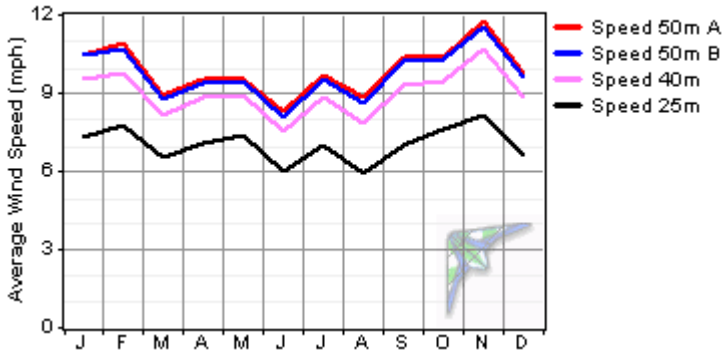



**Figure 12. Monthly Average Wind Speeds - Birch Hill**

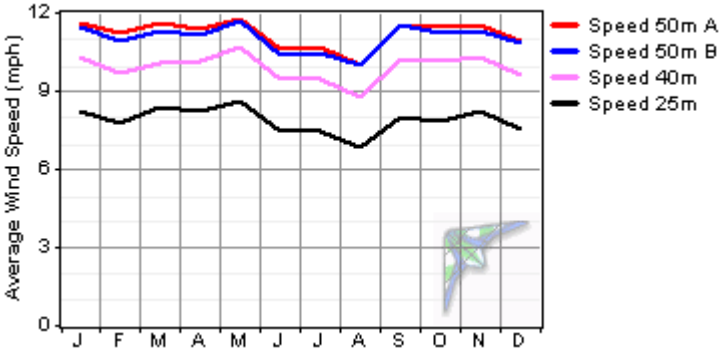
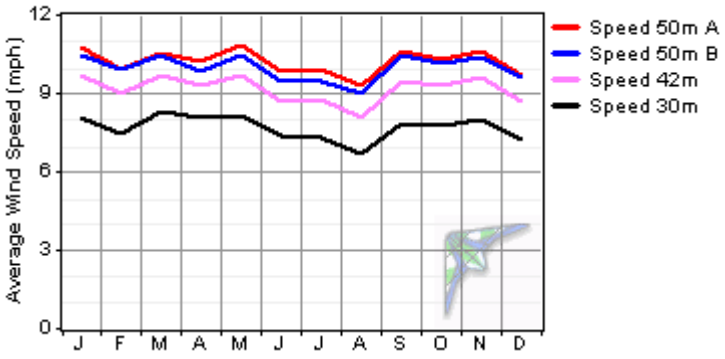



**Figure 13 Monthly Average Wind Speeds - Potato River**



## DIURNAL VARIATION

The diurnal (daily) hourly variation of the wind resource is shown in Table 4 below and graphically in Figure 14 through Figure 17 on the next page. Analysis of the data shows that the wind speed during the typical period of electric utility system peak demand (defined as 8 a.m. to 10 p.m.) is slightly lower than the off-peak average wind speed at three of the met tower sites. The Wake House met tower, on the other hand, shows slightly higher wind speeds during on-peak hours. If wind speeds were substantially greater during on-peak hours, the value of the power from a turbine should have a positive capacity value to the grid which may be useful if and when a power purchase agreement is being negotiated.

**Table 4. Diurnal Wind Speed Data (from primary 50m anemometer)**

| Tower | Lake Road | Wake House | Birch Hill | Potato River |
|---|---|---|---|---|
| Hour | Mean (MPH) | Mean (MPH) | Mean (MPH) | Mean (MPH) |
| 0.5 | 11.2 | 9.5 | 11.6 | 10.7 |
| 1.5 | 11.2 | 9.5 | 11.6 | 10.7 |
| 2.5 | 11.1 | 9.5 | 11.4 | 10.5 |
| 3.5 | 11.2 | 9.6 | 11.4 | 10.5 |
| 4.5 | 11.2 | 9.7 | 11.4 | 10.6 |
| 5.5 | 11.1 | 9.6 | 11.5 | 10.6 |
| 6.5 | 10.7 | 9.4 | 11.2 | 10.4 |
| 7.5 | 10.4 | 9.2 | 10.7 | 10.0 |
| 8.5 | 10.2 | 9.0 | 10.3 | 9.8 |
| 9.5 | 10.4 | 9.3 | 10.4 | 9.8 |
| 10.5 | 10.7 | 9.9 | 10.7 | 10.0 |
| 11.5 | 11.0 | 10.6 | 11.2 | 10.2 |
| 12.5 | 11.2 | 10.9 | 11.5 | 10.5 |
| 13.5 | 11.2 | 11.1 | 11.7 | 10.5 |
| 14.5 | 11.2 | 11.2 | 11.6 | 10.6 |
| 15.5 | 10.8 | 11.0 | 11.4 | 10.4 |
| 16.5 | 10.5 | 10.5 | 11.1 | 9.9 |
| 17.5 | 10.1 | 10.1 | 10.7 | 9.4 |
| 18.5 | 10.1 | 9.6 | 10.5 | 9.2 |
| 19.5 | 10.3 | 9.6 | 10.8 | 9.4 |
| 20.5 | 10.6 | 9.5 | 11.3 | 10.0 |
| 21.5 | 10.8 | 9.5 | 11.5 | 10.4 |
| 22.5 | 11.0 | 9.5 | 11.6 | 10.4 |
| 23.5 | 11.1 | 9.5 | 11.7 | 10.6 |
| Average | 10.8 | 9.9 | 11.2 | 10.2 |
| On-Peak Avg (shaded rows) | 10.7 | 10.1 | 11.1 | 10.0 |
| Off-Peak Avg | 11.0 | 9.5 | 11.4 | 10.5 |

**Figure 14. Diurnal Wind Speed Variation – Lake Road**

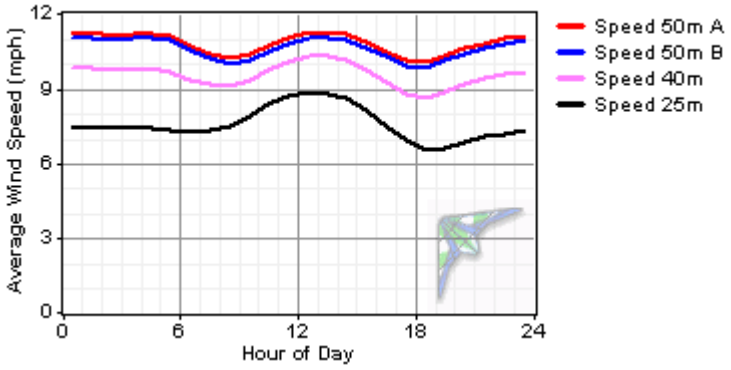



**Figure 15. Diurnal Wind Speed Variation – Wake House**

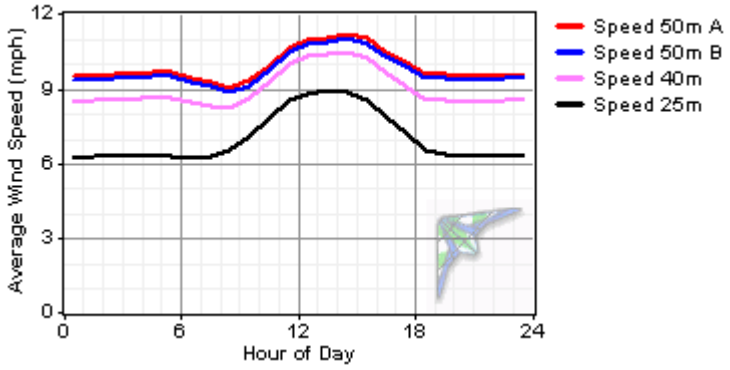



**Figure 16. Diurnal Wind Speed Variation – Birch Hill**

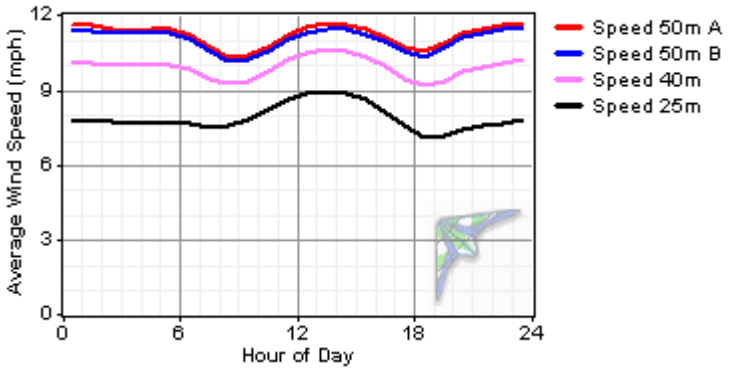
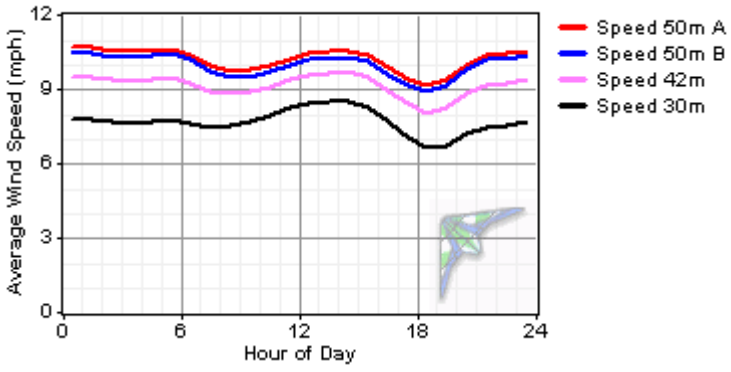



**Figure 17. Diurnal Wind Speed Variation – Potato River**



## WIND DIRECTION

The prevailing wind direction is an important factor to consider when determining the location of a turbine, especially in an area that has varied landscape characteristics, including ground cover, elevation changes and other obstacles to wind flow. The ideal site for a wind turbine is upwind of obstacles that impede the smooth flow of the wind.

The two wind vanes on each tower constantly measured wind direction and recorded the average value every ten minutes. The wind direction data were then processed into "wind roses" - graphical representations of the prevailing wind profiles. Figure 18 through Figure 21 show the wind rose frequency distribution (as a percent of time) of the wind speeds by degree direction from North. In this case, it is observed that the prevailing winds originate from the southwest with a smaller northeasterly component.

However, wind direction alone is insufficient to make an informed decision about the site layout requirements. The energy density of the wind as a function of the prevailing direction(s) must also be calculated. The result is a "wind energy direction" map that shows the direction of the winds with the highest energy content. Figure 22 through Figure 25 show the distribution of wind energy at each met tower site. At three sites (Lake Road, Birch Hill, Potato River), the highest energy clearly originates from the southwest. At these sites, about 50% of available energy is from southwestern and southern winds. The Wake House tower, on the other hand, shows wind energy evenly distributed in three different directions: about 30% from the southwest, 30% from the northwest and 25% from the northeast.

The prevailing wind direction has an interesting effect on the Potato River site. Even though this site's elevation is 500 ft greater than the Lake Road site and 85 ft greater than the Birch Hill site, the measured wind speed at Potato River is actually less than both of these lower elevation sites. This phenomenon results from the fact that the ridgeline that the Potato River met tower is located on is parallel with the primary wind direction. In cases where wind direction and a ridge's orientation align, rather than speeding up as wind travels over the top of a ridge, winds are actually diverted around the ridgeline.

**Figure 18. Wind Frequency Distribution – Lake Road**

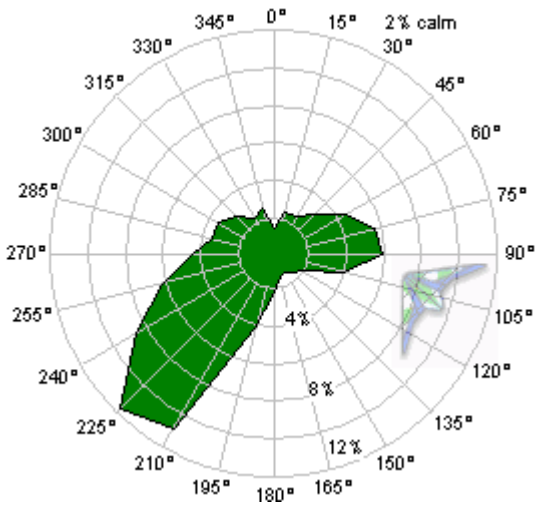



**Figure 19. Wind Frequency Distribution – Wake House**

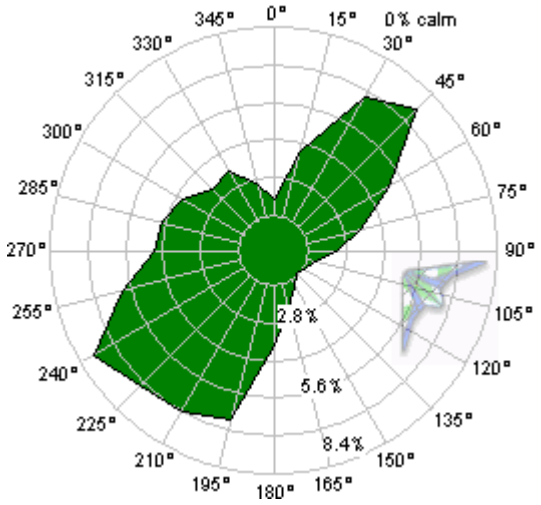



**Figure 20. Wind Frequency Distribution – Birch Hill**

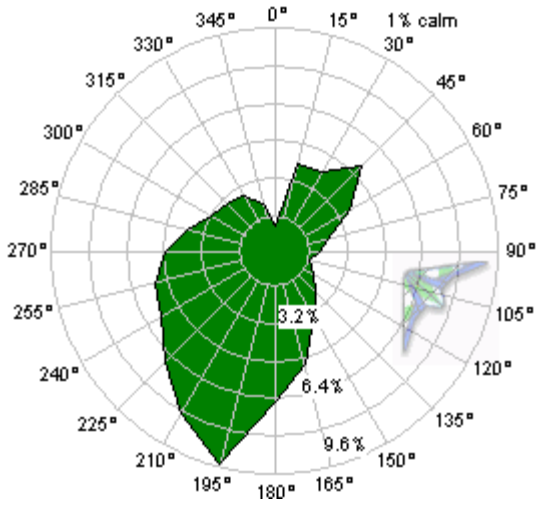



**Figure 21. Wind Frequency Distribution – Potato River**

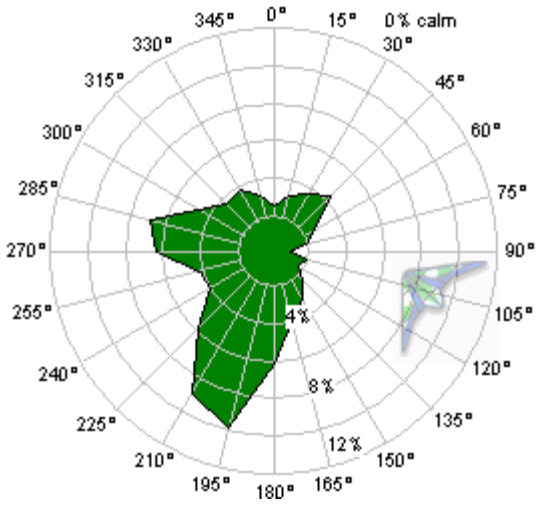


**Figure 22. Power Density Distribution – Lake Road**

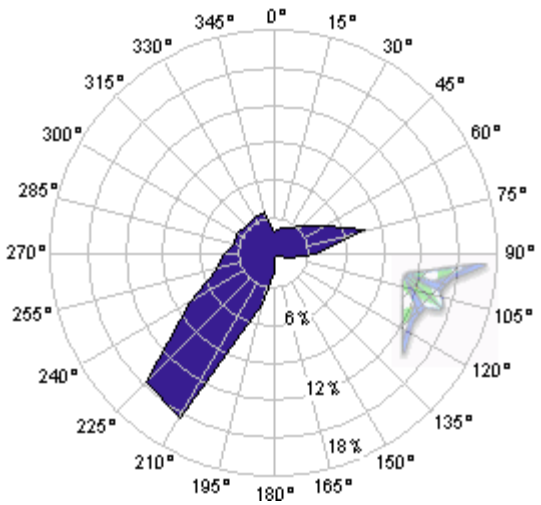



**Figure 23. Power Density Distribution – Wake House**

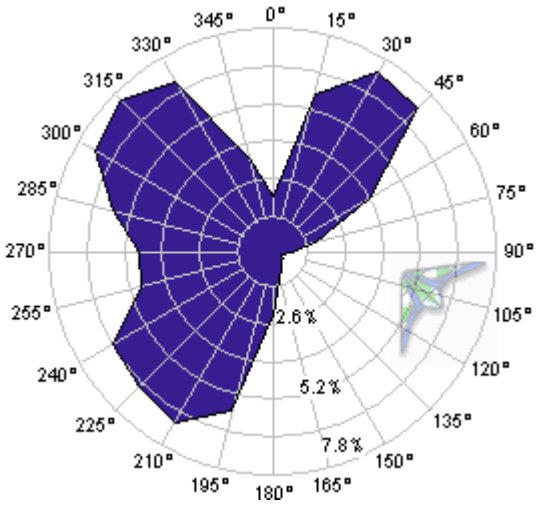



**Figure 24. Power Density Distribution – Birch Hill**

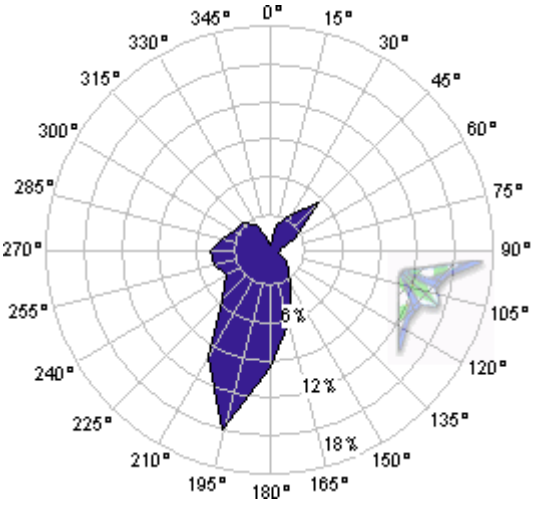
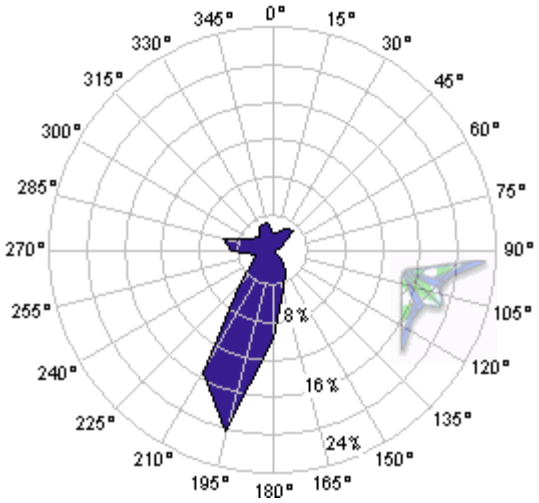



**Figure 25. Power Density Distribution – Potato River**



**WIND SHEAR**

Wind shear describes how the wind speed changes with increasing elevation above the ground. Small to medium size turbines are typically installed on towers between 30 and 45 meters while commercial-scale wind turbines are now typically installed on 80-meter towers and some companies are beginning to offer 100-meter towers. Given the wide range of possible turbine heights it is critical to accurately estimate the expected wind speed at a proposed turbine height based on information obtained from the met tower. This is why anemometers are installed at multiple elevations on a met tower: 30-meters, 40-meters and 50-meters in this case.

The difference in wind speed at each height enables calculation of a wind shear coefficient that is then used to predict the wind speed at other heights. In general, the rate at which the wind speed increases with height slows down as the height increases. In other words, the biggest wind speed change will occur at lower elevations due to the effect of trees, buildings, crops and other sources of ground drag. Regardless, since the power in the wind is proportional to the cube of the wind speed, small changes in average wind speeds at higher elevations will have a significant impact on the available power and the total amount of energy production.

A value known as the wind shear coefficient is used to estimate the wind speed at different elevations according to the following well-established formula:

$$V = (H/H_0)^{\alpha} V_0, \text{ where}$$

$V$ = the wind speed at wind turbine hub height
$V_0$ = the wind speed at reference height
$H$ = the wind turbine hub height
$H_0$ = the reference height
$\alpha$ = the wind shear coefficient.

Based on the actual wind speed measurements at 30-, 40- and 50-meters, the calculated wind shear coefficient for the Bad River sites is around 0.5. This is an extremely high value and we suggest using a slightly modified wind shear which is produced by ignoring all wind speeds less than 8.96 mph (4 m/s). By ignoring these low wind speeds which would not result in any energy generation we get a more practical wind shear coefficient, about 0.4. This value is indicative of a very rough, forested

topography. It suggests that these sites will see significant changes in wind speed with increased wind turbine tower height.

Table 5 presents the observed wind shear from each met tower as well as the adjusted wind shear with wind speeds less than 8.96 mph removed.

**Table 5. Wind Shear Coefficient**

| Met Tower | Lake Road | Wake House | Birch Hill | Potato River |
|---|---|---|---|---|
| Observed Wind Shear | 0.502 | 0.487 | 0.495 | 0.529 |
| Adjusted Wind Shear | 0.389 | 0.368 | 0.438 | 0.458 |

Table 6 below shows the measured average annual wind speed at each of the Lake Road met tower's three monitoring heights and the predicted wind speed at representative hub heights of 80-meters and 100-meters. Measured and predicted wind speeds are shown for all four met towers in Table 7 through Table 10.

This information is summarized graphically for the Lake Road site in Figure 26.

Wind shear tends to be greatest in Wisconsin during the lower wind speed summer months and lowest during the more robust winter months. A monthly plot of wind shear at the Lake Road site is shown in Figure 27.

**Table 6. Measured and Predicted Wind Speeds – Lake Road**

| Height (m) | Wind Speed (mph) | Incremental Change | Cumulative Change | Source |
|---|---|---|---|---|
| 25 | 7.57 | -- | -- | Measured |
| 40 | 9.56 | 26.3% | 26.3% | Measured |
| 50 | 10.81 | 13.1% | 39.4% | Measured |
| 80 | 13.60 | 25.8% | 65.2% | Predicted |
| 100 | 15.10 | 11.0% | 76.2% | Predicted |

**Figure 26. Wind Shear Profile – Lake Road**

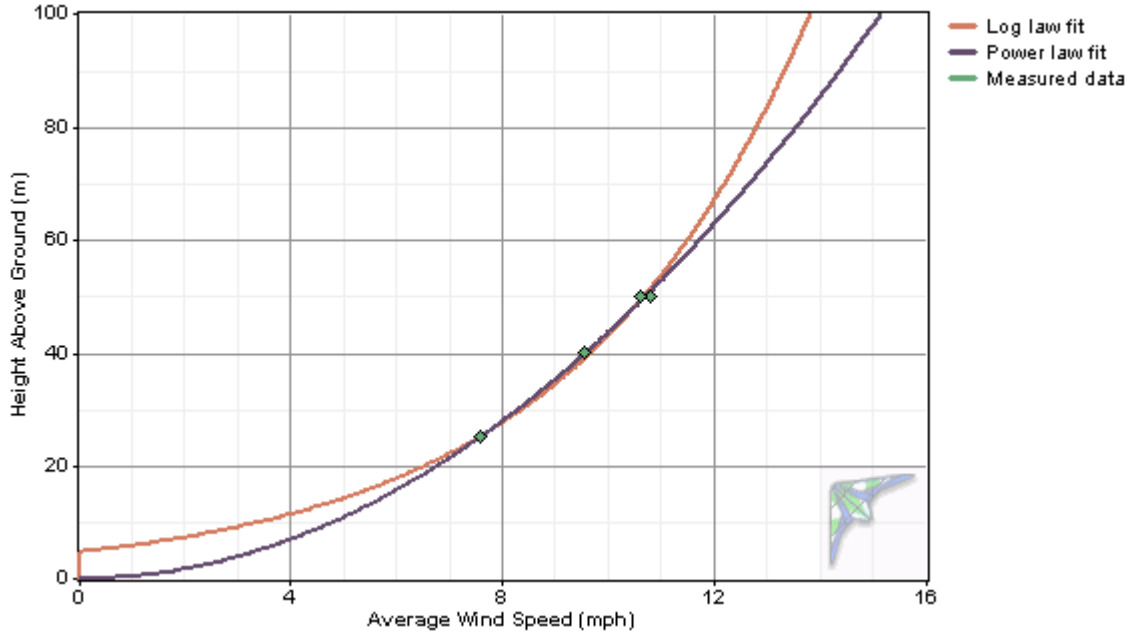
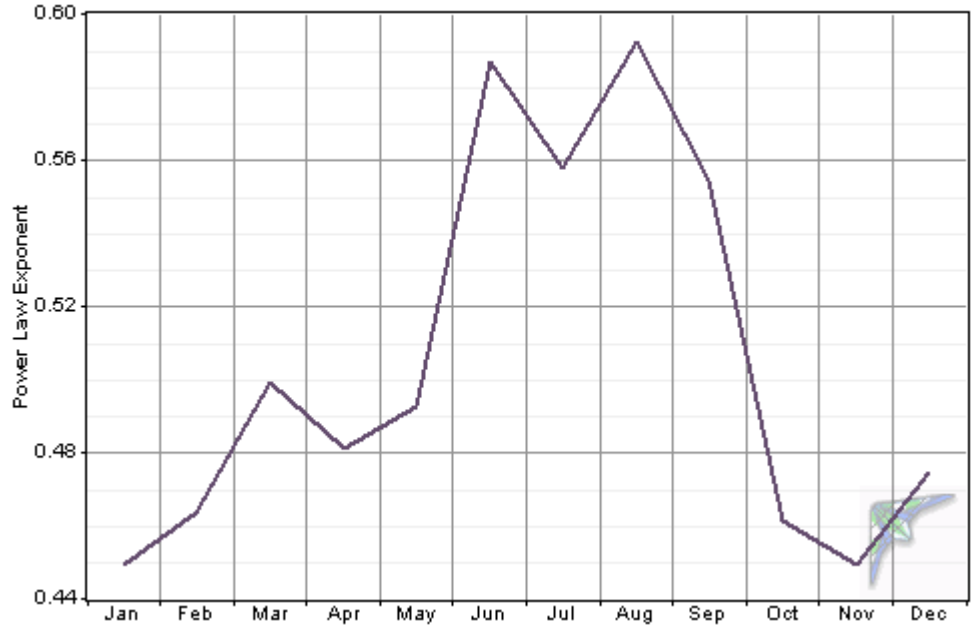



**Figure 27 Monthly Wind Shear Variation – Lake Road**



## HUB HEIGHT WIND RESOURCE ESTIMATES

**Table 7. Measured and Predicted Wind Speeds – Lake Road**

| Height (m) | Wind Speed (mph) | Incremental Change | Cumulative Change | Source |
|---|---|---|---|---|
| 25 | 7.57 | -- | -- | Measured |
| 40 | 9.56 | 26.3% | 26.3% | Measured |
| 50 | 10.81 | 13.1% | 39.4% | Measured |
| 80 | 13.6 | 25.8% | 65.2% | Predicted |
| 100 | 15.1 | 11.0% | 76.2% | Predicted |

**Table 8. Measured and Predicted Wind Speeds – Wake House**

| Height (m) | Wind Speed (mph) | Incremental Change | Cumulative Change | Source |
|---|---|---|---|---|
| 25 | 7.02 | | | Measured |
| 40 | 8.97 | 27.9% | 27.9% | Measured |
| 50 | 9.87 | 10.0% | 37.9% | Measured |
| 80 | 12.40 | 25.7% | 63.5% | Predicted |
| 100 | 13.80 | 11.3% | 74.8% | Predicted |

**Table 9. Measured and Predicted Wind Speeds – Birch Hill**

| Height (m) | Wind Speed (mph) | Incremental Change | Cumulative Change | Source |
|---|---|---|---|---|
| 25 | 7.89 | | | Measured |
| 40 | 9.92 | 25.8% | 25.8% | Measured |
| 50 | 11.20 | 12.9% | 38.7% | Measured |
| 80 | 14.00 | 25.0% | 63.7% | Predicted |
| 100 | 15.60 | 11.4% | 75.1% | Predicted |

**Table 10. Measured and Predicted Wind Speeds – Potato River**

| Height (m) | Wind Speed (mph) | Incremental Change | Cumulative Change | Source |
|---|---|---|---|---|
| 30 | 7.69 | | | Measured |
| 42 | 9.15 | 19.0% | 19.0% | Measured |
| 50 | 10.21 | 11.5% | 30.6% | Measured |
| 80 | 12.90 | 26.3% | 56.9% | Predicted |
| 100 | 14.50 | 12.4% | 69.3% | Predicted |

## WIND SPEED DISTRIBUTION

The primary goal of a wind resource monitoring project is to develop a data set that will allow accurate predictions of wind turbine energy production. Turbine energy production is determined by comparing a wind turbine's rated power at any given wind speed (its power curve) to the expected hours per year the wind blows at any given wind speed.

The wind variation for a typical site is usually described using the Weibull Distribution. The Weibull distribution is defined by the site's mean wind speed and a parameter known as the "shape factor" symbolized by the letter "k." A lower shape factor indicates a more uniformly distributed wind speed while a higher k-value indicates that more of the wind will tend to blow at speeds near the mean with less high-speed (high energy component) values.

The Bad River met tower sites show a "best-fit" shape factor of or slightly above 2. Table 11. presents the observed Weibull value at each met tower location. For comparison, most turbine energy production estimates assume that k=2. If the shape parameter is exactly 2, the distribution is known as a Rayleigh distribution. Wind turbine manufacturers often give standard performance figures for their machines using the Rayleigh distribution. Therefore three of the Bad River sites exhibits a slightly less than favorable wind speed distribution. Figure 28 below shows the recorded wind speed distribution as well as the best-fit shape factor curve at the Lake Road site.

**Table 11. Weibull Probability Distribution Shape Factor**

| Met Tower | **Lake Road** | **Wake House** | **Birch Hill** | **Potato River** |
|---|---|---|---|---|
| Weibull k | 2.21 | 1.98 | 2.42 | 2.31 |

Figure 29 shows how the wind speed distribution curve changes for a constant mean wind speed of 10.81 mph for several different shape factors. Inspection of the curves shows that the higher (k=2.21) shape factor curves have less high wind speed periods than lower k curves. Again, if the mean wind speed at each site was the same, this indicates the Lake Road (as well as Birch Hill and Potato River) site will produce slightly less energy from any given turbine than a more normal site with k = 2.

**Figure 28. Wind Resource Distribution (Percent of Time at Any Given Wind Speed)**

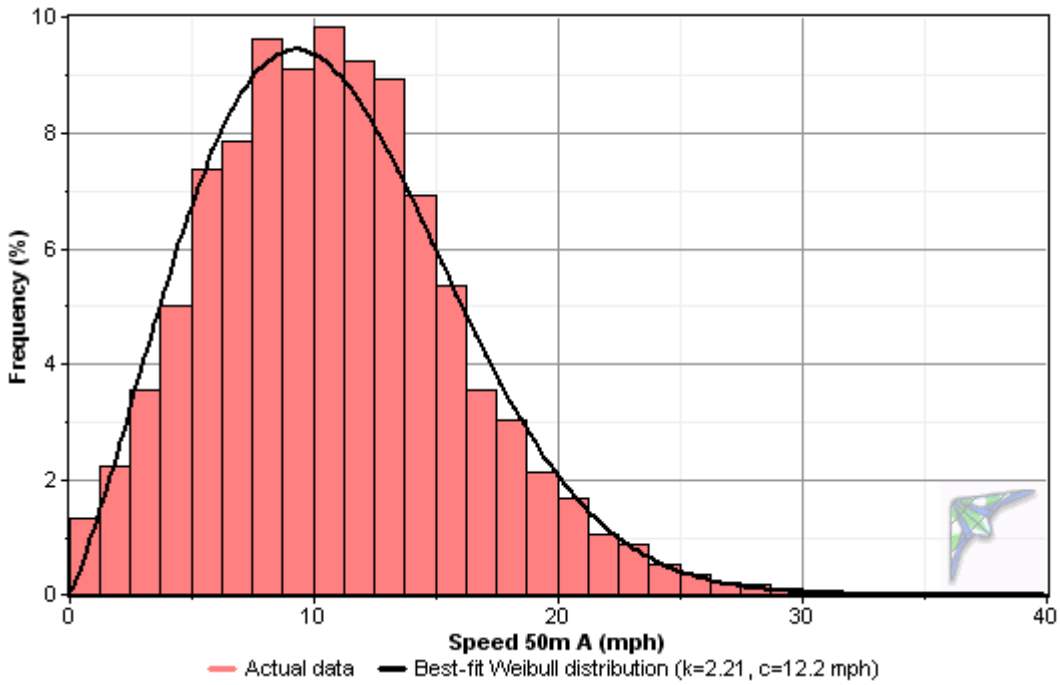
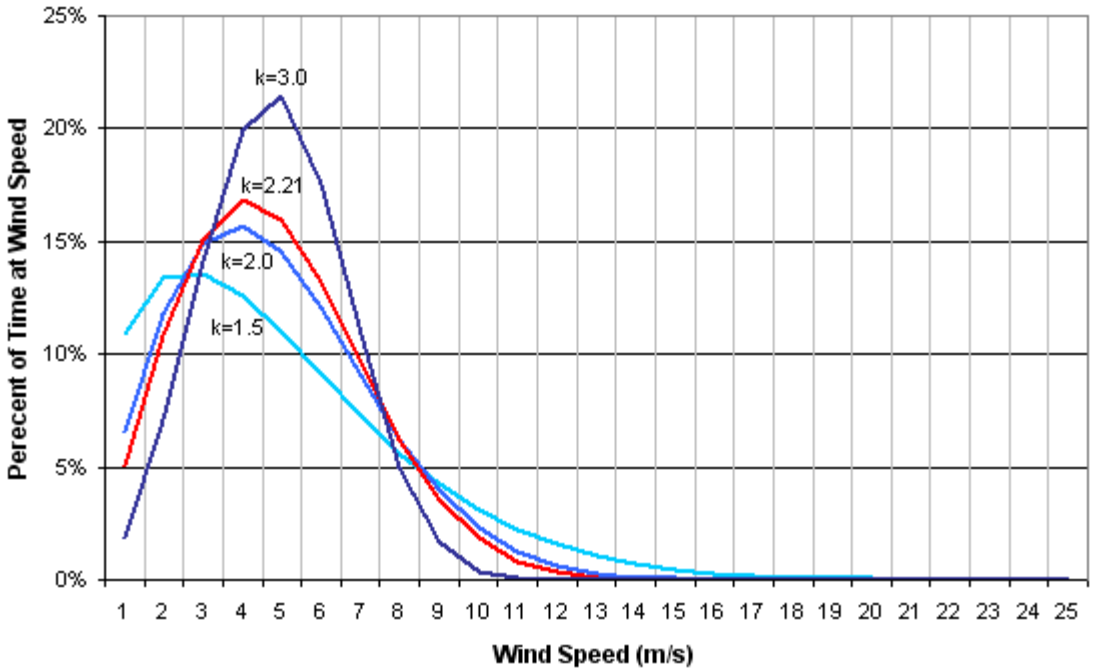



**Figure 29. Effect of Shape Factor (k) on Wind Speed Distribution Profile**



## Wind Turbine Selection & Performance

In this section we present five wind turbines of various sizes to demonstrate the different economic and production outcomes that are possible.

**Table 12. Turbine Type, Capacity and Dimensions**

| Turbine Name | Rated Output (kW) | Hub Height (m) | Rotor Diameter (m) | Total Height (m) | Total Height (ft) |
|---|---|---|---|---|---|
| ARE442 | 10 | 37 | 8 | 41 | 133 |
| Vestas V15 | 35 | 33 | 15 | 41 | 133 |
| Northwind 100 | 100 | 37 | 21 | 48 | 156 |
| Vestas V47 | 660 | 60 | 47 | 84 | 274 |
| GE 1.5xle | 1,500 | 80 | 83 | 121 | 398 |

The following performance estimates summarize the gross energy output for each of the turbines described above at each of the four Bad River met tower locations.

**Table 13. Turbine Electricity Production and Performance**

| | | Lake Road | | | Wake House | | | Birch Hill | | | Potato River | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Turbine Name | Hub Height (m) | Wind Speed at Hub Height (mph) | Annual Gross Energy Output (kWh) | Gross Capacity Factor (%) | Wind Speed at Hub Height (mph) | Annual Gross Energy Output (kWh) | Gross Capacity Factor (%) | Wind Speed at Hub Height (mph) | Annual Gross Energy Output (kWh) | Gross Capacity Factor (%) | Wind Speed at Hub Height (mph) | Annual Gross Energy Output (kWh) | Gross Capacity Factor (%) |
| ARE442 | 37 | 9.18 | 10,018 | 11.4% | 8.49 | 8,428 | 9.6% | 9.54 | 9,833 | 11.2% | 8.56 | 7,723 | 8.8% |
| Vestas V15 | 33 | 8.68 | 35,745 | 11.7% | 8.04 | 29,279 | 9.5% | 9.02 | 34,946 | 11.4% | 8.07 | 26,339 | 8.6% |
| Northwind 100 | 37 | 9.18 | 76,425 | 8.7% | 8.49 | 64,183 | 7.3% | 9.54 | 75,181 | 8.6% | 8.56 | 58,451 | 6.7% |
| Vestas V47 | 60 | 11.72 | 910,149 | 15.7% | 10.80 | 745,845 | 12.9% | 12.16 | 950,499 | 16.4% | 11.09 | 734,114 | 12.7% |
| GE 1.5xle | 80 | 13.64 | 3,534,891 | 26.9% | 12.58 | 2,991,824 | 22.8% | 14.12 | 3,765,741 | 28.7% | 13.01 | 3,072,342 | 23.4% |

## Financial Analysis and Summary

### Pricing

Table 14 provides an overview of how pricing varies from small turbines to very large turbines. Turbine, tower, and installation prices have varied significantly over the past few years and the figures used in the following table should be treated as rough estimates. Actual pricing will need to be determined by way of a more detailed economic feasibility study.

**Table 14. Estimated Wind Turbine Installation Costs**

| Turbine Name | Rated Output (kW) | Cost per kW | Total Cost |
|---|---|---|---|
| ARE442 | 10 | $8,000 | $80,000 |
| Vestas V15 | 35 | $5,000 | $175,000 |
| Northwind 100 | 100 | $4,000 | $400,000 |
| Vestas V47 | 660 | $3,500 | $2,300,000 |
| GE 1.5xle | 1,500 | $2,500 | $3,750,000 |

### Financial Incentives

Financial Incentives can significantly reduce the upfront cost of installing a renewable energy system or provide a source of ongoing revenue as energy is produced. The federal government and the state of Wisconsin offer grants that provide upfront funding. The federal government also provides tax credits to support wind turbine installations. Tax credits come as either a one-time, upfront credit based on wind turbine installation costs or credits that recur annually based on the turbine's energy production. Other tax benefits, such as accelerated depreciation may also be available to a project.

Key factors that affect which financial incentives would apply to a wind energy project include the size of system, ability to take advantage of tax benefits, and whether or not a grant is available to entities such as tribal governments.

As is true of turbine pricing, financial incentives change with regularity. Determination of which incentives apply to a project could be done as part of a more detailed economic feasibility study.

## Value of Energy

The financial performance of any renewable energy project is largely dependent on the value of the energy that is produced. Electricity produced from wind turbines on the Bad River Reservation would be purchased by one of the two utilities that serves the Band: Xcel Energy and Bayfield Electric Cooperative. Table 15 and Table 16 show the different rates that are offered by these utilities for purchase of electricity from customer-owned wind turbines. Notice that the rate that applies to a particular wind turbine installation is largely dependent on the rated output of the system.

**Table 15. Wind Energy Purchase Rates from Xcel Energy**

| Rate | Price per kWh | Size limit (kW) |
|---|---|---|
| Net Metering (Residential and Small General Commercial) | *$0.09664 | 20 or less |
| Net Metering (General Commercial) | *$0.04992 | 20 or less |
| Renewable Energy Buy-Back | $0.06600 | 20 to 1,000 |
| Parallel Generation | **$0.06490 | greater than 1000 |

* These Net Metering rates are the average of Xcel's winter and summer retail rates.
** This rate is the weighted average of the on-peak parallel generation rate of $0.10340 and off-peak parallel generation rate of $0.04430.

**Table 16. Wind Energy Purchase Rates from Bayfield Electric Cooperative**

| Rate | Price per kWh | Size limit (kW) |
|---|---|---|
| Net Metering - General | $0.0960 | 40 or less |
| Avoided Cost Rate | *$0.0750 | greater than 40 |

* Buy-back rates for larger systems in Bayfield Electric Cooperative territory are set by their energy supplier, Dairyland Power. The Avoided Cost Rate is an approximation provided by an employee of Dairyland Power who was unable to give a specific rate but was willing to provide a range of $0.05 to $0.10 per kWh. We use $0.075 per kWh, the midpoint of this range. A specific rate estimate could be requested by providing a project cost summary and negotiating with Dairyland Power.

## Financial Estimates

The following tables (Table 18 and Table 17) present a simplified estimation of the number of years it would take to recoup the initial investment required to install a wind turbine. The figures below are based on the financial returns gained from selling electricity to the utility minus an estimated cost to operate and maintain the wind turbine. As demonstrated by the simple payback column, given the available wind resource, current market conditions, and the rate schedules that the utilities offer, a project would not make sense if simple economic considerations are the only basis for deciding whether or not to install a wind turbine.

**Table 18. Turbine Payback Summary with Xcel Energy Rates**

| | | Lake Road | | Wake House | | Birch Hill | | Potato River | |
|---|---|---|---|---|---|---|---|---|---|
| Wind Turbine Name (hub height) | Applicable Rate (per kWh) | Energy Production | *Simple Payback (in years) | Energy Production | *Simple Payback (in years) | Energy Production | *Simple Payback (in years) | Energy Production | *Simple Payback (in years) |
| ARE442 (37m) | $0.09664 | 10,018 | 408 [T] | 8,428 | 4860 [T] | 9,833 | 458 [T] | 7,723 | ** [T] |
| Vestas V15 (33m) | $0.06600 | 35,745 | 187 [T] | 29,279 | 624 [T] | 34,946 | 204 [T] | 26,339 | ** [T] |
| Northwind (37m) | $0.06600 | 76,425 | 99 [T] | 64,183 | 134 [T] | 75,181 | 101 [T] | 58,451 | 161 [T] |
| Vestas V47 (60m) | $0.06600 | 910,149 | 47 | 745,845 | 61 | 950,499 | 45 | 734,114 | 62 |
| GE 1.5 xle (80m) | $0.0649 | 3,534,891 | 18 | 2,991,824 | 21 | 3,765,741 | 17 | 3,072,342 | 21 |

**Table 17. Turbine Payback Summary with Bayfield Electric Cooperative Energy Rates**

| | | Lake Road | | Wake House | | Birch Hill | | Potato River | |
|---|---|---|---|---|---|---|---|---|---|
| Wind Turbine Name (hub height) | Applicable Rate (per kWh) | Energy Production | *Simple Payback (in years) | Energy Production | *Simple Payback (in years) | Energy Production | *Simple Payback (in years) | Energy Production | *Simple Payback (in years) |
| ARE442 (37m) | $0.09600 | 10,018 | 495 | 8,428 | 8,803 | 9,833 | 556 | 7,723 | ** |
| Vestas V15 (33m) | $0.09600 | 35,745 | 104 | 29,279 | 165 | 34,946 | 109 | 26,339 | 225 |
| Northwind (37m) | $0.07500 | 76,425 | 107 | 64,183 | 142 | 75,181 | 110 | 58,451 | 168 |
| Vestas V47 (60m) | $0.07500 | 910,149 | 41 | 745,845 | 52 | 950,499 | 38 | 734,114 | 53 |
| GE 1.5 xle (80m) | $0.07500 | 3,534,891 | 15 | 2,991,824 | 18 | 3,765,741 | 14 | 3,072,342 | 18 |

* Estimated per year maintenance expense of 1% of turbine price for ARE442 and Vestas V15, 0.5% of turbine price for Northwind100, Vestas V47 and GE 1.5xle.

* Does not include an escalation rate for either energy prices or for turbine maintenance costs.

** Estimated annual maintenance costs outweigh the estimated annual energy savings resulting in negative simple payback.

[T] Calculation of simple payback includes state of Wisconsin wind implementation grant which reduces these systems' installed costs by 10% to 35%.

Several conclusions can be drawn from these financial estimates. First, the rate that is paid for electricity has a significant impact on the viability of a project. For example, The Vestas V15 at the Lake Road site shows a payback of 187 years given Xcel Energy's purchase rate of 6.6 cents per kWh. If the Lake Road site can be connected to Bayfield Electric Cooperative at their purchase rate of 9.6 cents per kWh, the simple payback drops by 44%, to 104 years. Neither of these are compelling payback periods, but other factors could have additional positive impacts on the financial performance of a project. These factors include the availability of incentives and an assumption that energy rates will continue to increase each year.

## Conclusions

The following conclusions and recommendations are presented to the Bad River Band for consideration of any wind energy project development.

1. The quality of the wind resource on the Bad River Reservation lands as measured during the study period at four met tower locations is a class 1 with a mean wind speed of between 10 and 11 miles per hour at 50 meters. At 30 meters, the measured wind speed is between 7.7 and 8.6 mph. This is close to the typical hub height for small wind turbines. At 80 meters, a standard height for large commercial-scale turbines, the measured wind speed is between 12.5 and 14 mph.

2. A wind turbine installation at any of the Bad River sites is technically feasible. Each site's measured annual wind resource is adequate to power a wind turbine but the performance of a turbine will be relatively low compared to commercial wind sites in Wisconsin. A turbine installation at the Bad River site will be hard to justify based purely on economic motivations at this time. In the future, several factors could lead to a more favorable scenario for a turbine installation including: a decrease in installed turbine prices, increase in energy prices, or technological improvements are made to harness low wind speeds more cost effectively.

3. An additional challenge to an economically successful project is the lack of established grant programs to reduce the capital cost of a wind energy system. The Band is not eligible for most federal and utility grant programs which means that in the absence of external funding it will be responsible for the full cost of a turbine. However, in Xcel Energy territory, the Band is eligible for grant money from the state of Wisconsin and the Band may be able to access other grant opportunities not available to the general public. If the Band can secure grants from the BIA, ANA, DOE or other agencies, then the viability of a wind energy project increases greatly.

4. The value of wind energy is measured by more than simple dollars and cents, especially when evaluated in the vacuum of free market economics that does not

include cost of resource depletion, adverse health effects or global insecurity. Wind power has the ability to inspire, to educate and to empower communities and to raise awareness about energy choices and use. In spite of the low wind resource and challenging economic environment, we recommend the Band give serious consideration to the installation of a wind energy system on reservation land.

5. Should the Band proceed with a turbine installation we offer the following recommendations:
   a. Based on the measured wind resource we estimate that wind turbines at the Lake Road and Birch Hill sites will produce 15 to 30 percent more energy than at the Wake House or Potato River sites.
   b. A wind energy system can achieve educational and marketing objectives. Selection of a location should take these factors into account. Schools around the country have been installing renewable energy systems on their property as part of youth energy education curriculum. To the degree that today's youth will be tomorrow's leaders, it is in our collective interest to have leaders who understand sustainable energy.

6. Lastly, the Band may want to consider its energy options as a sovereign nation to create more opportunities for Native-owned sustainable energy resources on its land. The rate structures and policies of the electric utilities serving Bad River are not designed to promote or support Band wind energy projects. Bad River could create its own Band-owned utility under the provisions of the Indian Tax Status Act which allows the creation of Tribal Political Subdivisions to operate with the full authority of the people but without jeopardizing sovereignty or land holdings. A tribal utility could buy and sell electric power on the wholesale market, resell it to Band members and facilities and create a level playing field for locally owned clean energy resources. To be sure, this would be a long-term, complex endeavor but one in which all peoples could benefit over the long-run. There is precedent for this activity and as a first step Bad River may simply work to understand which Tribes have embarked on this path, why, and what barriers and opportunities have been encountered.

## Next Steps

The next steps largely depend on the scale of the project that the Band would consider. Unless significant incentives are found to help fund the installation of a large machine, we recommend that a small to medium sized turbine be considered to help offset onsite energy use.

**Size of System**

Again, many feasibility and planning issues will revolve around the size of wind turbine that is desired. Below are some key issues to address as a project moves forward.

**Turbine Availability**

Currently, the market for large turbines is characterized by more customers than turbines, therefore, the availability of a large turbine would need to be researched further.

**Site Selection and Electric Infrastructure**

If a large turbine was the desired route, site selection becomes largely dependent on the availability of high-voltage electric lines. If a smaller turbine is considered, it could be tied into any existing building's electric panel. An additional site selection criteria is to determine which utility would purchase the electricity from a Band-owned wind turbine and what rate they would offer. These steps can be performed with the assistance of a wind site assessor who would make an on-site visit to analyze electrical infrastructure and speak with Band staff about other site-specific issues such as terrain, access to roads, setback from existing buildings, and political and cultural considerations.

**Financial**

The Band may wish to begin researching the availability of grants and what other financial incentives, such as federal tax credits, the Band would be eligible for. If the Bad River government isn't eligible directly, the Band may look into forming or partnering with other legal entities that do qualify for a desired incentive. If a large system is the desired route, an economic feasibility study may be necessary to determine actual equipment pricing, power purchase rate, and applicable grants and tax benefits.

# Appendices

## APPENDIX A. MET TOWER WIND CHARACTERISTICS SUMMARIES

**Table 19. Lake Road Met Tower Summary Results**

| **Anemometer** | **#1 Primary** (Speed 50 m A) | **#2 Redundant** (Speed 50 m B) | **#3 Primary** (Speed 40 m) | **#4 Primary** (Speed 25 m) |
|---|---|---|---|---|
| **Height above ground (m)** | **50** | **50** | **40** | **25** |
| **Mean wind speed (mph)** | **10.81** | **10.62** | **9.56** | **7.57** |
| Median wind speed (mph) | 10.5 | 10.3 | 9.2 | 7.1 |
| Min wind speed (mph) | 1 | 0.8 | 0.8 | 0.8 |
| Max wind speed (mph) | 40 | 39.5 | 37 | 32.3 |
| **Mean power density (W/m²)** | **121** | **117** | **90** | **49** |
| Mean energy content (kWh/m²/yr) | 1,057 | 1,027 | 789 | 433 |
| Energy pattern factor | 1.734 | 1.779 | 1.874 | 2.071 |
| **Weibull k** | **2.214** | **2.125** | **1.979** | **1.817** |
| Weibull c (mph) | 12.2 | 11.96 | 10.73 | 8.5 |
| 1-hr autocorrelation coefficient | 0.866 | 0.865 | 0.865 | 0.869 |
| Diurnal pattern strength | 0.019 | 0.02 | 0.022 | 0.088 |
| Hour of peak wind speed | 4 | 4 | 9 | 12 |
| **Mean turbulence intensity** | **0.183** | **0.194** | **0.222** | **0.29** |
| Standard deviation (mph) | 5.13 | 5.2 | 4.93 | 4.27 |
| Coefficient of variation (%) | 47.4 | 48.9 | 51.5 | 56.4 |
| Frequency of calms (%) | 0 | 1.56 | 2.41 | 4.14 |
| Possible records | 105,121 | 105,121 | 105,121 | 105,121 |
| Valid records | 105,121 | 105,090 | 105,121 | 105,121 |
| Missing records | 0 | 31 | 0 | 0 |
| Data recovery rate (%) | 100 | 100 | 100 | 100 |

**Table 20. Wake House Met Tower Summary Results**

| **Anemometer** | **#1 Primary** (Speed 50 m A) | **#2 Redundant** (Speed 50 m B) | **#3 Primary** (Speed 40 m) | **#4 Primary** (Speed 25 m) |
|---|---|---|---|---|
| **Height above ground (m)** | **50** | **50** | **40** | **25** |
| **Mean wind speed (mph)** | **9.87** | **9.71** | **8.97** | **7.01** |
| Median wind speed (mph) | 9.4 | 9.3 | 8.5 | 6.4 |
| Min wind speed (mph) | 0.9 | 0.8 | 0.8 | 0.8 |
| Max wind speed (mph) | 51.8 | 51.5 | 47.1 | 37.4 |
| **Mean power density (W/m²)** | **103** | **101** | **80** | **44** |
| Mean energy content (kWh/m²/yr) | 905 | 882 | 703 | 386 |
| Energy pattern factor | 1.951 | 1.993 | 2.016 | 2.318 |
| **Weibull k** | **1.984** | **1.922** | **1.932** | **1.716** |
| Weibull c (mph) | 11.12 | 10.92 | 10.1 | 7.87 |
| 1-hr autocorrelation coefficient | 0.845 | 0.843 | 0.842 | 0.846 |
| Diurnal pattern strength | 0.067 | 0.066 | 0.09 | 0.175 |
| Hour of peak wind speed | 15 | 15 | 14 | 14 |
| **Mean turbulence intensity** | **0.177** | **0.185** | **0.2** | **0.269** |
| Standard deviation (mph) | 5.17 | 5.2 | 4.82 | 4.22 |
| Coefficient of variation (%) | 52.4 | 53.5 | 53.7 | 60.2 |
| Frequency of calms (%) | 0 | 0 | 0 | 0 |
| Possible records | 52,561 | 52,561 | 52,561 | 52,561 |
| Valid records | 52,480 | 52,537 | 52,515 | 52,433 |
| Missing records | 81 | 24 | 46 | 128 |
| Data recovery rate (%) | 99.8 | 100 | 99.9 | 99.8 |

**Table 21. Birch Hill Met Tower Summary Results**

| **Anemometer** | **#1 Primary** (Speed 50 m A) | **#2 Redundant** (Speed 50 m B) | **#3 Primary** (Speed 40 m) | **#4 Primary** (Speed 25 m) |
|---|---|---|---|---|
| **Height above ground (m)** | **50** | **50** | **40** | **25** |
| **Mean wind speed (mph)** | **11.2** | **11.02** | **9.92** | **7.89** |
| Median wind speed (mph) | 11 | 10.8 | 9.7 | 7.5 |
| Min wind speed (mph) | 0.9 | 0.8 | 0.8 | 0.8 |
| Max wind speed (mph) | 38.9 | 38 | 34.9 | 29.2 |
| **Mean power density (W/m²)** | **121** | **116** | **88** | **45** |
| Mean energy content (kWh/m²/yr) | 1,063 | 1,020 | 771 | 397 |
| Energy pattern factor | 1.598 | 1.609 | 1.669 | 1.713 |
| **Weibull k** | **2.423** | **2.392** | **2.293** | **2.233** |
| Weibull c (mph) | 12.6 | 12.39 | 11.17 | 8.88 |
| 1-hr autocorrelation coefficient | 0.862 | 0.861 | 0.86 | 0.858 |
| Diurnal pattern strength | 0.021 | 0.023 | 0.006 | 0.061 |
| Hour of peak wind speed | 24 | 24 | 15 | 13 |
| **Mean turbulence intensity** | **0.189** | **0.195** | **0.223** | **0.28** |
| Standard deviation (mph) | 4.87 | 4.84 | 4.53 | 3.68 |
| Coefficient of variation (%) | 43.5 | 43.9 | 45.7 | 46.7 |
| Frequency of calms (%) | 0.67 | 0.96 | 1.28 | 1.55 |
| Possible records | 105,121 | 105,121 | 105,121 | 105,121 |
| Valid records | 103,875 | 104,821 | 104,744 | 104,059 |
| Missing records | 1,246 | 300 | 377 | 1,062 |
| Data recovery rate (%) | 98.8 | 99.7 | 99.6 | 99 |

**Table 22. Potato River Met Tower Summary Results**

| **Anemometer** | **#1 Primary** (Speed 50 m A) | **#2 Redundant** (Speed 50 m B) | **#3 Primary** (Speed 42 m) | **#4 Primary** (Speed 30 m) |
|---|---|---|---|---|
| **Height above ground (m)** | **50** | **50** | **42** | **30** |
| **Mean wind speed (mph)** | **10.21** | **9.97** | **9.15** | **7.69** |
| Median wind speed (mph) | 9.9 | 9.7 | 8.9 | 7.4 |
| Min wind speed (mph) | 1.1 | 0.8 | 0.8 | 0.8 |
| Max wind speed (mph) | 35 | 34.4 | 32 | 27 |
| **Mean power density (W/m²)** | **96** | **92** | **72** | **45** |
| Mean energy content (kWh/m²/yr) | 839 | 804 | 633 | 392 |
| Energy pattern factor | 1.671 | 1.716 | 1.749 | 1.828 |
| **Weibull k** | **2.314** | **2.211** | **2.167** | **2.075** |
| Weibull c (mph) | 11.51 | 11.23 | 10.31 | 8.67 |
| 1-hr autocorrelation coefficient | 0.851 | 0.85 | 0.848 | 0.845 |
| Diurnal pattern strength | 0.029 | 0.033 | 0.025 | 0.046 |
| Hour of peak wind speed | 4 | 4 | 7 | 11 |
| **Mean turbulence intensity** | **0.211** | **0.228** | **0.247** | **0.301** |
| Standard deviation (mph) | 4.66 | 4.71 | 4.4 | 3.86 |
| Coefficient of variation (%) | 45.6 | 47.2 | 48.1 | 50.2 |
| Frequency of calms (%) | 0 | 1.59 | 1.87 | 2.37 |
| Possible records | 105,121 | 105,121 | 105,121 | 105,121 |
| Valid records | 103,642 | 104,099 | 103,626 | 103,476 |
| Missing records | 1,479 | 1,022 | 1,495 | 1,645 |
| Data recovery rate (%) | 98.6 | 99 | 98.6 | 98.4 |