Small Wind Performance

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Small Wind Turbine Performance in Western North Carolina

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Abstract

Small wind turbines provide a source of clean, renewable energy for homes, farms, or businesses. Although the mountains of western North Carolina contain abundant wind resources, the deployment of small wind technology has not occurred in this region.

Over the past year, six small wind turbines ranging from 400W to 20kW have been installed and tested at the North Carolina Small Wind Initiative Research and Demonstration site on Beech Mountain. The study was designed to evaluate power performance and reliability of small wind systems available on the market.

During the test period, the turbines were subjected to energetic mountain winds resulting in turbine availabilities ranging from 50% for the Jacobs 31-20 to 100% for the Southwest Windpower AirX. Power curves were generated for each of the turbines. Some curves exceeded published performance curves while other produced less than expected.
Introduction

Small wind turbines provide a source of clean, renewable energy for homes, farms, or businesses by converting a portion of the energy in the wind into electricity. For the state of North Carolina to migrate away from non-renewable, polluting energy sources such as coal, natural gas, and nuclear, a diverse portfolio of renewable energy sources including solar, hydro, biomass, and wind will be adopted.

NC Wind Resources

According to the report prepared by Brower (2002), which accompanied the recently acquired NC Wind Resource Map, wind resources in the state are concentrated on the ridgelines in the western region and on the eastern coast. Brower stated that the NC mountains are predicted to have excellent wind resources in many locations.

This is because mountains tend to compress and accelerate the wind forced over them. Generally speaking, mountain peaks must be at least 1100 m (3600 ft) high if they are to have a very good wind resource. (p. 2)

An inspection of the wind map in the western region of the state (figure 1) supports Brower’s statement. The shaded regions represent areas with a class 2 through 7 wind resource. According to Brower, “small turbines are designed to operate at
lower wind speeds, and may be useful at mean speeds (at 30 m height) as low as 5-6 m/s (NREL class 2 to 3)” (p. 2).

Figure 1. Western North Carolina wind power classes at 50 meters above the surface. Derived from the 2002 AWS Truewind map.

Mountain Conditions

In the Acqua Spruzza Report (Botta, Cavaliere, Viani, & Pospo, 1998), several test turbines were installed on a mountain ridge top in Spain to study the effects of a hostile site on the performance and loads of a wind turbine. A ridge top was chosen due to an expected high value of turbulence and vertical component of wind velocity. The report states that “topography can significantly modify turbulence characteristics of wind flow compared to an undisturbed stream, in such a way that the standard turbulence models considered in the design of wind turbines may be unrealistic” (p. 420).

Ice accumulation in the winter was found to be responsible for a reduction in power output. According to the Acqua Spruzza
“the shape of the blade itself is changed and, therefore, its aerodynamic performance; this can alter the energy output, if the wind turbine is operating, or, otherwise, prevent the machine from starting” (p. 423).

The data acquired at the site was analyzed for error since “the performance of sensors and data acquisition systems is not always faultless in such a hostile condition” (Botta et al., 1998, p. 424). The Acqua Spruzza test concluded that Harsh climate condition and complex terrain can affect both the energy output and the steady and fatigue loading of wind turbines. It has therefore been learned that the construction of wind turbines in mountain sites needs special attention, and that a critical appraisal of present design procedures is needed as far as hostile terrain is concerned. (Botta et al., 1998, p. 431)

Winds present on mountain ridge tops are inherently more variable and turbulent than those winds at sites with a more simple terrain. According to Nanayakkara, Nakamura, and Hatazaki (1997), Undesirable fluctuations of the output power of a wind turbine and the difficulties in maintaining the output power at the desired level are mainly due to the time delays associated with the wind turbine and the rapid
variations of wind speed in turbulent conditions. (p. 1068)

Due to the lag time associated with wind turbine startup, power output will suffer losses in variable and turbulent winds.

Turbulence

The Wind Resource Assessment Handbook (AWS Scientific, Inc., 1997) provides recommendations for siting of wind turbines. These guidelines should be followed when choosing a test site. “Features to be avoided include areas immediately upwind and downwind of higher terrain, the lee side of ridges, and excessively sloped terrain. In each of these situations, increased turbulence may occur” (p. 3-4).

Wind Shear

Wind shear is defined by Piggott (2000) as “the rate at which wind speed changes with height above the ground” (p. 145). A range of coefficients are recommended for predicting wind shear in wooded and hilly terrain. These factors assist consumers with tower height selection and properly siting turbines to harness the maximum energy available at a particular site.

Small Wind Turbine Performance Testing Standards

The International Electrotechnical Commission (IEC) (1998) has created an international standard for the testing of wind turbine power performance, IEC 61400-12. The purpose of the standard is “to provide a uniform methodology that will ensure
consistency and accuracy in the measurement and analysis of power performance by wind turbine generator systems (WTGS)” (p. 5).

A disclaimer in IEC 61400-12 applies to this study: “In complex terrain situations it is not adequate to state that results are accurate since the uncertainties might be 10% to 15% in standard deviation. A new measurement standard, accounting for these problems, will be developed in the future” (p. 5). Complex terrain is defined as “terrain surrounding the test site that features significant variations in topography and terrain obstacles that may cause flow distortion” (p. 7). At this time, no new or revised standards have emerged.

Based upon this information, the methods used in collecting data at a North Carolina mountain ridge top test site will require intense scrutiny into the validity of the data due the complexity of the terrain.

Data Collection Schema

IEC 61400-12 details the configuration of the test site and installation of meteorological test equipment. The power produced by the WTGS “shall be measured using a power measurement device (e.g. power transducer) and be based on measurements of current and voltage on each phase” (p. 13).

Gipe (2000) used several methods of measuring power at his test site and finally decided to use the Ohio Semitronics power
transducer. He recommended measuring the power delivered to the batteries for a battery charging system because “in the real world, it’s what we put in our batteries that’s important, not what’s being produced at the top of the tower” (p. 14).

The IEC standard recommends measuring wind speed using a calibrated cup anemometer installed within 2.5% of hub height of the WTGS. The anemometer may be installed on a boom attached to the tower pointed into the prevailing wind direction. Flow distortion should be minimized.

Wind direction is to be measured using a wind vane mounted within 10% of hub height. Flow distortion should be minimized and the absolute accuracy of the wind direction measurement should be better than 5°.

Air pressure and temperature should be measured to derive air density. The thermometer and barometer should be installed near the hub height of the WTGS to provide a good representation of air density at the center of the hub.

The data acquisition system should have a sampling rate of at least 0.5 Hz (one measurement per 2 seconds). Temperature and pressure may be sampled at a slower rate, at least one sample per minute. The data sets should be comprised of mean, standard deviation, maximum value, and minimum value. This raw data will be process into 10 minute averages and corrected for flow distortion and air density if the barometer is not installed at
hub height. The data will be normalized to standard conditions and arranged into wind speed bins in increments of 0.5 m/s. Each bin can be considered complete when it includes at least 30 minutes of data and “the total duration of the measurement period includes a minimum of 180 hours with the WTGS available within the wind speed range” (IEC, 1998, p. 16).

IEC Standards and Small Wind Turbines

The IEC standard was adopted with medium to large wind turbines in mind. Gipe (2004) defines medium-size wind turbines as those having blade diameters of 10 to 50 meters. Gipe (2004, p.66) states that power curves for medium-size wind turbines are typically derived from 10-minute averages per the international standards, but small wind turbines may use 1-minute averages.

Support for 1-minute averages

Michael Klemen has been operating a Wisconsin-based small wind turbine test site since 1991. He is attempting to test turbines in real-life conditions for the benefit of consumers. His data is presented via his website and he states that “this is the real performance of real turbines. It isn't the glitz and glamour that manufacturers might want to present. This site tells you what works, what doesn't, what went wrong, and how badly things can go wrong” (Klemen, 2001).

Klemen supports the idea that wind speed and power sampling intervals are critical to the accuracy of power curves
due to faster response times of small turbines as compared to large turbines. Wind speed should be measured “in the same time frame that the wind generator can respond to the wind (response time)” (Klemen, 1997, p.34). When Klemen asked wind energy expert Mick Sagrillo how fast a small wind turbine can respond to a gust of wind, the answer was “that a small wind machine can respond in a split-second, and a bigger machine like the Jacobs 10kW will take a couple of seconds” (Klemen, 1997, p.35). Due to the variable speed and fast response of small wind turbines, 1-minute averaging will produce more accurate performance results than the 10-minutes averaging scheme developed for larger machines.

The Need for This Study

Gipe (2000) explained “the rating game” with small wind turbines and the absence of rules, standards, or norms pertaining to small turbine ratings. He stated “the only way to find out if small wind turbines can do what their manufacturers say they’ll do is to test them. But there’s never been enough money in small turbine testing to warrant the attention of the major institutes” (p. 4). Gipe’s intent was to determine if the turbines would meet or exceed their power curves. He decided to not pursue long-term testing of reliability or durability, considerations deemed equally as important as power curves.

Although a few small wind test sites exist, none are located
in mountain terrain similar to the mountains of western North Carolina. To benefit consumers in this region, this study will utilize quantitative data to perform power curve verification and both qualitative and quantitative data to describe turbine reliability.

Statement of Problem

The small wind turbine market continues to grow globally and although the mountains of western North Carolina contain abundant wind resources, the deployment of small wind technology has not occurred in this region. The purpose of this study was to test the performance of small wind turbine technology in western North Carolina. Owners of windy land in the region hoping to adopt the technology will benefit greatly from the results of a regional test site. The study was designed to evaluate power performance and reliability of small wind systems available on the market.

Assessing the performance and reliability at the test site will serve three main purposes. First, the test site will serve as a demonstration site for the public to gain experiential access to a collection of functioning turbines. Second, the results of the test will help customers make a more informed decision when choosing a wind turbine for their site and will assist manufacturers in making a more reliable product. Third, the research will help establish a testing protocol for small
wind turbine systems, a task currently being addressed by the American Wind Energy Association (AWEA).

Research Question

How do current small wind turbine systems perform in terms of power production and reliability at a typical western North Carolina wind site?

Definition of Terms

*Air Density:* The mass of air relative to its volume. The density of air at sea level is 1.225 kg/m$^3$. Density decreases with increased elevation and temperature.

*Anemometer:* A sensor for measuring wind speed. The output is transmitted to an instrument for logging and analysis.

*Availability:* The percent of time a turbine is available for operation relative to the total amount of time during the period.

*Battery Charging turbines:* Small wind systems that utilize a charge controller to charge a battery bank. Power is measured as delivered to the batteries.

*Battery-less, Grid-tie turbines:* Small wind systems that feed power directly onto the grid instead of charging a battery bank. The system only operates when the grid is present, therefore, no backup power is provided during a grid outage.
Bin: Wind speed interval used for grouping wind speed data used in the *method of bins* calculation. Bin width is typically 1 mph or 0.5 m/s.

Furling: To roll up or take down a flag or sail. Form of over-speed protection used on traditional European windmills where the miller rolled up the sail. Also, a form of over-speed protection used in small upwind HAWTs where the rotor folds to reduce its swept area.

Method of Bins: A technique for collecting or analyzing a wind speed frequency distribution by grouping wind speed data into discrete bins.

Horizontal Axis Wind Turbine (HAWT), downwind: The axis of rotation is approximately horizontal. A conical rotor shape faces the rotor away from the wind.

Horizontal Axis Wind Turbine (HAWT), upwind: The axis of rotation is approximately horizontal. A tail faces the turbine into the wind.

Power Curve: Chart of a turbine’s power in a range of winds.

Rayleigh Distribution: A modeled distribution of wind speeds using a Weibull function with k=2 and shape=average wind speed.

Swept Area: The area swept by a wind turbine rotor \( (A = \pi R^2) \).

Turbulence: Sudden changes in both wind speed and direction. Turbulence is undesirable because of decreased harnessable power and increases wear and tear on the machine.
Turbulence Intensity: Quotient of instantaneous wind speed divided by the mean wind speed for a given period.

Vertical Axis Wind Turbine (VAWT): The axis of rotation is vertical. Two examples are the drag-type Savonius and the lift-type Darrieus.

Limitations of the Study

Findings will be limited to power output, meteorological, and reliability data collected at the Beech Mountain test site during the testing period. Other factors related to wind turbine performance, such as acoustic noise emissions and avian impacts, are being addressed but will not be included in this study.

The small wind market includes a variety of manufacturers and sizes of turbines, and typically each turbine is available in various configurations. This test will not be exhaustive; all turbines and configurations on the market will not be tested. The six-turbine sample chosen for this research includes a broad range of turbine sizes (400W to 20kW) and configurations (24Vdc and 48Vdc battery-charging as well as battery-less, grid-tie).

Methodology

Sample

Six small wind turbines ranging from 400W to 20kW were selected as detailed in Table 1. The turbines selected represent a sampling of the machines available on the market at the time of the study. An internet-based small wind turbine market
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analysis reveals an availability of approximately 15 upwind turbines ranging from 400W to 250kW and four downwind turbines ranging from 600W to 50kW.

Table 1 Beech Mountain Test Turbines

<table>
<thead>
<tr>
<th>Turbine Description</th>
<th>Rated Power (Watts)</th>
<th>Tower Height (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a   Southwest Windpower AirX, 24VDC</td>
<td>400</td>
<td>35</td>
</tr>
<tr>
<td>b   Southwest Windpower Whisper H40/100, 48VDC</td>
<td>900</td>
<td>80</td>
</tr>
<tr>
<td>c   Bergey XL.1, 24VDC</td>
<td>1000</td>
<td>105</td>
</tr>
<tr>
<td>d   African Wind Power AWP 3.6 Grid-tie</td>
<td>1500</td>
<td>105</td>
</tr>
<tr>
<td>e   Southwest Windpower Whisper 175, 48VDC</td>
<td>3000</td>
<td>70</td>
</tr>
<tr>
<td>f   Jacobs 31-20, Grid-tie</td>
<td>20,000</td>
<td>120</td>
</tr>
</tbody>
</table>

All turbines were three-bladed, horizontal-axis, upwind machines with the exception of the Whisper 175, which was a two-bladed machine. All were supported on tilt-up, guyed towers with the exception of the Jacobs, which was installed on a tilt-up, freestanding lattice tower.

The power produced by the turbines was transmitted to a central building, which housed the balance of the system. Four
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turbines--the Bergey, AirX, Whisper 100 and Whisper 175--were set up as battery chargers. The AWP3.6 and Jacobs were set up as direct grid-tie with no battery storage.

All power was inverted from DC to AC and connected directly to the main AC load center using grid-tie inverters. For battery-charging systems, the wind turbine charged the batteries via a charge controller and the DC power from the batteries was fed into a battery-based grid-tie inverter. For battery-less, grid-tie systems, an interface between the wind turbine and the grid-tie inverter rectified the turbine output to DC and fed into a grid-tie inverter designed particularly for the system.

Any surplus power not used on site was fed onto the local Mountain Electric Cooperative grid. All energy produced at the site was metered before reaching the load center and was sold at a rate of $0.15 per kilowatt-hour (kWh) as part of the TVA Green Power Switch program.

Instruments

Performance was assessed by producing power curves for each turbine. Accurate measurements were made of power output, wind speed, wind direction, temperature, and barometric pressure.

Power. For the battery chargers, the DC power was measured between the charge controller and the battery bank. For the grid-tie machines, the AC power was measured at the AC output of the inverter. Power transducers from Ohio Semitronics measured
the current and voltage of the output power and multiplied the two values to get power. A low-voltage DC signal (0-5Vdc) corresponding to the measured turbine power was transmitted to the data logger and translated into turbine power using a multiplier. Each transducer was calibrated to a unique scale. For example, the Jacobs transducer output was 0-5Vdc which corresponds to a power output of 0-40kW, so the multiplier was 8.0 per the following equation.

\[ \text{TurbinePower} = V_{dc}(\text{output}) \times \text{multiplier} \]

Example: \( \text{JacobsPower} = 2.1V_{dc} \times 8.0 = 16.8kW \)

Wind Speed. Wind speed was measured using two NRG #40 anemometers per tower as shown in figure 2. With two known wind measurements at two known heights, the shear exponent, alpha, was derived for each tower. A site average was used to estimate the hub height wind speeds from the upper anemometer wind speeds. Table 2 shows the anemometer heights and hub heights.

Figure 2. A calculated wind shear exponent was used to estimate the hub-height wind speed from the upper anemometer readings.
Table 2 *Anemometer and hub heights*

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Lower Anemometer</th>
<th>Upper Anemometer</th>
<th>Hub Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWP 3.6</td>
<td>20 m</td>
<td>29 m</td>
<td>32.3 m</td>
</tr>
<tr>
<td>Whisper 175</td>
<td>12 m</td>
<td>17.3 m</td>
<td>21.6 m</td>
</tr>
<tr>
<td>Jacobs 31-20</td>
<td>N/A</td>
<td>17.8 m</td>
<td>36.6 m</td>
</tr>
<tr>
<td>Whisper 100</td>
<td>15.1 m</td>
<td>22.2 m</td>
<td>24.7 m</td>
</tr>
<tr>
<td>AirX</td>
<td>10 m</td>
<td>12.2 m</td>
<td>13.7 m</td>
</tr>
<tr>
<td>Bergey XL.1</td>
<td>18.3 m*</td>
<td>28 m</td>
<td>30.5 m</td>
</tr>
</tbody>
</table>

* Lower XL.1 anemometer changed to 20m on 5/31/05 to reduce vibration

**Wind Direction.** Wind direction was measured in order to record when the anemometers were in the shadow of the towers. The air downwind of the tower is turbulent and wind speed measurements are inaccurate during times when the anemometers are in this tower shadow. One NRG #200P wind vane was mounted on each tower on a boom at the height of the upper anemometer.

**Air Density.** Absolute air density during data collection will be calculated by measuring the temperature and barometric pressure. Temperature will be measured using an NRG 110S temperature sensor with radiation shield. Barometer pressure will be measured using an NRG BP20 pressure sensor.

**Data Collection**
The Site. The research was conducted at the NC Small Wind Initiative Research & Demonstration Site on Beech Mountain, North Carolina. Elevation is 5148 feet (1560 m), and according to the North Carolina wind map shown in figure 3, the site is rated as class 5 with an average annual wind speed of 7 m/s at 30 meters above the ground.

Figure 3. The Beech Mountain test site is rated as a high class 5 site with an annual average wind speed of 7.08 m/s at 30 m.

Sensor output. The anemometers and power transducers transmitted measurements as a low-voltage DC signal to the data

Data Logging. A Campbell Scientific CR-1000 data logger was used to collect the data. Wind speed, wind direction, and power was collected once per second. Temperature and pressure were measured once per minute. The real-time data streamed into the logger. Campbell Scientific software, called Logger Net, produced and displayed real-time tables and graphs of the data, calculated one-minute and ten-minute averages for the wind speed and power, and archived the data on the hard drive of an attached PC. The data tables were viewed and manipulated using Microsoft Excel.

Reliability Data. All activity at the research site was documented using log books or electronic logs. Breakdowns, damages, repairs, installations, and other notable observations were photographed using a digital camera and videoed when possible. Using the logs, the availability of the turbines was calculated. For example, if a turbine was not functional for half of the test period, the availability was 50%.

Data Analysis

Power curves were produced for each wind turbine. Per standard practice, the power curves were normalized to sea level conditions and standard temperature to enable comparison to
published normalized power curves. The curves were used to calculate annual energy output for each turbine.

**Excluded Data Sets.** Data sets were excluded for periods where the wind turbine was not operating properly or when the measurement equipment was not functioning properly due to ice, bugs, or other externalities.

**Data Normalization.** Air density was calculated using the following equation from Gipe (2004):

$$\rho_{1\text{min}} = \frac{B_{1\text{min}}}{RT_{1\text{min}}}$$

where

$\rho_{1\text{min}}$ is the calculated air density averaged over 1 minute in hg/m$^3$;

$B_{1\text{min}}$ is the measured air pressure averaged over 1 minute in Pascal;

$R$ is the gas constant 287.05 J/(kg K);

$T_{1\text{min}}$ is the measured absolute air temperature averaged over 1 minute in Kelvin.

The power output was normalized using the following equation from Gipe (2004):

$$P_n = P_{1\text{min}} \times \frac{\rho_o}{\rho_{1\text{min}}}$$

where
$P_n$ is the normalized power output; 

$P_{1min}$ is the measured power averaged over 1 minute; 

$\rho_o$ is standard sea level air density (1.225 kg/m$^3$) 

$\rho_{1min}$ is the calculated air density averaged over 1 minute; 

**Power Curve Generation.** The measured wind speed and normalized power output data points were arranged into one mile-per-hour (mph) bins. The data set was considered complete when each bin contains 30 minutes of measured data and the total duration of measurement period is 180 hours of turbine operation up to 20 m/s or 44 mph. 

**Uncertainty.** Error bars were added to each bin of the normalized power curves. Uncertainty was calculated as the standard deviation of the power in each wind speed bin divided by the square root of the number of data points. 

**Annual Energy Output (AEO).** For each wind speed bin, the normalized power was multiplied by the annual hours of wind at that speed according the measured wind distribution. Annual hours of wind for each wind speed bin will be calculated by multiplying the distribution probability derived from the wind distribution times 8760 hours per year. Annual energy output was derived for average wind speeds of 11-15 miles per hour.
Findings

Availability

From the 10/21/04 installation until the 6/16/05 decommissioning, the Whisper 175 has been available 82% of the time as shown in figure 4. Three periods of downtime were experienced, all due to wiring failures as detailed in table 3. Replacement parts were covered under warranty. All repairs were performed onsite by SWI personnel.

![Figure 4. Whisper 175 availability from 10/21/04 to 6/16/05](image_url)
Table 3 Failures and repairs for the Whisper 175

<table>
<thead>
<tr>
<th>Failure</th>
<th>Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/3/04</td>
<td>Short in tail light circuit</td>
</tr>
<tr>
<td>12/17/04</td>
<td>Removed light circuit, tightened J-box</td>
</tr>
<tr>
<td>3/17/05</td>
<td>Brush card short</td>
</tr>
<tr>
<td>4/8/05</td>
<td>Soldering attempt failed; new brush card assembly installed</td>
</tr>
<tr>
<td>6/12/05</td>
<td>Brush card short</td>
</tr>
<tr>
<td>6/16/05</td>
<td>Decommissioned; making room for new Whisper 500; repaired machine crated up</td>
</tr>
</tbody>
</table>

From the 10/18/04 installation until 11/28/05, the AirX has been available 100% of the time as shown in figure 5. This machine is the only turbine at the site which has not suffered from downtime.

Figure 5. AirX availability from 10/18/04 to 11/28/05

From the 9/30/04 installation until the 11/17/05 decommissioning, the AWP3.6 has been available 82% of the time as shown in figure 6. Two periods of downtime were experienced
due to controller and inverter overcurrent damage and tail hinge wear as detailed in table 4. Replacement parts were covered under warranty with the exception of the WindyBoy inverter. All repairs were performed onsite by SWI personnel with the exception of the yaw head tail hinge repair by Abundant Renewable Energy and the electronics repair performed by SMA.

Figure 6. AWP 3.6 availability from 9/30/04 to 11/17/05

Table 4 Failures and repairs for the AWP 3.6

<table>
<thead>
<tr>
<th>Failure</th>
<th>Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/3/04 Voltage clamp &amp; Windy Boy overcurrent damage</td>
<td>12/17/04 Repaired voltage clamp at factory; new Windy Boy</td>
</tr>
<tr>
<td>5/22/05 Excessive tail hinge wear discovered</td>
<td>6/22/05 Repaired yaw head at factory</td>
</tr>
</tbody>
</table>
From the 7/15/04 installation until the 9/13/05 decommissioning, the Bergey XL.1 has been available 81% of the time as shown in figure 7. Periods of downtime were experienced due to hurricane damage, controller failure, yaw shaft failure, and breaker tripping as detailed in table 5. Replacement parts and turbines were covered under warranty except for the first set of replacement blades. All repairs were performed onsite by SWI personnel.

Figure 7. Bergey XL.1 availability from 7/15/04 to 9/13/05
Table 5 Failures and repairs for the Bergey XL.1

<table>
<thead>
<tr>
<th>Failure</th>
<th>Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/17/04</td>
<td>Damaged blades and alternator (Hurricane Ivan)</td>
</tr>
<tr>
<td>11/1/04</td>
<td>New turbine and blades</td>
</tr>
<tr>
<td>12/9/04</td>
<td>Controller damaged (badly burned)</td>
</tr>
<tr>
<td>12/16/04</td>
<td>New controller (with DC breaker)</td>
</tr>
<tr>
<td>12/25/04</td>
<td>Yaw shaft failure; machine fell from tower</td>
</tr>
<tr>
<td>1/13/05</td>
<td>New turbine (with larger yaw shaft) and blades</td>
</tr>
<tr>
<td>8/30/05</td>
<td>Breaker tripped</td>
</tr>
<tr>
<td>9/8/05</td>
<td>Reset breaker</td>
</tr>
</tbody>
</table>

From the 10/20/04 installation until 11/28/05, the Whisper H40/Whisper100 has been available 81% of the time as shown in figure 8. Three periods of downtime were experienced due to controller failure, damaged turbine wiring, and board failure as detailed in table 6. Replacement parts and turbines were covered under warranty. All repairs were performed onsite by SWI personnel. The damaged wiring was repaired by installing a complete new turbine head (less tail and blades), now called the Whisper 100. This was considered a replacement part, so this log will continue.
Figure 8. Whisper H40/100 availability from 10/20/04 to 11/28/05.

Table 6 Failures and repairs for the Whisper H40/100

<table>
<thead>
<tr>
<th>Failure</th>
<th>Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/3/04 Controller failure</td>
<td>12/15/04 New controller</td>
</tr>
<tr>
<td>3/3/05 Wiring damage in turbine head</td>
<td>4/28/05 New Whisper 100 head</td>
</tr>
<tr>
<td>7/4/05 Controller board failure</td>
<td>7/23/05 Replacement board</td>
</tr>
</tbody>
</table>

From the 6/12/04 installation until 11/28/05, the Jacobs has been available 50% of the time. Three long periods of downtime were experienced due to Mastermind controller and grid connection issues, hurricane damage, and winter storm damage. The machine was considered available during the period grid voltage issues. The repairs were done onsite by SWI personnel.
and Bob Cantrell. New blades and hardware were purchased from the distributor, Wind Turbine Industries (WTI), and were not covered under the warranty (windstorm, lightning and hail damage not covered).

One short downtime was experienced due to a failed rectifier component in the Mastermind. A used replacement was sent from WTI at no cost which solved the problem. The machine is currently down due to another tail failure. A new tail was purchased at cost and we are awaiting good weather for the repair.

Figure 9. Jacobs 31-20 availability from 6/12/04 to 11/28/05.
Table 7 Failures and repairs for the Jacobs 31-20

<table>
<thead>
<tr>
<th>Failure</th>
<th>Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/14/04 Mastermind controller issues</td>
<td>9/1/04 New board and wire</td>
</tr>
<tr>
<td>9/17/04 Damaged tail and brake failure (Hurricane Ivan)</td>
<td>10/30/05 Spring rod replaced; brake pads replaced</td>
</tr>
<tr>
<td>10/30/05 Unable to bring the machine online due to grid voltage issues</td>
<td>1/20/05 Upgraded main utility service to 200A, new primary cable, new transformer, new secondary line</td>
</tr>
<tr>
<td>1/24/05 Tail failed in a winter storm; two blades damaged</td>
<td>6/6/05 Installed repaired tail and two new blades</td>
</tr>
<tr>
<td>10/15/05 Diode in rectifier failed</td>
<td>11/8/05 Installed replacement diode</td>
</tr>
<tr>
<td>11/11/05 Tail failed in winter storm; one blade damaged</td>
<td>pending</td>
</tr>
</tbody>
</table>

Wind Shear

The one-second raw data contained the only archive of the lower anemometer wind speeds. This was merely an oversight as the upper and lower wind speeds were intended to be logged as 10-minute averages for wind shear calculations. Since analyzing the one-second data is quite arduous, a relatively small sample was used to calculate a site average wind shear.

Upper and lower wind speeds were analyzed for the AirX, Bergey XL.1, and AWP 3.6 for the period of 7/10/05 to 7/14/05. The wind shear coefficient, alpha, was calculated from the
432,000 lines of data per tower. Table 8 shows that a site average alpha of .242 was derived from the analysis.

Table 8 Beech Mountain wind shear was calculated as a site average using data from 7/10/05 to 7/14/05.

<table>
<thead>
<tr>
<th>Tower</th>
<th>Average Alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td>AirX</td>
<td>.220</td>
</tr>
<tr>
<td>AWP 3.6</td>
<td>.210</td>
</tr>
<tr>
<td>Bergey XL.1</td>
<td>.296</td>
</tr>
<tr>
<td>Test site average</td>
<td>.242</td>
</tr>
</tbody>
</table>

Power Curves

The Whisper 175 power curve scatter plot is shown in figure 10. The highest filled bin (30 minutes of data) is the 30 mph bin with 200 hours of total test points used. Figure 11 shows the binned power curve as compared to the published power curve. Error bars are greater in bins with few data points and more variability.
**Figure 10.** Whisper 175 scatter plot.

**Figure 11.** Whisper 175 normalized power curve as compared to the published curve.
The Whisper H40/100 power curve scatter plot is shown in figure 12. The highest filled bin is the 40 mph bin with 181 hours of total test points used. Figure 13 shows the binned power curve as compared to the published power curve.
Figure 13. Whisper H40/100 normalized power curve as compared to the published curve.

The AirX power curve scatter plot is shown in figure 14. The highest filled bin is the 34 mph bin with 202 hours of total test points used. Figure 15 shows the binned power curve as compared to the published power curve.
Figure 14. AirX scatter plot.

Figure 15. AirX normalized power curve as compared to the published curve.
The Bergey XL.1 power curve scatter plot is shown in figure 16. The highest filled bin is the 37 mph bin with 219 hours of total test points used. Figure 17 shows the binned power curve as compared to the published power curve.

Figure 16. Bergey XL.1 scatter plot.
Figure 17. Bergey XL.1 normalized power curve as compared to the published curve.

The AWP 3.6 power curve scatter plot is shown in figure 18. The highest filled bin is the 45 mph bin with 191 hours of total test points used. Figure 19 shows the binned power curve as compared to the published power curve.

New experimental blades were installed on the AWP 3.6 on 10/10/05 for comparison to the stock blades. Figure 20 shows the scatter plot. The highest filled bin is the 43 mph bin with 184 hours of total test points used. Figure 21 compares the power performance of the stock blades and new blades as well as the published curve.
Figure 18. AWP 3.6 scatter plot.

Figure 19. AWP 3.6 normalized power curve as compared to the published curve.
Figure 20. AWP 3.6 scatter plot with test blades.

Figure 21. AWP 3.6 normalized power curves comparing test blades to stock blades and the published curve.
The power curves produced were used to estimate energy output for a variety of average wind speeds using the method of bins and a Rayleigh distribution. Table 9 shows estimated monthly energy outputs for each turbine.

![Table 9](image)

**Discussion of results**

**Reliability**

Keeping up with repairs at the test site was no easy job. With the exception of the AirX, all turbines experienced multiple failures resulting in considerable downtime. Installing the turbines on tilt-up towers made the repairs manageable and typically inexpensive. In contrast, repairs to the Jacobs were quite challenging and costly since all work was done at the 120’ tower top using climbing gear and sometimes a crane.
For the most part, replacement parts were covered under the manufacturer’s warranty and customer service was excellent from Southwest Windpower, Abundant Renewable Energy, Bergey Windpower, and Wind Turbine Industries. In the event of a failure, I would typically email a photo and description of the problem to an established contact at the manufacturer and responses were prompt and clear.

Most repairs were performed on site using replacement parts. The Whisper 175 was sent back to the Southwest Windpower to repair the 12 field wires from the alternator. A short in the junction box melted the connections and wire identifications making the repair too complicated for our skills. The AWP yaw head was sent back to Abundant Renewable Energy for a tail hinge repair. The wear to the hinge mechanism was assessed as five years of wear in nine months time. This speaks to the ferocity of the winds the turbines experienced at our energetic test site.

Overall, reliability was disappointing. Wind turbines installed on our mountain ridges will see many high wind events and heavy-duty, robust machines should be chosen to maximize up time.

Power performance

Surprisingly, I was only able to produce a complete power curve for the AWP 3.6. The other turbines require more data
points at high wind speeds to fill the uppermost bins with the minimum 30 minutes of measurements over the full range of wind speeds (up to 20 m/s or 44 mph). Data collection was performed over the summer, the season of low winds. Upper bins will certainly be filled during winter and spring data collection. The only concern for winter data is icing of the anemometers. While constructing these power curves, anemometer icing was observed while importing data from late November. The turbines power output was high while measured wind speeds were low. This data was removed. This is typical as the small, lightweight anemometers will experience icing before the heavier turbines with more rotational momentum.

The Bergey XL.1 power curve exceeded the published power curve quite significantly, peaking out at nearly 1400 watts instead of the published peak of just over 1000 watts. The curve also rose more quickly than the published curve. The scatter plot shows an interesting bifurcated section which may reflect the intermittent breaker-tripping issue with this machine.

As observed during testing, the AirX continues to produce power at high wind speeds instead of stalling to near zero at around 30 mph per the published curve. Other reports demonstrate the AirX not meeting the published curve yet our curve shows the turbine closely matching the published rise but exceeding the 400 watt peak at higher wind speeds rising to nearly 700 watts.
The scatter plot shows a clean and tight data set with few outliers.

The Whisper H40/Whisper 100 power curve did not peak at the rated 900 watts as expected. Sporadic power at wind speeds above 20 mph dropped the average peak to just under 700 watts. As expected, the angle-furling turbine maintains this maximum power throughout high wind speeds.

The Whisper 175 power curve closely matches the published curve but more data is needed at higher wind speeds to fill the bins and further define the peak. The scatter plot shows some outliers which likely infiltrated the data set during one the machine’s several wiring shorts where the turbine produced less-than-typical power for a period of time.

The AWP 3.6 scatter plot shows a clean rise to a peak of 1600 watts. The side-furling turbine output drops erratically at higher wind speeds as expected. The published power curve shows an earlier and high peak and a steeper drop after furling.

The AWP blade test resulted in a power curve which more closely resembles the published curve than the stock blades. The rise is close to published and a peak power of 1600 watts is reached at 23 mph. The machine appears to furl sooner than the stock blades. This may be attributed to the higher density blade profile of the test blades. A denser rotor may experience a higher rotor force and thus an earlier furl. No considerable
improvement in energy output was measured for the test blades. The new blades will produce only 1-2% more energy.

The Jacobs power data was corrupted by the data logging software. All values were truncated to 7999 watts, so no values above that level have been logged, thus, no power curve can be generated at this time. We have attempted to resolve this issue but the problem has not been found.

Recommendations and Further Research

Wind Speed measurements

A more exhaustive study of the wind shear at the test site could increase the accuracy of hub height wind speed estimates. SAS should be used to analyze the existing one-second data and 10-minute averages of the upper and lower wind speeds should be added to the Logger Net program.

To increase the accuracy even further, a meteorological tower could be installed at the test site with dual anemometers installed at each hub height per the IEC standards. This could both increase the accuracy of the measured hub height wind speeds and increase sensor life by removing the sensors from the vibrations of the turbine towers. An investment in calibrated anemometers would increase confidence in the wind speed data.

Wind speed measurements during times when the anemometers are in the flow distorted tower shadow should be excluded from the power curve data set to further improve accuracy.
Wind/solar hybrid research

Wind speed and solar insolation data should be analyzed to evaluate the performance of a wind/solar hybrid system at the site. Many of the turbine controllers are prepped for PV input so installing a wind/solar hybrid system would provide valuable performance data.

Turbulence Intensity
The apparent ferocity of the winds on Beech Mountain should be confirmed by an analysis of turbulence intensity at the site.

Wind rose
The wind direction measurements collected on each tower can be used to generate a wind rose for the test site. A wind rose shows the frequency and speeds of winds with respect to direction.

Data management
Selecting clean data for power curves where the turbines and instrumentation are online and functioning properly is a challenge. The data should be analyzed weekly and a detailed log should be maintained specifically noting any events which would affect data integrity such as sensor damage, icing, and stopping the turbines. A system should be established for backing up the data on a regular basis to ensure no loss of data.

Energy
Energy should be measured and logged for each turbine. Perhaps this could be performed using a Logger Net function.
standard kilowatt-hour meter would serve as a simple redundant comparison to calculated energy output.

Summary

The Beech Mountain test site has proven to be an energetic wind site with frequent high-wind events. Even in the low-wind season of summer, average wind speeds of over 40 mph were recorded. With the exception of the 400W AirX, all of the test turbines experienced multiple failures resulting in considerable downtime, requiring repair or replacement. For a wind turbine to perform reliably at a typical western North Carolina wind site, a heavy-duty, robust machine must be selected. The small wind market is continually evolving and reliability is at the forefront of the technological developments. Real world test sites such as ours will help identify failures and aid in increasing the reliability of small wind turbines.

Power performance research resulted in some turbines exceeding published power curves and others falling short of expectations. Perhaps these discrepancies shed light on the lack of a small wind testing standards available to manufacturers and independent testers. Such a standard testing protocol is currently being developed for small wind turbines. A common testing protocol will only aid consumers in comparing apples to apples while deciding on a small wind system.
References


Appendix A: Logger Net program used for data acquisition

'CR1000
'Program by Kevin Rhodes; Campbell Scientific, Inc.
'19 Feb 2005
'
'BWR4 - added wind vanes to table, changed to 1 min averages, commented WindVector, BJS
'BWR6 - corrected wind vane offset programming, BJS
'Program will measure 12 Wind Speed and 6 Watt Meter sensors every second. It will also measure 6 Wind Dir,
'1 Air Temp, 1 Barometric Press, and 1 Solar Radiation sensor once per minute.
'Output is stored every 10 minutes, 1 minute, and 1 second
'BWR8 - changed Jacobs averages from FP2 to IEEE4...BS...7/23/05

'Wiring:
  CR1000 MUX/SDM Sensor
  1H       + Sig Jacobs watt meter
  1L       - Sig Jacobs
  2H       + Sig SWWP175 watt meter
  2L       - Sig SWWP175
  3H       + Sig Afri36 watt meter
  3L       - Sig Afri36
  4H       + Sig BergXL watt meter
  4L       - Sig BergXL
  5H       + Sig SWWPH40 watt meter
  5L       - Sig SWWPH40
  6H       + Sig SWWPAirX watt meter
  6L       - Sig SWWPAirX
--------------------------------------
  5V       Red #110S
  G        Shield / Black #110S
  7H       Sig Clear #110S
--------------------------------------
  12V      Red BP20
  G        Shield / Black BP20
  7L       Sig Green BP20
--------------------------------------
  C1  SDM
  C2  SDM
  C3  SDM
  12V  SDM
  G   SDM
    INT8 ADD 0
  CH1   + Sig WS1_Jacobs
  G     - Sig WS1_Jacobs
  CH2   + Sig WS2_Jacobs
  G     - Sig WS2_Jacobs
  CH3   + Sig WS1_SWWP175
  G     - Sig WS1_SWWP175
  CH4   + Sig WS2_SWWP175
  G     - Sig WS2_SWWP175
  CH5   + Sig WS1_Afri36
  G     - Sig WS1_Afri36
  CH6   + Sig WS2_Afri36
  G     - Sig WS2_Afri36
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--------------------------------------
|     INT8 ADD 1                   |
|     CH1    + Sig WS1_BergXL     |
|     G     - Sig WS1_BergXL      |
|     CH2    + Sig WS2_BergXL     |
|     G     - Sig WS2_BergXL      |
|     CH3    + Sig WS1_SWWPH40    |
|     G     - Sig WS1_SWWPH40     |
|     CH4    + Sig WS2_SWWPH40    |
|     G     - Sig WS2_SWWPH40     |
|     CH5    + Sig WS1_SWWPAirX   |
|     G     - Sig WS1_SWWPAirX    |
|     CH6    + Sig WS2_SWWPAirX   |
|     G     - Sig WS2_SWWPAirX    |

--------------------------------------
| AM 16/32 set to 4 X 16            |
| 12V 12V                          |
| G       G                         |
| C5     Clock                      |
| C4     Reset                      |
| EX2    Com Odd H                  |
| G       Com Odd L                 |
| 8H     Com Even H                 |
| 8L     Com Even L                 |
| 1H1    Ex WD_Jacobs               |
| 1L1    G WD_Jacobs                |
| 1H2    Sig WD_Jacobs              |
| 1L2    G WD_Jacobs                |
| 2H1    Ex WD_SWWP175              |
| 2L1    G WD_SWWP175               |
| 2H2    Sig WD_SWWP175             |
| 2L2    G WD_SWWP175               |
| 3H1    Ex WD_Afri36               |
| 3L1    G WD_Afri36                |
| 3H2    Sig WD_Afri36              |
| 3L2    G WD_Afri36                |
| 4H1    Ex WD_BergXL               |
| 4L1    G WD_BergXL                |
| 4H2    Sig WD_BergXL              |
| 4L2    G WD_BergXL                |
| 5H1    Ex WD_SWWPH40              |
| 5L1    G WD_SWWPH40               |
| 5H2    Sig WD_SWWPH40             |
| 5L2    G WD_SWWPH40               |
| 6H1    Ex WD_SWWPAirX             |
| 6L1    G WD_SWWPAirX              |
| 6H2    Sig WD_SWWPAirX            |
| 6L2    G WD_SWWPAirX              |
| 7H1    White / Clear LI200X       |
| 7H2    + Sig Red LI200X           |
| 7L2    - Sig Black LI200X         |

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Declare Variables and Units

Dim LCount
Dim vane_offset(6)

Public Batt_Volt

Public NRG40A(6)
Public NRG40B(6)
Alias NRG40A(1) = WS1_Jacobs
Alias NRG40A(2) = WS2_Jacobs
Alias NRG40A(3) = WS1_SWWP175
Alias NRG40A(4) = WS2_SWWP175
Alias NRG40A(5) = WS1_Afri36
Alias NRG40A(6) = WS2_Afri36
Alias NRG40B(1) = WS1_BergXL
Alias NRG40B(2) = WS2_BergXL
Alias NRG40B(3) = WS1_SWWPH40
Alias NRG40B(4) = WS2_SWWPH40
Alias NRG40B(5) = WS1_SWWPAirX
Alias NRG40B(6) = WS2_SWWPAirX

'Public rpm(4)
'alias rpm(1)=rpm_SWWP175

Public PC5(6)
Alias PC5(1) = Watt_Jacobs
Alias PC5(2) = Watt_SWWP175
Alias PC5(3) = Watt_Afri36
Alias PC5(4) = Watt_BergXL
Alias PC5(5) = Watt_SWWPH40
Alias PC5(6) = Watt_SWWPAirX

Public NRG200P(6)
Alias NRG200P(1) = WD_Jacobs
Alias NRG200P(2) = WD_SWWP175
Alias NRG200P(3) = WD_Afri36
Alias NRG200P(4) = WD_BergXL
Alias NRG200P(5) = WD_SWWPH40
Alias NRG200P(6) = WD_SWWPAirX

Public NRG110S
Public NRGBP20
Public LI200X

'Power Transducer calibration factors
'Mult1: Jacobs
'changed to corrected multiplier for Jake transducer 6/8/05 BJS
'Const mult1 = 4.0   '20,000W / 5,000mv PC5-070CX5
Const mult1 = 8.0   '40,000W / 5,000mv PC5-070CX5

'Mult2: 175 (now the 500)
'changed to new Whisper 500 AC Transducer PC5-110CX5
'Const mult2 = 1.0   '5,000W / 5,000mv PC8-002-01X5
Const mult2 = .8    '4,000W / 5,000mv PC5-110CX5

'Mult3: AWP
'Changed to new AWP transducer: PC5-117CX5
'Const mult3 = 0.30  '1,500W / 5,000mv PC5-019CX5
Const mult3 = 0.40  '2,000W / 5,000mv PC5-117CX5

'Mult4: AirX
Const mult4 = 0.50  '2,500W / 5,000mv PC8-001-01X5

'Mult5: H40 (now Whisper100) new on 9/22/05
Const mult5 = 1.0   '5,000W / 5,000mv PC8-002-01X5

'Mult6: Bergey (now the Whisper200) new on 9/22/05
Const mult6 = .3     '1,500W / 5,000mv PC5-019CX5

DataTable(Tab_1Min,True,-1)  
'BJS changed to 1 min average, 4/3/05
DataInterval(0,1,Min,1)
Average (6,PCS(),FP2,False)
'BJS commented WindVectors
'WindVector (1,WS2_Jacobs,WD_Jacobs,FP2,False,0,0,0)
Average (1,WS1_SWWP175,FP2,False)
'WindVector (1,WS2_SWWP175,WD_SWWP175,FP2,False,0,0,0)
Average (1,WS1_Afri36,FP2,False)
'WindVector (1,WS2_Afri36,WD_Afri36,FP2,False,0,0,0)
Average (1,WS1_BergXL,FP2,False)
'WindVector (1,WS2_BergXL,WD_BergXL,FP2,False,0,0,0)
Average (1,WS1_SWWPH40,FP2,False)
'WindVector (1,WS2_SWWPH40,WD_SWWPH40,FP2,False,0,0,0)
Average (1,WS1_SWWPAirX,FP2,False)
'WindVector (1,WS2_SWWPAirX,WD_SWWPAirX,FP2,False,0,0,0)
'BJS added Jacobs WS1
'Average (1,WS1_Jacobs,FP2,False)
'changed to Jacobs Average to IEEE4
Average (1,WS1_Jacobs,IEEE4,False)
'BJS added wind directions
Average (1,WD_SWWP175,FP2,False)
Average (1,WD_Afri36,FP2,False)
Average (1,WD_SWWPAirX,FP2,False)
Average (1,WD_BergXL,FP2,False)
Average (1,WD_SWWPH40,FP2,False)
'changed to Jacobs Average to IEEE4
'Average (1,WD_Jacobs,FP2,False)
Average (1,WD_Jacobs,IEEE4,False)
'added max wind speeds
Maximum (1,WS1_SWWP175,FP2,False,False)
Maximum (1,WS1_Afri36,FP2,False,False)
Maximum (1,WS1_BergXL,FP2,False,False)
Maximum (1,WS1_SWWPH40,FP2,False,False)
Maximum (1,WS1_SWWPAirX,FP2,False,False)
'changed to Jacobs Average to IEEE4
'Maximum (1,WS1_Jacobs,FP2,False,False)
Maximum (1,WS1_Jacobs,IEEE4,False,False)
'added max power
Maximum (1,Watt_SWWP175,FP2,False,False)
Maximum (1,Watt_Afri36,FP2,False,False)
Maximum (1,Watt_BergXL,FP2,False,False)
Maximum (1,Watt_SWWPH40,FP2,False,False)
Maximum (1,Watt_SWWPAirX,FP2,False,False)
'changed to Jacobs Average to IEEE4
'Maximum (1,Watt_Jacobs,FP2,False,False)
Maximum (1,Watt_Jacobs,IEEE4,False,False)

Average (1,NRG110S,FP2,False)
Average (1,NRGBP20,FP2,False)
Average (1,LI200X,FP2,False)
Minimum(1,Batt_Volt,FP2,False,False)

EndTable

DataTable(Tab_10M,True,-1)
'BJS changed to 1 min average, 4/3/05
DataInterval(0,10,Min,1)
Average (6,PC5(),FP2,False)
'bwr standard dev array added 4/22/05
StdDev (6,PC5(),FP2,False)
'BJS commented WindVectors
'WindVector (1,WS2_Jacobs,WD_Jacobs,FP2,False,0,0,0)
Average (1,WS1_SWWP175,FP2,False)
'WindVector (1,WS2_SWWP175,WD_SWWP175,FP2,False,0,0,0)
Average (1,WS1_Afri36,FP2,False)
'WindVector (1,WS2_Afri36,WD_Afri36,FP2,False,0,0,0)
Average (1,WS1_BergXL,FP2,False)
'WindVector (1,WS2_BergXL,WD_BergXL,FP2,False,0,0,0)
Average (1,WS1_SWWPH40,FP2,False)
'WindVector (1,WS2_SWWPH40,WD_SWWPH40,FP2,False,0,0,0)
Average (1,WS1_SWWPAirX,FP2,False)
'WindVector (1,WS2_SWWPAirX,WD_SWWPAirX,FP2,False,0,0,0)
'BJS added Jacobs WS1
Average (1,WS1_Jacobs,FP2,False)
'BJS added wind directions
Average (1,WD_SWWP175,FP2,False)
Average (1,WD_Afri36,FP2,False)
Average (1,WD_SWWPAirX,FP2,False)
Average (1,WD_BergXL,FP2,False)
Average (1,WD_SWWPH40,FP2,False)
Average (1,WD_Jacobs,FP2,False)
'added max wind speeds
Maximum (1,WS1_SWWP175,FP2,False,False)
Maximum (1,WS1_Afri36,FP2,False,False)
Maximum (1,WS1_BergXL,FP2,False,False)
Maximum (1,WS1_SWWPH40,FP2,False,False)
Maximum (1,WS1_SWWPAirX,FP2,False,False)
Maximum (1,WS1_Jacobs,FP2,False,False)

'added max power
Maximum (1,Watt_SWWP175,FP2,False,False)
Maximum (1,Watt_Afri36,FP2,False,False)
Maximum (1,Watt_BergXL,FP2,False,False)
Maximum (1,Watt_SWWPH40,FP2,False,False)
Maximum (1,Watt_SWWPAirX,FP2,False,False)
Maximum (1,Watt_Jacobs,FP2,False,False)
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```plaintext
Average (1,NRG110S,FP2,False)
Average (1,NRGBP20,FP2,False)
Average (1,LI200X,FP2,False)
Minimum(1,Batt_Volt,FP2,False,False)

EndTable

DataTable(Tab_1Sec,True,-1)
' added 4/5/05 bwr
  DataInterval(0,1,Sec,2)
  Sample (6,NRG40A(),FP2)
  Sample (6,NRG40B(),FP2)
  Sample (6,PC5(),FP2)
  'add rpm
  ' sample (4,rpm(),fp2)
EndTable

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

'Main Program
BeginProg

'vane offsets
'vane_offset(1) = Jacobs_offset
'vane_offset(2) = SWWP175_offset
'vane_offset(3) = Afri36_offset
'vane_offset(4) = BergXL_offset
'vane_offset(5) = SWWPH40_offset
'vane_offset(6) = SWWPAirX_offset
'BJS changed offsets back to 0 on 4/18/05 @ 3p,
'BJS & JL estimated and added offsets on 4/22/05 @ 3pm
vane_offset(1) = 61
vane_offset(2) = 310
vane_offset(3) = 295
'changed from 200 to 40 for new Whisper200 tower 10/20/05 BJS
vane_offset(4) = 40
vane_offset(5) = 270
vane_offset(6) = 93

'fast (1 second) scan of CR1000
Scan(1,Sec,2,0)

'Datalogger Battery Voltage measurement Batt_Volt:
Battery(Batt_Volt)

'Wind Speed sensors for 6 turbines using NRG#40
'2 anemometers for each turbine:
SDMINT8 (NRG40A(),0,0022,2222,0022,2222,0,0,1,0)
NRG40A(1) = NRG40A(1)*1280 + 2.24 'heated anemometer
NRG40A(3) = NRG40A(3)*1711 + 0.78
NRG40A(4) = NRG40A(4)*1711 + 0.78
NRG40A(5) = NRG40A(5)*1711 + 0.78
NRG40A(6) = NRG40A(6)*1711 + 0.78
'changed transfer functions from Campbell's to NRG's
'old (Campbell) transfer function was Freq*1708 + 0
```
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'bwr 8/26/05
SDMINT8 (NRG40B(),1,0022,2222,0022,2222,0,0,1708,0)
'read 175 current donut to get rpm
' sdmint8(rpm(),0,2000,0000,2000,0000,0,0,1,0)

'Power output for 6 turbines from PM5 transducers PM5:
VoltDiff(PC5(),6,mV5000,1,True,0,60Hz,1.0,0.0)
'Apply multpliers for FSR of transducer:
Watt_Jacobs = Watt_Jacobs * mult1
Watt_SWWP175 = Watt_SWWP175 * mult2
Watt_Afri36 = Watt_Afri36 * mult3
Watt_BergXL = Watt_BergXL * mult6
Watt_SWWPH40 = Watt_SWWPH40 * mult5
Watt_SWWPAirX = Watt_SWWPAirX * mult4

'Ai Temperture measurements NRG110S:
' VoltSe (NRG110S,1,mV2500,13,1,0,60Hz,.05555,-86.38)
'Air Temp in F
VoltSe (NRG110S,1,mV2500,13,1,0,60Hz,.1,-123.5)

'Barometric Pressure measurements NRGBP20:
'VoltSe (NRGBP20,1,mV5000,15,1,0,60Hz,.02179,10.55)
VoltSe (NRGBP20,1,mV5000,14,1,0,60Hz,.02179,11.09)
'altitude correction for 5200 ft
NRGBP20 = NRGBP20 * 760 / 101.325 / 25.4 + 5.414

'Call Data Tables and Store Data
CallTable(Tab_1Sec)
CallTable(Tab_1Min)
CallTable(Tab_10M)
NextScan

'slow (10 second) scan of multiplexer
SlowSequence
'%%%%% Scan(1,Min,1,0)
Scan (10,Sec,2,0)
'Turn AM16/32 Multiplexer On every 10 sec
PortSet(4,1)
For LCount = 1 To 6
'SubScan(0,uSec,6)
'Switch to next AM16/32 Multiplexer channel
PulsePort(5,10000)
'Wind Direction sensor measurements NRG200P on the AM16/32
Multiplexer:
'BrHalf
(NRG200P(LCount),1,mV2500,13,Vx1,1,2500,False,10000,60Hz,0.144,0)
BrHalf (NRG200P(LCount),1,mV2500,15,Vx1,1,2500,False,0,60Hz,1,0)
'from voltage to uncalibrated direction
NRG200P(LCount) = NRG200P(LCount)*360
'calibrate by applying offset
IF (NRG200P(LCount) + vane_offset(LCount)) < 360 THEN
  NRG200P(LCount) = NRG200P(LCount) + vane_offset(LCount)
ELSE
  NRG200P(LCount) = NRG200P(LCount) - (360 - vane_offset(LCount))
ENDIF
'NRG200P(LCount) = NRG200P(LCount)*360 + vane_offset(LCount)
next LCount
  '    NextSubScan
  'Switch to next AM16/32 Multiplexer channel
  PulsePort(5,10000)
  'LI200X Pyranometer measurements SlrkW:
  VoltDiff(LI200X,1,mV7_5,8,TRUE,10000,_60Hz,1,0)
  If LI200X<0 Then LI200X=0
  LI200X=LI200X*200

  'Turn AM16/32 Multiplexer Off
  PortSet(4,0)

NextScan
EndProg
Appendix B: Logs

Attached logs:

- Main activity log
- AirX Activity Log
- AWP 3.6 Activity Log
- Whisper 175 Activity Log
- Bergey XL.1 Activity Log
- Jacobs 31-20 Activity Log
- Whisper H40 Activity Log