

WIND DATA REPORT

Barnstable, MA

April 1, 2005 – March 31, 2006

Prepared for

Massachusetts Technology Collaborative
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Westborough, MA 01581

by

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EXECUTIVE SUMMARY

All the work presented in this Wind Data Report including installation and decommissioning of the meteorological tower and instrumentation, and the data analysis and reporting was performed by the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts, Amherst.

Wind monitoring equipment was first installed in Barnstable, MA in late March 2005, with data collection starting from the 30th of that month through April 28, 2006. Five anemometers, three vanes, a temperature sensor, and a data logger are mounted on a 40 m monitoring tower.

Data collection percentages during the twelve month period of April 2005 through March 2006 were excellent: the raw data recovery rate was 100%, and after quality assurance the percentage of good data was 99.98%. The average wind speed during the twelve months was 5.28 m/s at 39 m height (11.81 mph at 128 ft.)*. Turbulence intensity for this time period was an average of 0.2. The prevailing wind was from the West overall.

Additional information about interpreting the data presented in this report can be found in the Fact Sheet, "Interpreting Your Wind Resource Data", produced by RERL and the Massachusetts Technology Collaborative (MTC). This document is found through the RERL website:

http://www.ceere.org/rerl/about_wind/RERL_Fact_Sheet_6_Wind_resource_interpretation.pdf

* 1 m/s = 2.237 mph

SECTION 1 - Station Location

The monitoring tower is located on a plateau adjacent to the town's wastewater treatment plant (WWTP), on the corner of Route 28 and Bearses Way. The wind monitoring tower is mounted on a 40 m NRG tubular steel tower, anchored with guy lines at four directions. Site coordinates are 41° 39.885' North, 70° 18.270' West per the WSG84 standard (the World Geodetic System 1984, an international standard for absolute localization with earthly coordinates). See the figure below for a map of the tower location, which is at the map center (at the first letter "S" in the label "Sewage Disposal").

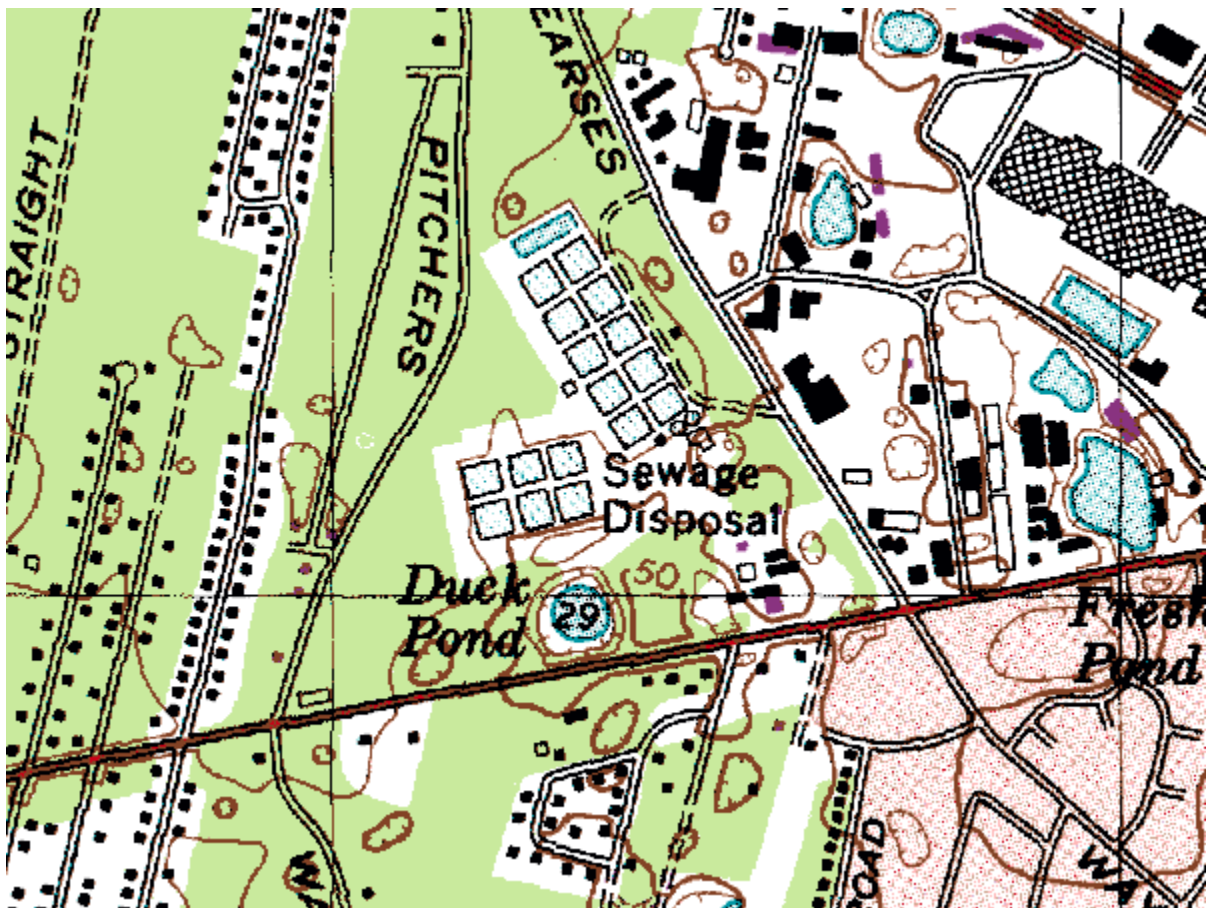


Figure 1 – Map of Barnstable wind tower site

SECTION 2 - Instrumentation and Equipment

An alternating-color, red and white 40 m NRG tower holds five NRG anemometers on three booms: one at 10 m, two at 30 m, and two at 39 m. Each anemometer is 54" away from the tower, and 18" above its boom. Also on a separate boom is an NRG 200P Wind Vane. In addition, an FAA-compliant red hazard light is mounted on the tower top.

The installed equipment comprises:

- Symphonie data logger
- NRG 110S Temperature Sensor
- Five #40 anemometers, standard calibration (slope 0.765 m/s, offset 0.350 m/s)
- Three #200P wind direction vanes
- Medium booms for vanes, 39" from tower mast
- Long side booms for anemometers, 54" from tower mast
- Lightning rod and grounding cable
- FAA hazard light

SECTION 3 - Data Collection and Maintenance

During the period of April 1, 2005 through March 31, 2006, no maintenance events occurred. Data collection during this period was excellent, with results summarized below:

| Date | 39m Mean 10 min | 39m Max | 30m Mean 10 min | 30m Max | 10m Mean 10 min | 10m Max | 39m Turbulence Intensity | 39m Prevailing Wind Direction | 30m Turbulence Intensity | 30m Prevailing Wind Direction | Wind shear coefficient |
|--------------------------------|--------------------------|------------|--------------------------|------------|--------------------------|------------|--------------------------------|--|--------------------------------|--|------------------------------|
| | [m/s] | [m/s] | [m/s] | [m/s] | [m/s] | [m/s] | [] | [] | [] | [] | [] |
| 2005 April | 5.68 | 13.2 | 5.25 | 12.6 | 3.87 | 10.7 | 0.2 | 202.5 | 0.21 | 225 | 0.34 |
| May | 5.72 | 19.1 | 5.41 | 17.9 | 4.19 | 15 | 0.21 | 360 | 0.22 | 360 | 0.28 |
| June | 5 | 11.5 | 4.7 | 11 | 3.72 | 9.4 | 0.2 | 225 | 0.21 | 225 | 0.24 |
| July | 4.55 | 13.7 | 4.21 | 12.8 | 3.13 | 10.2 | 0.21 | 225 | 0.22 | 225 | 0.32 |
| August | 4.46 | 11.1 | 4.1 | 10.1 | 2.91 | 8 | 0.19 | 225 | 0.21 | 225 | 0.37 |
| September | 4.64 | 12.5 | 4.26 | 11.9 | 3.02 | 9.9 | 0.2 | 225 | 0.21 | 202.5 | 0.41 |
| October | 5.64 | 16.7 | 5.19 | 15.6 | 3.66 | 10.8 | 0.21 | 360 | 0.22 | 270 | 0.38 |
| November | 5.33 | 14.4 | 4.82 | 13.6 | 3.37 | 10.9 | 0.19 | 225 | 0.21 | 225 | 0.41 |
| December | 5.22 | 20.7 | 4.75 | 18.6 | 3.46 | 14.9 | 0.19 | 270 | 0.21 | 270 | 0.39 |
| 2006 January | 5.91 | 15.9 | 5.42 | 14.9 | 4 | 11.9 | 0.2 | 315 | 0.21 | 225 | 0.36 |
| February | 5.94 | 18.3 | 5.45 | 17.7 | 4.11 | 15.4 | 0.2 | 292.5 | 0.21 | 292.5 | 0.36 |
| March | 5.23 | 12.7 | 4.82 | 11.7 | 3.7 | 9.6 | 0.2 | 315 | 0.21 | 315 | 0.31 |
| April 05 – March 06 | 5.28 | 20.7 | 4.87 | 18.6 | 3.6 | 15.4 | 0.2 | 270, W | 0.21 | 225, SW | 0.35 |

Data Statistics Summary

Wind data statistics in the table are reported when more than 90% of the data during the reporting period are valid. In cases when a larger amount of data are missing, the percent of the available data that are used to determine the data statistics is noted.

No measurement of wind speed can be perfectly accurate. Errors occur due to anemometer manufacturing variability, anemometer calibration errors, the response of anemometers to turbulence and vertical air flow and due to air flows caused by the anemometer mounting system. Every effort is made to reduce the sources of these errors. Nevertheless, the values reported in this report have an expected uncertainty of about $\pm 2\%$ or ± 0.2 m/s, whichever is greater.

When data at multiple heights are available, shear coefficients, α , have been determined. They can be used in the following formula to estimate the average wind speed, $U(z)$, at height z , when the average wind speed, $U(z_r)$, at height z_r is known:

$$U(z)=U(z_r)\left(\frac{z}{z_r}\right)^\alpha$$

The change in wind speed with height is a very complicated relationship related to atmospheric conditions, wind speed, wind direction, time of day and time of year. This formula may not provide the correct answer at any given site. Nevertheless the calculated shear coefficient, based on measurements at two heights, can be used to characterize the degree of increase in wind speed with height at a site.

SECTION 4- Significant Meteorological Events

The months of April 2005 through March 2006 were unremarkable meteorologically. There were no major wind events shown in the wind speed time series. For further information see:

<http://www.erh.noaa.gov/box/MonthlyClimate2.shtml>

SECTION 5 - Data Recovery and Validation

All raw wind data are subjected to a series of tests and filters to weed out data that are faulty or corrupted. Definitions of these quality assurance (QA) controls are given below under Test Definitions and Sensor Statistics. These control filters were designed to automate the quality control process and used many of the previous hand-worked data sets made at UMass to affect a suitable emulation. The gross percentage of data recovered (ratio of the number of raw data points received to data points expected) and net percentage (ratio of raw data points which passed all QA control tests to data points expected) are shown below.

| | |
|--------------------------|--------|
| Gross Data Recovered [%] | 100.00 |
| Net Data Recovered [%] | 99.98 |

Test Definitions

All raw data were subjected to a series of validation tests, as described below. The sensors tested and the parameters specific to each sensor are given in the Sensor Performance Report which is included in APPENDIX A. Data which were flagged as invalid were not included in the statistics presented in this report.

MinMax Test: All sensors are expected to report data values within a range specified by the sensor and logger manufacturers. If a value falls outside this range, it is flagged as invalid. A data value from the sensor listed in Test Field 1 (TF1) is flagged if it is less than Factor 1 (F1) or greater than Factor 2. This test has been applied to the following sensors (as applicable): wind speed, wind speed standard deviation, wind direction, temperature, and solar insolation.

$$F1 > TF1 > F2$$

MinMaxT Test: This is a MinMax test for wind direction standard deviation with different ranges applied for high and low wind speeds. A wind direction standard deviation data value (TF1) is flagged either if it is less than Factor 1, if the wind speed (TF2) is less than Factor 4 and the wind direction standard deviation is greater than Factor 2, or if the wind speed is greater than or equal to Factor 4 and the wind direction standard deviation is greater than Factor 3.

$$\begin{aligned} & (TF1 < F1) \\ & \text{or } (TF2 < F4 \text{ and } TF1 > F2) \\ & \text{or } (TF2 \geq F4 \text{ and } TF1 > F3) \end{aligned}$$

Icing Test: An icing event occurs when ice collects on a sensor and degrades its performance. Icing events are characterized by the simultaneous measurements of near-zero standard deviation of wind direction, non-zero wind speed, and near- or below-freezing temperatures. Wind speed, wind speed standard deviation, wind direction, and wind direction standard deviation data values are flagged if the wind direction standard deviation (CF1) is less than or equal to Factor 1 (F1), the wind speed (TF1) is greater than Factor 2 (F2), and the temperature (CF2) is less than Factor 3 (F3). To exit an icing event, the wind direction standard deviation must be greater than Factor 4.

$$CF1 \leq F1 \text{ and } TF1 > F2 \text{ and } CF2 < F3$$

CompareSensors Test: Where primary and redundant sensors are used, it is possible to determine when one of the sensors is not performing properly. For anemometers, poor performance is characterized by low data values. Therefore, if one sensor of the pair reports values significantly below the other, the low values are flagged. At low wind speeds (Test Fields 1 and 2 less than or equal to Factor 3) wind speed data are flagged if the absolute difference between the two wind speeds is greater than Factor 1. At high wind speeds (Test Fields 1 or 2 greater than Factor 3) wind speed data are flagged if the absolute value of the ratio of the two wind speeds is greater is greater than Factor 2.

$$\begin{aligned} & [TF1 \leq F3 \text{ and } TF2 \leq F3 \text{ and } \text{abs}(TF1 - TF2) > F1] \\ & \text{or } [(TF1 > F3 \text{ or } TF2 > F3) \text{ and } (\text{abs}(1 - TF1 / TF2) > F2 \text{ or } \text{abs}(1 - TF2 / TF1) > F2)] \end{aligned}$$

Sensor Statistics

Expected Data Points: the total number of sample intervals between the start and end dates (inclusive).

Actual Data Points: the total number of data points recorded between the start and end dates.

% Data Recovered: the ratio of actual and expected data points (this is the *gross data recovered percentage*).

Hours Out of Range: total number of hours for which data were flagged according to MinMax and MinMaxT tests. These tests flag data which fall outside of an expected range.

Hours of Icing: total number of hours for which data were flagged according to Icing tests. This test uses the standard deviation of wind direction, air temperature, and wind speed to determine when sensor icing has occurred.

Hours of Fault: total number of hours for which data were flagged according to CompareSensors tests. These tests compare two sensors (e.g. primary and redundant anemometers installed at the same height) and flag data points where one sensor differs significantly from the other.

% Data Good: the filter results are subtracted from the gross data recovery percentage to yield the *net data recovered percentage*.

SECTION 6 - Data Summary

This report contains several types of wind data graphs. Unless otherwise noted, each graph represents data from 1 year (12 months) at the topmost sensor height, 39m. The following graphs are included:

- Time Series – 10-minute average wind speeds are plotted against time, Figure 2. We can see that the wind speeds exhibit an average around 5 m/s, and generally do not exceed 10 m/s.
- Wind Speed Distribution – A histogram plot giving the percentage of time that the wind is at a given wind speed, Figure 3. We can see that the wind speed is between 4 and 5 m/s most frequently.
- Monthly Average – A plot of the monthly average wind speed, over a 12-month period, Figure 4. This graph shows the trends in the wind speed over the year.

Twelve months, April 2005 through March 2006 inclusive, are shown. A seasonal decline of wind speed during the summer is evident.

- Diurnal – A plot of the average wind speed for each hour of the day, Figure 5. The plot clearly shows wind speed rising during daylight hours.
- Turbulence Intensity – A plot of turbulence intensity as a function of wind speed, Figure 6. Turbulence Intensity is calculated as the standard deviation of the wind speed divided by the wind speed and is a measure of the gustiness of a wind resource. Lower turbulence results in lower mechanical loads on a wind turbine. Below, we can see the turbulence values clustering around 0.2.
- Wind Rose – A plot, by compass direction showing the percentage of time that the wind comes from a given direction and the average wind speed in that direction, Figure 7. The winter season showed a clear bias from the West and Southwest directions.

SECTION 7 - Graphs

Data for the wind speed histograms, monthly and diurnal average plots, and wind roses are included in APPENDIX B.

Wind Speed Time Series

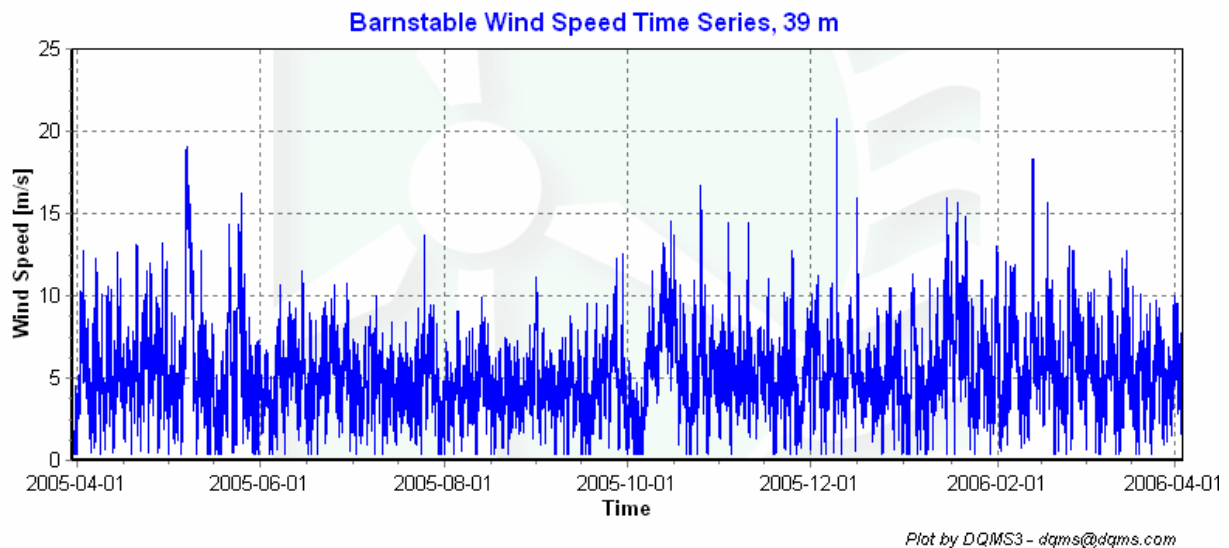
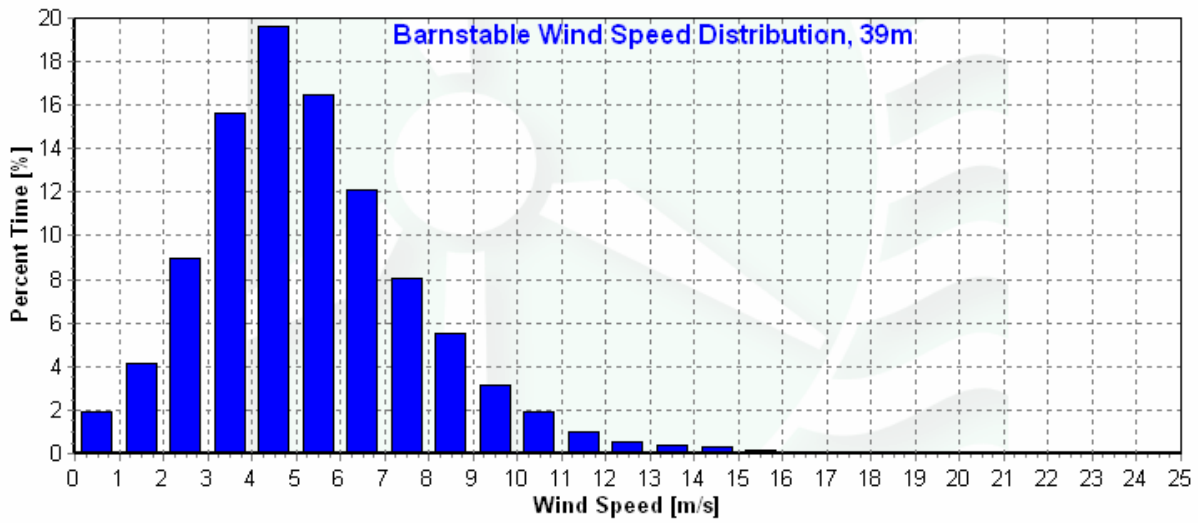


Figure 2 – Barnstable wind speed time series, April 1, 2005 – March 31, 2006

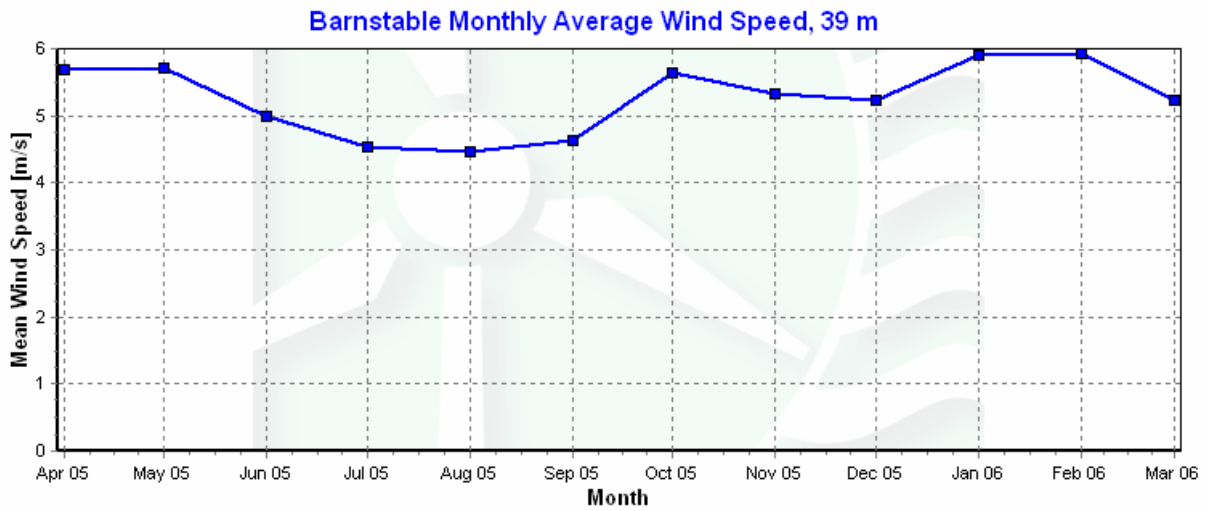
Wind Speed Distributions



Plot by DQMS3 - dqms@dqms.com

Figure 3 – Barnstable wind speed distribution, April 1, 2005 – March 31, 2006

Monthly Average Wind Speeds



Plot by DQMS3 - dqms@dqms.com

Figure 4 – Barnstable monthly average wind speed, April 2005 – March 2006

Diurnal Average Wind Speeds

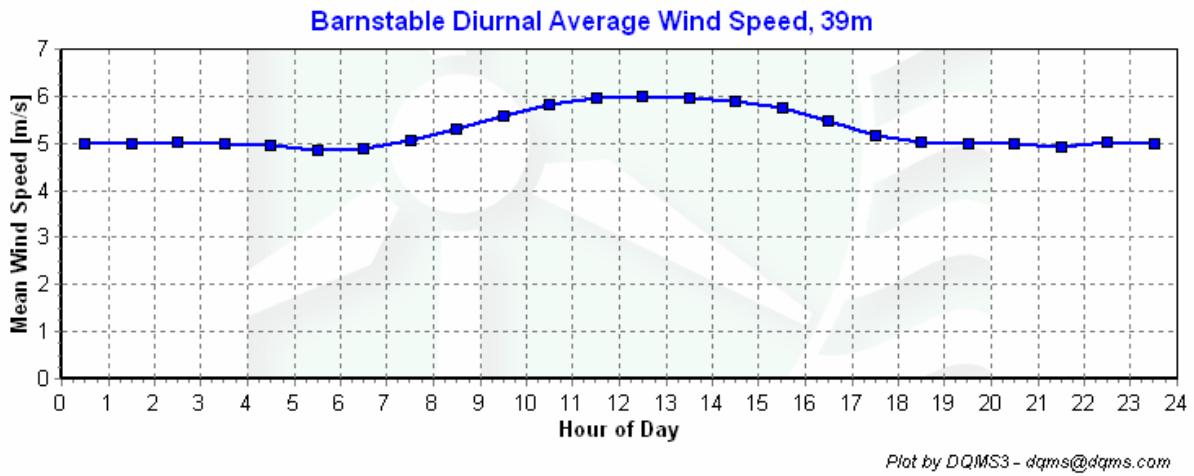


Figure 5 – Barnstable diurnal average wind speed, April 1, 2005 – March 31, 2006

Turbulence Intensities

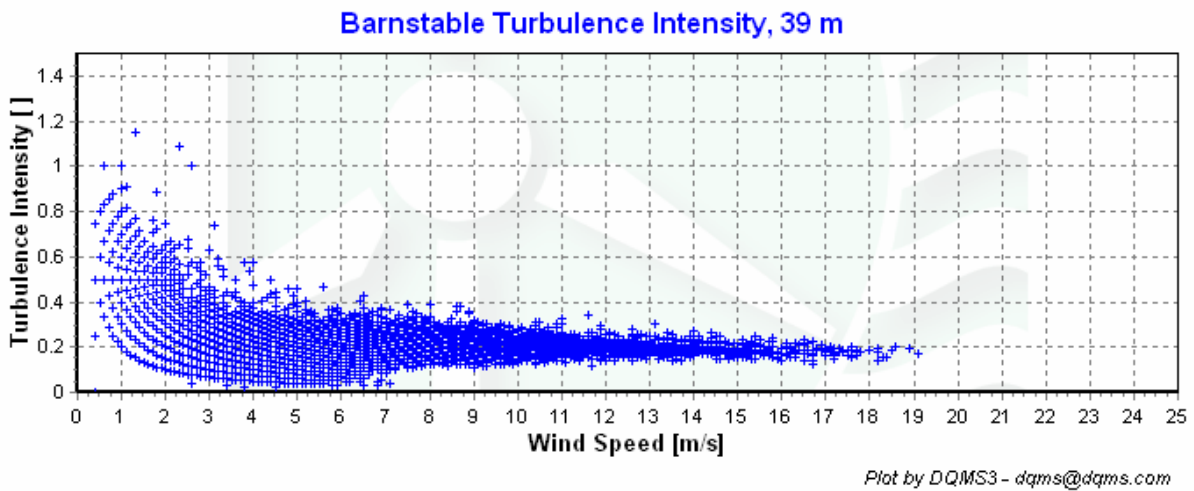
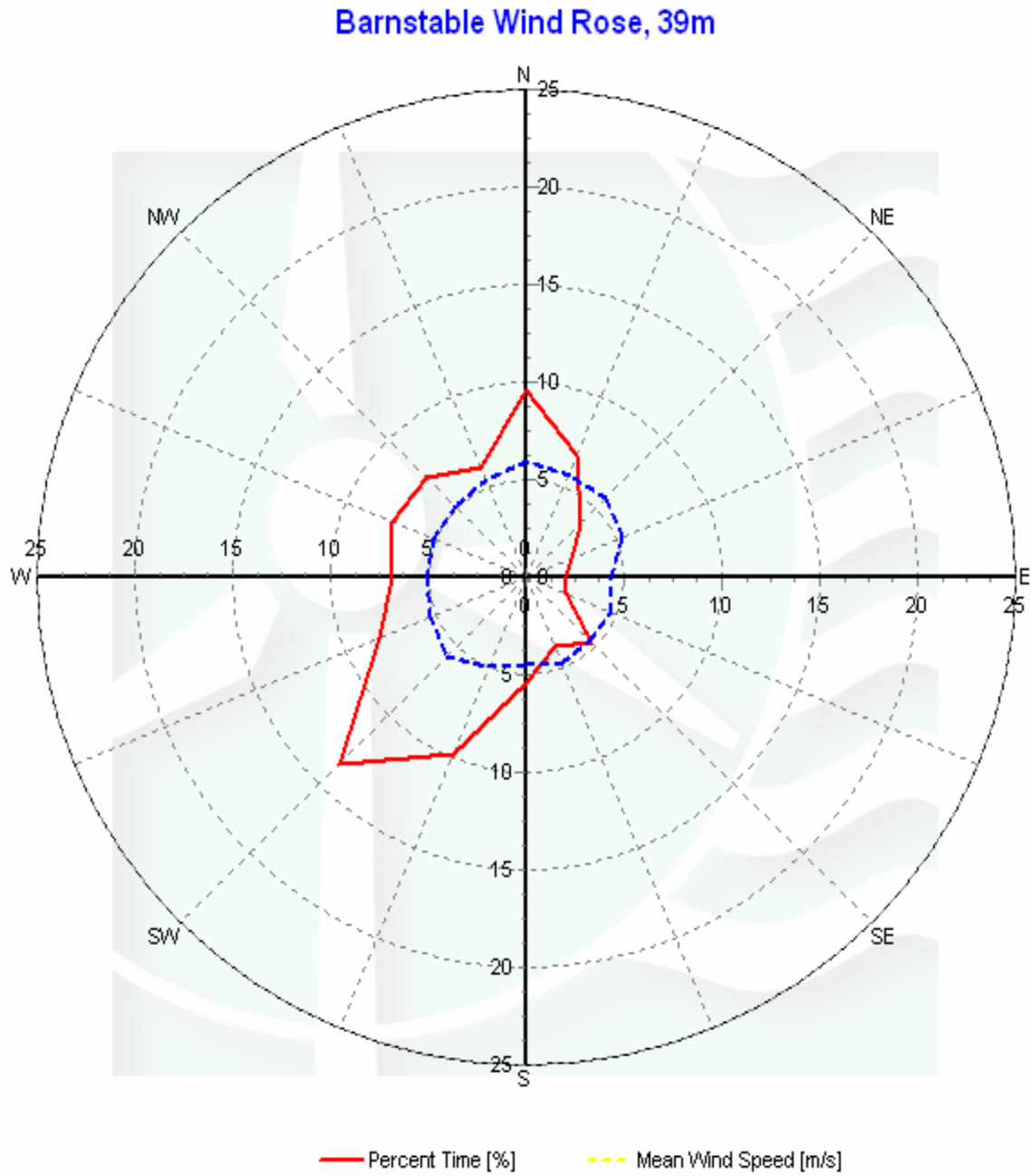


Figure 6 – Barnstable turbulence intensity, April 1, 2005 – March 31, 2006

Wind Roses



Plot by DQMS3 - dqms@dqms.com

Figure 7 – Barnstable wind rose, April 1, 2005 – March 31, 2006

APPENDIX A - Sensor Performance Report

Test Definitions

| Test Order | TestField1 | TestField2 | TestField3 | CalcField1 | CalcField2 | TestType | Factor1 | Factor2 | Factor3 | Factor4 |
|------------|--------------|-------------|------------|-------------|------------|----------------|---------|---------|---------|---------|
| 1 | | | | | | | | | | |
| 2 | Etmp2DEGC | | | | | MinMax | -30 | 60 | | |
| 3 | EtmpSD2DEGC | | | | | MinMax | -30 | 60 | | |
| 4 | Etmpmax2DEGC | | | | | MinMax | -30 | 60 | | |
| 5 | Etmpmin2DEGC | | | | | MinMax | -30 | 60 | | |
| 10 | Anem39aMS | | | | | MinMax | 0 | 90 | | |
| 11 | Anem39bMS | | | | | MinMax | 0 | 90 | | |
| 12 | Anem30aMS | | | | | MinMax | 0 | 90 | | |
| 13 | Anem30bMS | | | | | MinMax | 0 | 90 | | |
| 14 | Anem10MS | | | | | MinMax | 0 | 90 | | |
| 20 | AnemSD39aMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 21 | AnemSD39bMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 22 | AnemSD30aMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 23 | AnemSD30bMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 24 | AnemSD10MS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 30 | Vane39DEG | | | | | MinMax | 0 | 359.9 | | |
| 31 | Vane30DEG | | | | | MinMax | 0 | 359.9 | | |
| 32 | Vane10DEG | | | | | MinMax | 0 | 359.9 | | |
| 50 | Turb39zNONE | | | | | MinMax | 0 | 2 | | |
| 51 | Turb30zNONE | | | | | MinMax | 0 | 2 | | |
| 52 | Turb10zNONE | | | | | MinMax | 0 | 2 | | |
| 60 | Wshr0zNONE | | | | | MinMax | -100 | 100 | | |
| 200 | VaneSD39DEG | Anem39yMS | | | | MinMaxT | 0 | 100 | 100 | 10 |
| 201 | VaneSD30DEG | Anem30yMS | | | | MinMaxT | 0 | 100 | 100 | 10 |
| 202 | VaneSD10DEG | Anem10MS | | | | MinMaxT | 0 | 100 | 100 | 10 |
| 301 | Anem39aMS | AnemSD39aMS | Vane39DEG | VaneSD39DEG | Etmp2DEGC | Icing | 0.5 | 1 | 2 | 2 |
| 302 | Anem39bMS | AnemSD39bMS | Vane39DEG | VaneSD39DEG | Etmp2DEGC | Icing | 0.5 | 1 | 2 | 2 |
| 303 | Anem30aMS | AnemSD30aMS | Vane30DEG | VaneSD30DEG | Etmp2DEGC | Icing | 0.5 | 1 | 2 | 2 |
| 304 | Anem30bMS | AnemSD30bMS | Vane30DEG | VaneSD30DEG | Etmp2DEGC | Icing | 0.5 | 1 | 2 | 2 |
| 305 | Anem10MS | AnemSD10MS | Vane10DEG | VaneSD10DEG | Etmp2DEGC | Icing | 0.5 | 1 | 2 | 2 |
| 400 | Anem39aMS | Anem39bMS | | | | CompareSensors | 1 | 0.35 | 3 | 0 |
| 401 | Anem30aMS | Anem30bMS | | | | CompareSensors | 1 | 0.35 | 3 | 0 |
| 500 | Amax39aMS | | | | | MinMax | 0 | 90 | | |
| 501 | Amin39aMS | | | | | MinMax | 0 | 90 | | |
| 502 | Amax39bMS | | | | | MinMax | 0 | 90 | | |
| 503 | Amin39bMS | | | | | MinMax | 0 | 90 | | |

| | | | | | | | | | | |
|-----|-----------|--|--|--|--|--------|---|-------|--|--|
| 504 | Amax30aMS | | | | | MinMax | 0 | 90 | | |
| 505 | Amin30aMS | | | | | MinMax | 0 | 90 | | |
| 506 | Amax30bMS | | | | | MinMax | 0 | 90 | | |
| 507 | Amin30bMS | | | | | MinMax | 0 | 90 | | |
| 508 | Amax10MS | | | | | MinMax | 0 | 90 | | |
| 509 | Amin10MS | | | | | MinMax | 0 | 90 | | |
| 510 | Vmax39DEG | | | | | MinMax | 0 | 359.9 | | |
| 511 | Vmin39DEG | | | | | MinMax | 0 | 359.9 | | |
| 512 | Vmax30DEG | | | | | MinMax | 0 | 359.9 | | |
| 513 | Vmin30DEG | | | | | MinMax | 0 | 359.9 | | |
| 514 | Vmax10DEG | | | | | MinMax | 0 | 359.9 | | |
| 515 | Vmin10DEG | | | | | MinMax | 0 | 359.9 | | |

Sensor Statistics

| Sensor | Expected Data Points | Actual Data Points | % Data Recovered | Hours Out of Range | Hours of Icing | Hours of Fault | % Data Good |
|--------------|----------------------|--------------------|------------------|--------------------|----------------|----------------|---------------|
| Etmp2DEGC | 52561 | 52561 | 100 | 0 | 0 | 0 | 100 |
| EtmpSD2DEGC | 52561 | 52561 | 100 | 0 | 0 | 0 | 100 |
| Anem39aMS | 52561 | 52561 | 100 | 0.5 | 0 | 4.5 | 99.943 |
| AnemSD39aMS | 52561 | 52561 | 100 | 0.5 | 0 | 4.5 | 99.943 |
| Anem39bMS | 52561 | 52561 | 100 | 0.5 | 0 | 0.333 | 99.99 |
| AnemSD39bMS | 52561 | 52561 | 100 | 0.5 | 0 | 0.333 | 99.99 |
| Anem30aMS | 52561 | 52561 | 100 | 0.5 | 0 | 1.667 | 99.975 |
| AnemSD30aMS | 52561 | 52561 | 100 | 0.5 | 0 | 1.667 | 99.975 |
| Anem30bMS | 52561 | 52561 | 100 | 0.5 | 0 | 0.333 | 99.99 |
| AnemSD30bMS | 52561 | 52561 | 100 | 0.5 | 0 | 0.333 | 99.99 |
| Anem10MS | 52561 | 52561 | 100 | 0 | 0 | 0 | 100 |
| AnemSD10MS | 52561 | 52561 | 100 | 0 | 0 | 0 | 100 |
| Vane39DEG | 52561 | 52561 | 100 | 0.333 | 0 | 0 | 99.996 |
| VaneSD39DEG | 52561 | 52561 | 100 | 2.167 | 0 | 0 | 99.975 |
| Vane30DEG | 52561 | 52561 | 100 | 0.5 | 0 | 0 | 99.994 |
| VaneSD30DEG | 52561 | 52561 | 100 | 2.167 | 0 | 0 | 99.975 |
| Vane10DEG | 52561 | 52561 | 100 | 0.833 | 0 | 0 | 99.99 |
| VaneSD10DEG | 52561 | 52561 | 100 | 3 | 0 | 0 | 99.966 |
| Total | 946098 | 946098 | 100 | 13 | 0 | 13.667 | 99.983 |

APPENDIX B - Plot Data

Wind Speed Distribution Data

| Bin Center Wind Speed [m/s] | April 05 – March 06 [%] |
|--|--|
| 0.5 | 1.95 |
| 1.5 | 4.15 |
| 2.5 | 8.95 |
| 3.5 | 15.61 |
| 4.5 | 19.59 |
| 5.5 | 16.47 |
| 6.5 | 12.1 |
| 7.5 | 8.06 |
| 8.5 | 5.5 |
| 9.5 | 3.12 |
| 10.5 | 1.95 |
| 11.5 | 1.01 |
| 12.5 | 0.55 |
| 13.5 | 0.35 |
| 14.5 | 0.29 |
| 15.5 | 0.19 |
| 16.5 | 0.08 |
| 17.5 | 0.06 |
| 18.5 | 0.02 |
| 19.5 | 0 |
| 20.5 | 0 |
| 21.5 | 0 |
| 22.5 | 0 |
| 23.5 | 0 |
| 24.5 | 0 |

Monthly Average Wind Speed Data

| Date | 39m Mean 10 min [m/s] |
|--------------------------------|-----------------------------|
| 2005 April | 5.68 |
| May | 5.72 |
| June | 5 |
| July | 4.55 |
| August | 4.46 |
| September | 4.64 |
| October | 5.64 |
| November | 5.33 |
| December | 5.22 |
| 2006 January | 5.91 |
| February | 5.94 |
| March | 5.23 |
| April 05 – March 06 | 5.28 |

Diurnal Average Wind Speed Data

| Hour of Day | April 05 – March 06 |
|----------------|------------------------|
| 0 | 5 |
| 1 | 5 |
| 2 | 5.02 |
| 3 | 4.98 |
| 4 | 4.94 |
| 5 | 4.86 |
| 6 | 4.88 |
| 7 | 5.05 |
| 8 | 5.3 |
| 9 | 5.58 |
| 10 | 5.82 |
| 11 | 5.94 |
| 12 | 5.99 |

| | |
|----|------|
| 13 | 5.97 |
| 14 | 5.88 |
| 15 | 5.74 |
| 16 | 5.47 |
| 17 | 5.15 |
| 18 | 5.02 |
| 19 | 4.99 |
| 20 | 4.99 |
| 21 | 4.94 |
| 22 | 5.01 |
| 23 | 4.99 |

Wind Rose Data

| | April 05 – March 06 | |
|------------|------------------------|--------------------------|
| Direction | Percent Time [%] | Mean Wind Speed [m/s] |
| N | 9.6 | 5.92 |
| NNE | 6.78 | 5.69 |
| NE | 3.9 | 5.72 |
| ENE | 2.51 | 5.32 |
| E | 2.07 | 4.39 |
| ESE | 2.16 | 4.66 |
| SE | 4.66 | 4.55 |
| SSE | 3.87 | 4.77 |
| S | 5.38 | 4.5 |
| SSW | 9.76 | 5.02 |
| SW | 13.55 | 5.79 |
| WSW | 8.15 | 5.29 |
| W | 6.88 | 5.09 |
| WNW | 7.44 | 5.07 |
| NW | 7.21 | 5.13 |
| NNW | 6.07 | 5.38 |