WIND DATA REPORT

Worcester County Jail
West Boylston, MA

February 2009 to January 2010

Prepared for

Massachusetts Division of Capital Asset Management
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by

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NOTICE AND ACKNOWLEDGEMENTS

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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 Wind Energy Center (WEC) at the University of Massachusetts, Amherst.

Wind monitoring equipment was installed on a 50 m tower at the Worcester County Jail grounds in West Boylston, Massachusetts on January 27th 2009. This is the final wind data report written which encompasses data recorded up to January 31st, 2010.

At 49 m, the mean recorded wind speed was 4.84 m/s (10.83 mph)* and the prevailing wind direction was from the NNE. The average wind shear power-law factor is 0.27, and is calculated from data from the 49 m and 38 m anemometers. The average turbulence intensity at 49 m for wind speeds between 10 m/s and 11 m/s was 0.20, well within the normal values recorded by the WEC at wind monitoring sites it maintains in Massachusetts.

The gross data recovery percentage (the actual percentage of expected data received) was 100% and the net data recovery percentage (the percentage of expected data which passed all of the quality assurance tests) was 99.1%.

Additional information about interpreting the data presented in this report can be found in the Fact Sheet, "Interpreting Your Wind Resource Data," produced by WEC and the Massachusetts Technology Collaborative (MTC). This document is found through the WEC 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 50 m met tower is located in an open field within the grounds of the Worcester County Jail and House of Correction grounds in West Boylston. Its coordinates are 42° 19’ 11.40” N, 71° 45’ 55.56” W and marked with the white square in Figure 1.

Figure 1 – Site Location

SECTION 2 - Instrumentation and Equipment

The wind monitoring equipment is mounted on a 50 m (164 ft) meteorological tower. The wind monitoring equipment comes from NRG systems and consists of the following items:

- NRG Symphonie data logger
- 4 – NRG #40 Anemometers, standard calibration (Slope – 0.765 m/s, Offset – 0.350 m/s). Two anemometers are located at 49 m (160.8 ft), and two anemometers are located at 38 m (124.7 ft).
- 2 – NRG #200P Wind direction vanes. The vanes are located at 49 m (160.8 ft) and 38 m (124.7 ft).
- NRG 110S temperature Sensor located near the base of the tower.

The logger samples wind speed and direction once every two second. These samples are combined into 10-minute averages and are put into a binary file along with the maximum, minimum and standard deviation for each 10-minute interval. The binary data file from the Symphonie logger is sent to WEC via a cellular modem daily. These files are converted to ASCII text files using NRG software. The text files are then imported into a database software program where they are subjected to quality assurance tests prior to data usage.

SECTION 3- Data Summary

A summary of the wind speeds and wind directions measured during the reporting period is included in Table 1. Table 1 includes the mean wind speeds measured at each measurement height, the maximum instantaneous wind speed measured at each measurement height and the prevailing wind direction measured at each measurement height. These values are provided for each month of the reporting period and for the whole reporting period.

Table 1. Wind Speed and Direction Data Summary

Date	Mean Wind Speed	Max Wind Speed	Prevailing Wind Direction	Mean Wind Speed	Max Wind Speed	Prevailing Wind Direction
Height Units	49 m [m/s]	49 m [m/s]	49 m [m/s]	38 m [m/s]	38 m [m/s]	38 m [m/s]
Feb 2009	6.02	16.5	NW	5.51	15.2	WNW
Mar 2009	5.01	11.5	NW	4.569	10.9	NW
Apr 2009	5.52	14.8	W	5.068	14	W
May 2009	4.75	14.2	SW	4.226	13.4	SW
Jun 2009	3.45	9	NNE	2.968	8.5	NNE
Jul 2009	4.12	11	W	3.61	10.6	W
Aug 2009	3.85	12.5	SW	3.351	11.4	SW
Sep 2009	4.30	11.3	NNE	3.724	9.7	NNE
Oct 2009	4.79	14.9	WNW	4.209	14	WNW
Nov 2009	4.91	15.4	NNE	4.343	14.6	NNE
Dec 2009	5.90	17.5	NW	5.4	16.3	WNW
Jan 2010	5.61	15.3	NW	5.129	14.7	WNW
Feb 2009- Jan 2010	**4.84**	**17.5**	**WNW**	**4.33**	**16.3**	**WNW**

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 is missing, the percent of the available data that is used to determine the data statistics is noted.

No measurement of wind speed or direction can be perfectly accurate. Wind speed measurement 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 ± 2% or ± 0.2 m/s, whichever is greater. Wind direction measurement errors occur due to sensor measurement uncertainty, tower effects, boom alignment measurement errors and twisting of pipe sections during the raising of a pipe tower. Efforts are also made to reduce these errors, but the reported wind directions are estimated to have an uncertainty of +/- 5 degrees.

A summary of the turbulence intensity and mean wind shear measured at each measurement height during the reporting period is included in Table 2. These values are provided for each month of the reporting period and for the whole reporting period. Turbulence Intensity is calculated by dividing the standard deviation of the wind speed by the mean wind speed and is a measure of the gustiness of a wind resource. Lower turbulence results in lower mechanical loads on a wind turbine. Turbulence intensity varies with wind speed. The average turbulence intensity presented in Table 2 is the mean turbulence intensity when the wind speed at each measurement height is between 10 and 11 m/s.

Shear coefficients provide a measure of the change in wind speed with height. When data at multiple heights is 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 will not always 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.

The mean wind shear coefficient that is provided here is calculated based on the mean wind speeds in Table 1, where z_{high} and z_{low} are the heights of the higher and lower mean wind speeds used in the calculation and $U(z_{low})$ and $U(z_{high})$ are the mean wind speeds at the two heights.

$$\alpha = \log\left(\frac{U(z_{high})}{U(z_{low})}\right) \Big/ \log\left(\frac{z_{high}}{z_{low}}\right)$$

Table 2. Shear and Turbulence Intensity Data Summary

Date Height Units	Turbulence Intensity at 10 m/s 49 m [-]	Turbulence Intensity at 10 m/s 38 m [-]	Mean Wind Shear Coefficient, α Between 49 m and 38 m [-]
Feb 2009	0.18	0.19	0.32
Mar 2009	0.19	0.21	0.21
Apr 2009	0.19	0.20	0.22
May 2009	0.21	0.21	0.23
Jun 2009	-	-	0.22
Jul 2009	0.19	0.19	0.15
Aug 2009	0.23	-	0.36
Sep 2009	0.19	-	0.60
Oct 2009	0.22	0.23	0.25
Nov 2009	0.18	0.19	0.21
Dec 2009	0.19	0.21	0.28
Jan 2010	0.20	0.21	0.16
Feb 2009-Jan 2010	**0.20**	**0.21**	**0.27**

No turbulence intensity value is reported for the month of June, August and September, 2009 at 38 m and June 2009 at 49 m because there were no recorded mean wind speeds between 10 m/s and 11 m/s. The turbulence intensity for the year is calculated based on values excluding these.

SECTION 4- Long Term Estimate and Capacity Factor

Wind speed varies year by year and the mean obtained over the measurement period may be less or more compared to what is seen over a longer time period. Therefore, the use of the long term mean at the site is preferred when projecting the performance of a wind turbine. The long term mean at a site may be estimated by using the Measure-Correlate-Predict (MCP) method.

The MCP method correlates wind speed measurements at the target site to a reference site which collects data over the same period of time and has been collecting data for a much longer period. Based on this correlation, the reference wind speed data is used to predict long term mean at the site.

Long term data from Logan Airport in Boston between January 1st, 1996 and December 31st, 2009 is used as reference in the case of the West Boylston site. A Correlation between the two sites is obtained from concurrent data between January 27th, 2009 and January 31st, 2010. The long term mean at the West Boylston site at 49 m is estimated to be 5.06 m/s with an uncertainty of 1.1% for the MCP process. This estimate may also be used to calculate the long term mean at different heights by using the mean wind shear at site and the equation described in the previous section. The long term mean wind speed at 70 m height is estimated at 5.58 m/s.

The capacity factor of a wind turbine at a given site depends on the hub height, wind speed distribution at the hub height, the wind turbine power curve and any assumptions about down time and losses due to wake effects from upwind wind turbines, etc. If the hub height wind speed is estimated from data at lower heights, then the capacity factor will also depend on the estimated wind shear and the wind speeds measured at lower heights. No simple estimate of capacity factor at a site could take all of these effects and choices into account. Nevertheless, an estimate of the capacity factor of a wind turbine at this site is provided here to help the reader understand the order of magnitude of the wind resource at this site.

The estimates assume a GE 1.5 sl turbine with a hub height of 80 m and the long term mean wind speed estimate at the highest measurement height and the mean wind shear at the site, in order to determine the mean hub height wind speed, in this case 5.78 m/s. The wind speed probability distribution is assumed to be given by a Rayleigh distribution. The average wind turbine power is then estimated from:

$$\overline{P_W} = \int_0^\infty P_W(U)\,p(U)\,dU$$

where $P_W(U)$ is the wind turbine power curve and $p(U)$ is the wind speed probability distribution. The capacity factor is then calculated from:

$$CF = \frac{\overline{P_W}}{P_{rated}}$$

where P_{rated} is the rated capacity of the turbine, i.e., 1500 kW. Based on this equation, the estimated capacity factor of a wind turbine at this site would be about 0.24].

SECTION 5- Graphs

This report contains several types of wind data graphs. Unless otherwise noted, each graph represents data from 1 year. The following graphs are included:

- Time Series – 10-minute average wind speeds are plotted against time. The graph shows that there were only a few occasions where the 10-minute average wind speeds rise above 10 m/s.

- Wind Speed Distribution – A histogram plot giving the percentage of time that the wind is at a given wind speed. The distribution peak occurs between 4 and 5 m/s and approximately 60% of the time the 10-minute average wind speed is higher than 4 m/s

- Monthly Average – A plot of the monthly average wind speed over a 5 month period. This graph shows the trends in the wind speed over the period. The .monthly average wind speed of the fall months are expected to have an upward trend compared to the spring and summer months.

- Diurnal – A plot of the average wind speed for each hour of the day. The graph shows that there is very small increase of wind speeds in the early afternoon.

- Turbulence Intensity – A plot of turbulence intensity as a function of wind speed. 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. The graph shows that the turbulence intensity at the site is comparable to other sites in Massachusetts.

- 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. The substantial majority of the wind is blowing from the north-northeast, although the wind is also frequently coming in from the west and west-northwest. The average wind speed coming in from the general western direction is also slightly higher.

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

Wind Speed Time Series

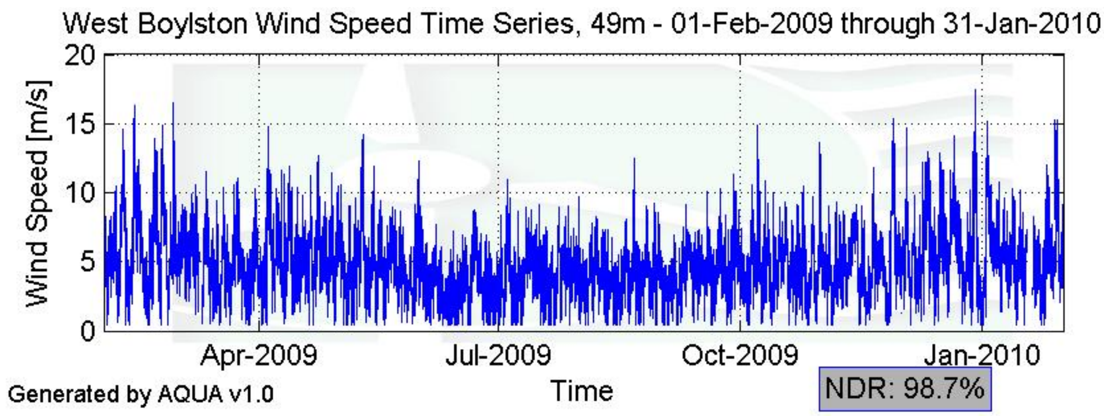

Figure 1 – Wind Speed Time Series, February 1, 2009 – January 31, 2010

Wind Speed Distributions

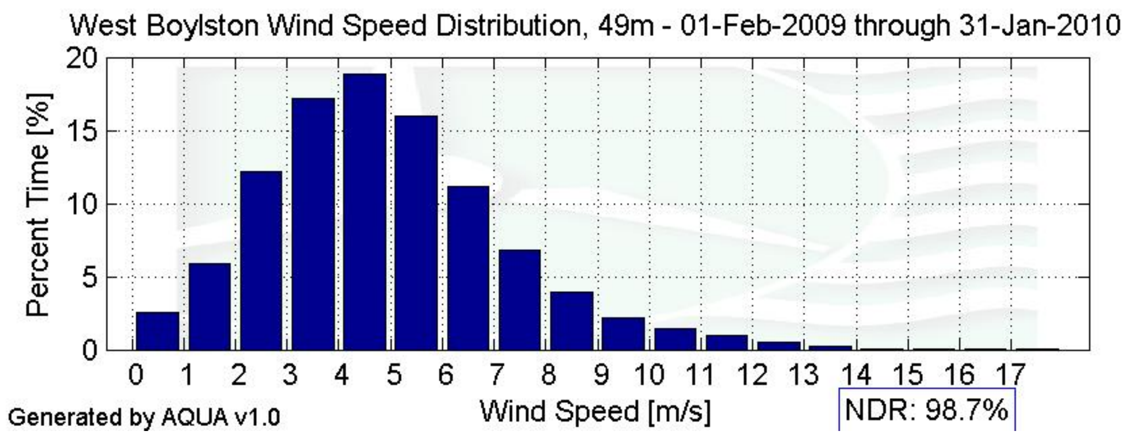

Figure 2 – Wind Speed Distribution, February 1, 2009 – January 31, 2010

Monthly Average Wind Speeds

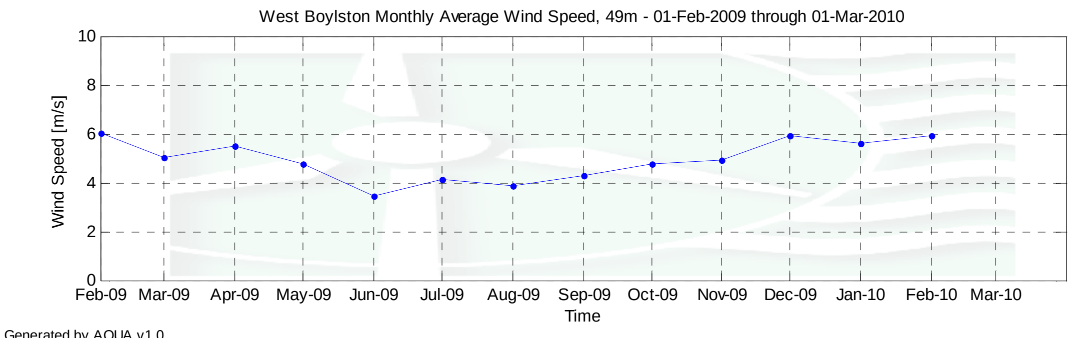

Figure 3 - Monthly Average Wind Speed, February 2009 – February 2010

Diurnal Average Wind Speeds

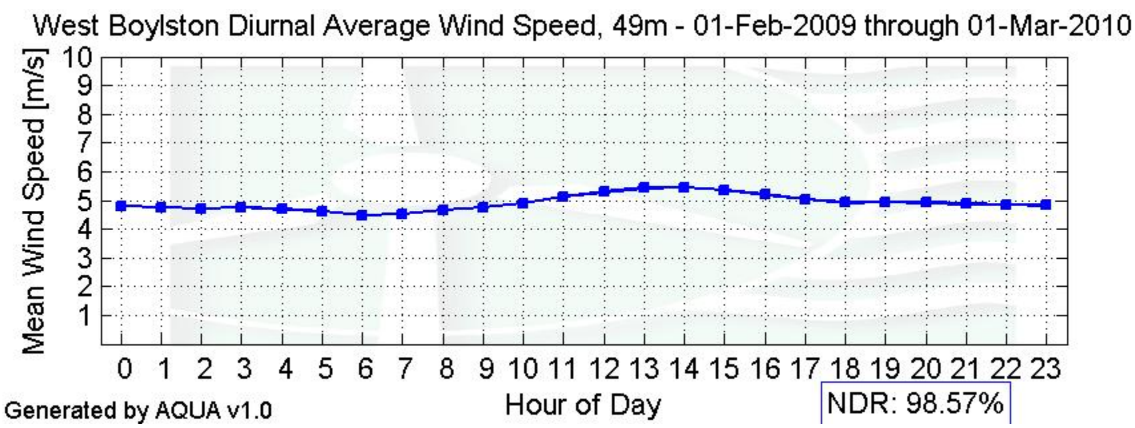

Figure 4 - Diurnal Average Wind Speeds, February 1, 2009 – February 28, 2010

Turbulence Intensities

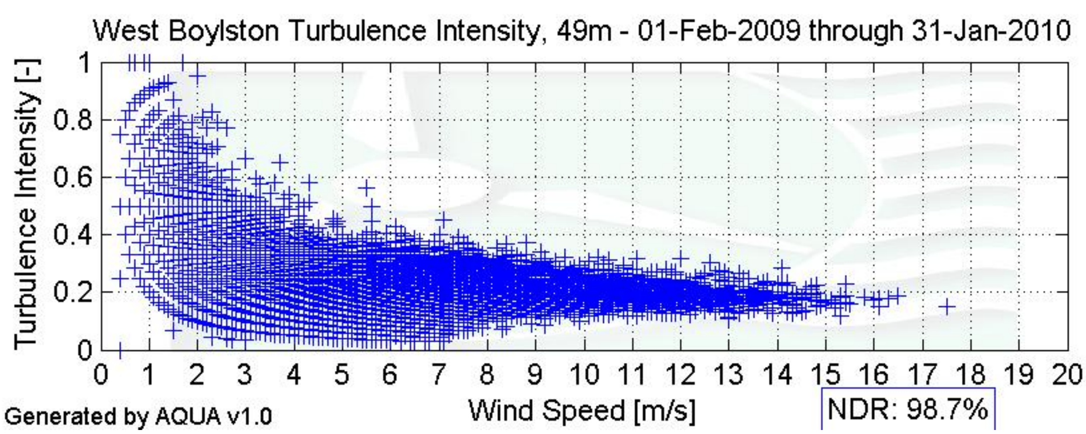

Figure 5 - Turbulence Intensity vs. Wind Speed, February 1, 2009 – January 31, 2010

Wind Roses

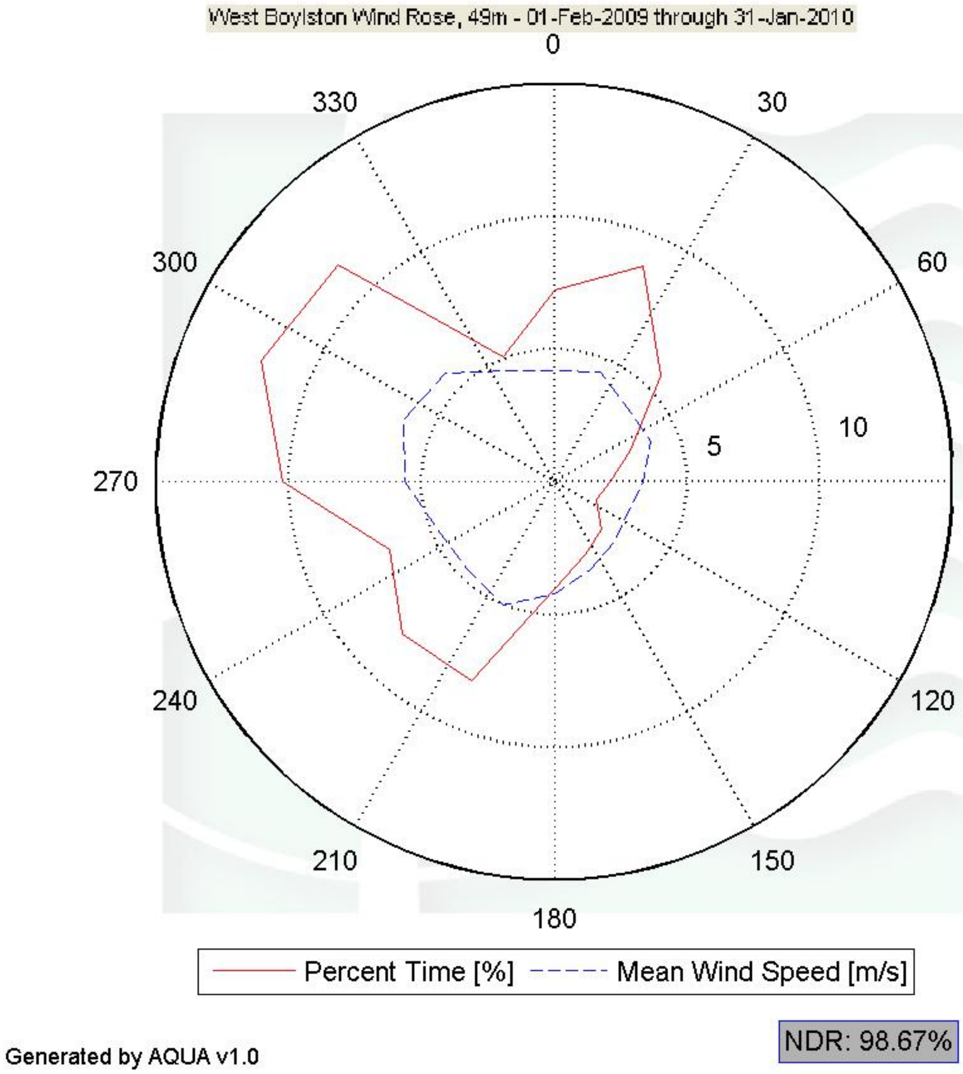

Figure 6 - Wind Rose, February 1, 2009 – January 31, 2010

SECTION 6 - Significant Meteorological Events

There were no significant meteorological events during the reporting period.

SECTION 7 - Data Collection and Maintenance

All sensors and equipment functioned properly throughout the monitoring period. No maintenance was performed during this year.

SECTION 8 - 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
Net Data Recovered [%]	99.1

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.

$$F1 > TF1 > F2$$

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 belowfreezing 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.

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

Compare Sensors 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.

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

Sensor Statistics

A summary of the results of the data collection and filtering are given in the Sensor Performance Report which is included in APPENDIX A. The following categories of information, tabulated for each sensor, are included in that report.

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 test. 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*.

APPENDIX A - Sensor Performance Report

Test Definitions

Test Order	TestField1	TestField2	TestField3	CalcField 1	CalcField 2	Test Type	Factor 1	Factor2	Factor3	Factor4
1						TimeTest Insert	0	0	0	0
2	Anem49a					MinMax	0	90	0	0
3	Anem49b					MinMax	0	90	0	0
4	Anem38a					MinMax	0	90	0	0
5	Anem38b					MinMax	0	90	0	0
6	Anem49y					MinMax	0	90	0	0
7	Anem38y					MinMax	0	90	0	0
8	Vane49a					MinMax	0	359.9	0	0
9	Vane38a					MinMax	0	359.9	0	0
10	Etmp2a					MinMax	-30	60	0	0
11	Batt2a					MinMax	10.5	15	0	0
12	Turb49z					MinMax	0	2	0	0
13	Turb38z					MinMax	0	2	0	0
14	AnemSD49a					MinMax	0	4	0	0
15	AnemSD49b					MinMax	0	4	0	0
16	AnemSD38a					MinMax	0	4	0	0
17	AnemSD38b					MinMax	0	4	0	0
18	AnemSD49y					MinMax	0	4	0	0
19	AnemSD38y					MinMax	0	4	0	0
21	EtempSD2a					MinMax	-30	60	0	0
22	BattSD2a					MinMax	0	5	0	0
200	VaneSD49a	Anem49y				MinMaxT	0	100	100	10
201	VaneSD38a	Anem38y				MinMaxT	0	100	100	10
300	Anem49a	AnemSD49a	Vane49a	VaneSD49a	Etemp2a	Icing	0.5	1	2	4
301	Anem49b	AnemSD49b	Vane49a	VaneSD49a	Etemp2a	Icing	0.5	1	2	4
302	Anem38a	AnemSD38a	Vane38a	VaneSD38a	Etemp2a	Icing	0.5	1	2	4
303	Anem38b	AnemSD38b	Vane38a	VaneSD38a	Etemp2a	Icing	0.5	1	2	4
400	Anem49a	Anem49b				Compare Sensors	1	0.25	3	0
401	Anem38a	Anem38b				Compare Sensors	1	0.25	3	0

Sensor Statistics

Sensor	Expected Data Points	Actual Data Points	% Data Recovered	Hours Out of Range	Hours of Icing	Hours of Fault	%Data Good
Etmp2a	52560	52560	100	0	0	0	100
Batt2a	52560	52560	100	0	0	0	100
Anem38a	52560	52560	100	0.5	86.333	2	98.986
Vane38a	52560	52560	100	2	86.333	0	98.992
Anem38b	52560	52560	100	0.5	86.333	1.333	98.999
Anem49a	52560	52560	100	0.5	114.5	7	98.621
Vane49a	52560	52560	100	1.167	114.5	0	98.68
Anem49b	52560	52560	100	0.5	113.667	0.167	98.697
Total	**420480**	**420480**	**100**	**5.167**	**601.667**	**10.5**	**99.122**

APPENDIX B - Plot Data

Wind Speed Distribution Data

Net Data Recovery Percentage for this Interval: 98.70

Bin Center Wind speed [m/s]	Percent Time [%]
0.5	2.57
1.5	5.9
2.5	12.21
3.5	17.17
4.5	18.86
5.5	15.98
6.5	11.12
7.5	6.79
8.5	3.94
9.5	2.2
10.5	1.42
11.5	0.96
12.5	0.55
13.5	0.22
14.5	0.08
15.5	0.03
16.5	0.01
17.5	0

Monthly Average Wind Speed Data

Month	Mean Wind Speed [m/s]
Feb-09	6.022
Mar-09	5.006
Apr-09	5.518
May-09	4.747
Jun-09	3.451
Jul-09	4.124
Aug-09	3.849
Sep-09	4.303
Oct-09	4.787
Nov-09	4.907
Dec-09	5.901
Jan-10	5.607
Feb-10	5.916

Diurnal Average Wind Speed Data

Net Data Recovery Percentage for this Interval: 98.57

Hour of Day	Mean Wind Speed [m/s]
0	4.79
1	4.75
2	4.7
3	4.76
4	4.69
5	4.63
6	4.48
7	4.52
8	4.65
9	4.75
10	4.9
11	5.12
12	5.28
13	5.44
14	5.45
15	5.37
16	5.2
17	5.03
18	4.92
19	4.95
20	4.92
21	4.86
22	4.85
23	4.83

Wind Rose Data

Bin Center [deg]	Percent Time [%]	Mean Wind Speed [m/s]
0	7.21	4.18
22.5	8.79	4.48
45	5.66	3.9
67.5	3.1	3.95
90	2.14	3.35
112.5	1.74	3
135	2.55	3.21
157.5	3	3.58
180	4.05	4.25
202.5	8.13	5.02
225	8.11	4.65
247.5	6.69	4.74
270	10.24	5.65
292.5	11.97	6.12
315	11.53	5.81
337.5	5.07	4.51