WIND DATA REPORT

Scituate Waste Water Treatment Plant, MA

July27th, 2006 to August 1st, 2007

Prepared for

Massachusetts Technology Collaborative
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by

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NOTICE AND ACKNOWLEDGEMENTS

TABLE OF CONTENTS

TABLE OF FIGURES

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.

This report covers meteorological data, in particular wind data, at the Scituate waste water treatment plant in Massachusetts, which was installed on June 27, 2006 and decommissioned August 1, 2007. Two anemometers and one wind vane are mounted at heights of 39 m (127.9 ft), and 30 m (98.4 ft). A single anemometer and wind vane are mounted at 10 m (32.8 ft).

This report coves the year and three days worth of data collecting during the tower's operation. The annual mean wind speed at 39 m was 5.50 m/s (12.30 mph)* and the prevailing wind direction was from the south west. For the year, the gross data recovery percentage (the actual amount of data received compared to the expected amount of data) was 99.750 % and the net recovery percentage for the year (the percentage of data received which passed all the quality assurance tests) was 99.501%.

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 station is located at the Scituate waste water treatment plant. The tower base is located at 42.17581° N, 70.72806° W (WGS84/NAD83) (Figure 1). The red cross indicates the approximate location of the tower.

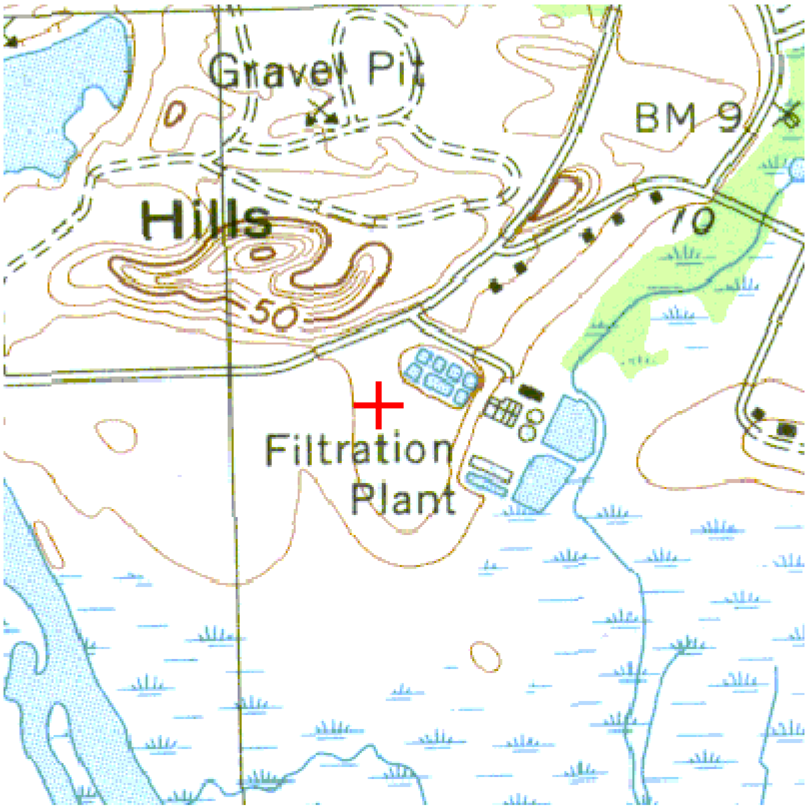

Figure 1 - Scituate Waste Water Treatment Plant Site Location

Source: www.massgis.com

SECTION 2 - Instrumentation and Equipment

The wind monitoring equipment is mounted on an NRG Systems 40 m (131.2 ft) meteorological tower. All the remaining monitoring equipment is from NRG Systems, and consists of the following items:

- Symphonie Data Logger
- 5 - #40 Anemometers, standard calibration (Slope – 0.765 m/s, Offset – 0.350 m/s). Two anemometers are located at 39 m (127.9 ft), two at 30 m (98.4 ft), and one at 10 m (32.8 ft).
- 3 - #200P Wind direction vanes. One vane is at each height of 39 m (127.9 ft), 30m (98.4 ft), and 10 m (32.8 ft), respectively.

- #11OS Temperature sensor. The sensor is located 2m (6.6 ft) from the tower base.
- 8 – Sensor booms, five 59” in length, three 53” in length
- Lightning rod and copper grounding cable
- Shielded sensor wire

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	Mean Wind Speed	Max Wind Speed	Prevailing Wind Direction
Height Units	**39m [m/s]**	**39 m [m/s]**	**39 m [deg]**	**30 m [m/s]**	**30 m [m/s]**	**30 m [deg]**	**10 m [m/s]**	**10 m [m/s]**	**10 m [deg]**
Aug 2006	5.01	13.56	225	4.53	12.8	247.5	2.52	8.07	225
Sept 2006	5.01	11.27	247.5	4.46	10.17	225	3.03	8.36	225
Oct 2006	5.95	19.33	292.5	5.31	18.18	247.5	3.02	12.99	292.5
Nov 2006	5.10	18.05	225	4.62	16.60	247.5	2.59	11.54	292.5
Dec 2006	5.64	19.37	247.5	5.13	17.92	247.5	2.70	12.35	247.5
Jan 2007	6.03	15.39	315	5.48	14.59	315	3.07	10.43	292.5
Feb 2007	6.25	15.38	270	5.75	14.21	270	3.08	9.54	270
Mar 2007	6.93	16.99	225	6.35	15.63	225	3.72	10.83	225
Apr 2007	6.31	23.03	112.5	5.81	21.43	22.5	3.65	15.19	247.5
May 2007	5.44	12.57	225	4.95	11.64	247.5	2.83	7.49	225
Jun 2007	4.99	13.48	225	4.5	12.72	247.5	2.35	7.41	202.5
July 2007	4.38	15.17	225	3.94	14.09	225	2.06	9.91	202.5
Aug2006 - July 2007	5.50	23.03	225	4.99	21.43	247.5	2.82	15.19	225

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 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 the highest measurement height is between 9.5 and 10.5 m/s.

Shear coefficients provide a measure of the change in wind speed with height. 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 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	Turbulence Intensity at 10 m/s	Turbulence Intensity at 10 m/s	Turbulence Intensity at 10 m/s	Mean Wind Shear Coefficient, α
Height Units	**39 m [-]**	**30 m [-]**	**10 m [-]**	**Between 39 m and 30 m [-]**
Aug 2006	0.16	0.18	0.25	0.38
Sept 2006	0.20	0.21	0.26	0.44
Oct 2006	0.17	0.18	0.21	0.43
Nov 2006	0.16	0.18	0.24	0.38
Dec 2006	0.18	0.20	0.25	0.36
Jan 2007	0.19	0.21	0.20	0.36
Feb 2007	0.20	0.22	0.27	0.32
Mar 2007	0.18	0.20	0.26	0.33
Apr 2007	0.16	0.18	0.23	0.31
May 2007	0.15	0.18	0.26	0.36
Jun 2007	0.15	0.16	0.23	0.39
July 2007	0.16	0.18	0.24	0.40
Aug2006 -July 2007	**0.18**	**0.19**	**0.22**	**0.37**

Over the one year of data collected, August 2006 through July 2007, the mean wind speed was 5.50 m/s with a maximum ten minute averaged wind speed of 23.03 m/s and the mean wind direction was from the south west at the 39 m level. At the same level the mean turbulence intensity was 0.18. The average power law wind shear coefficient between the 39 and 30 m levels was 0.37.

SECTION 4- Capacity Factor

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 hub height of 80 m, a 1.8 MW wind turbine with a rotor diameter of 80 m and the mean wind speed at the highest measurement height and the mean wind shear at the site, in order to determine the mean hub height wind speed. The capacity factor (CF) is then estimated from (see G.M. Masters, Renewable and Efficient Electric Power Systems, Wiley, 2004):

$$CF = (0.087)U_{hub} - \frac{P_{rated}}{D^2}$$

where U_{hub} is the mean annual hub height wind speed in m/s, P_{rated} is the rated power of the wind turbine in kW and D is the diameter of the rotor in meters. Based on this equation, the estimated capacity factor of a wind turbine at this site would be about 0.343.

SECTION 5- Graphs

This report contains several types of wind data graphs. Unless otherwise noted, each graph represents data from one calendar year (August, 2006 to July, 2007). The following graphs are included:

- Time Series – 10-minute average wind speeds are plotted against time. This graph includes all of the collected data.
- Wind Speed Distribution – A histogram plot giving the percentage of time that the wind is at a given wind speed. The wind speed is between 4 and 5 m/s more than any other wind speed.
- Monthly Average – A plot of the monthly average wind speed over a 12-month period. This graph shows the trends in the wind speed over the whole period of data collection. The wind speed was highest in the spring and lowest in the summer.
- Diurnal – A plot of the average wind speed for each hour of the day. The wind speed was highest in the middle of the day
- 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. Above 4m/s the turbulence intensity is almost always below 0.4.
- 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 wind predominantly comes from the west, particularly from the south west.

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

Wind Speed Time Series

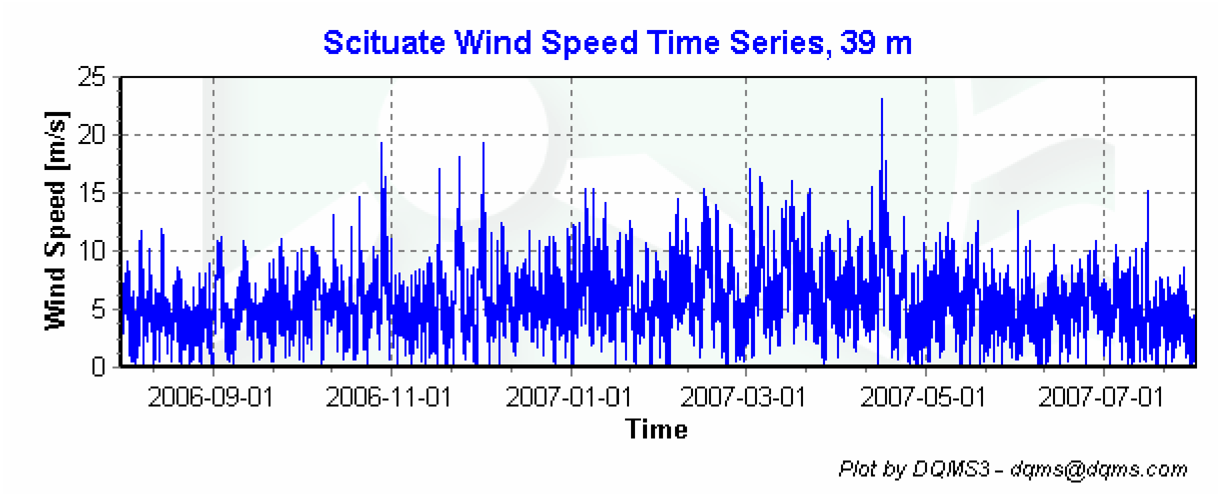

Figure 2 – Wind Speed Time Series, August 1, 2006 – July 31, 2007

Wind Speed Distributions

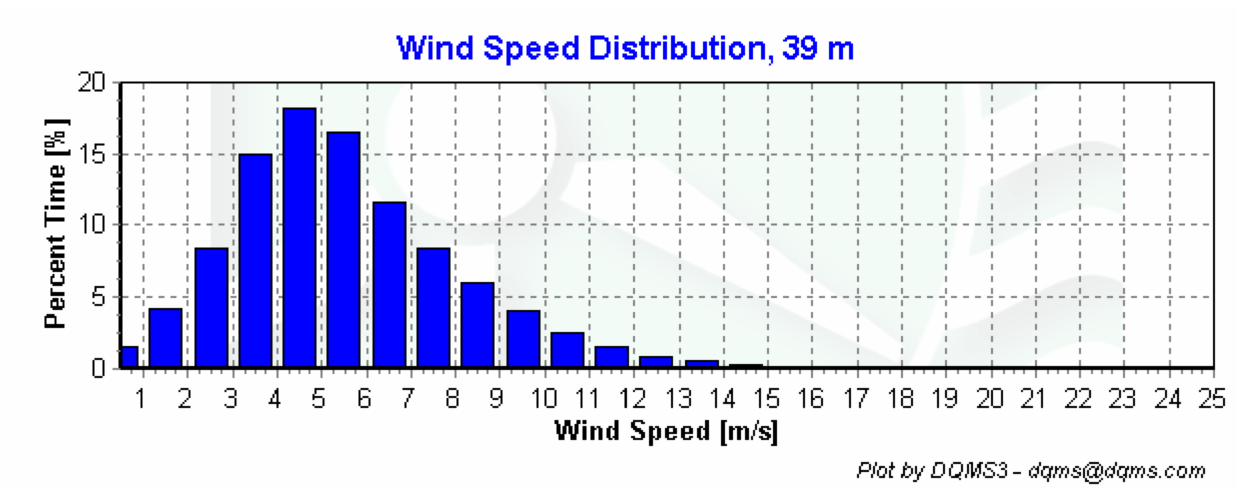

Figure 3 – Wind Speed Distribution, August 1, 2006 – July 31, 2007

Monthly Average Wind Speeds

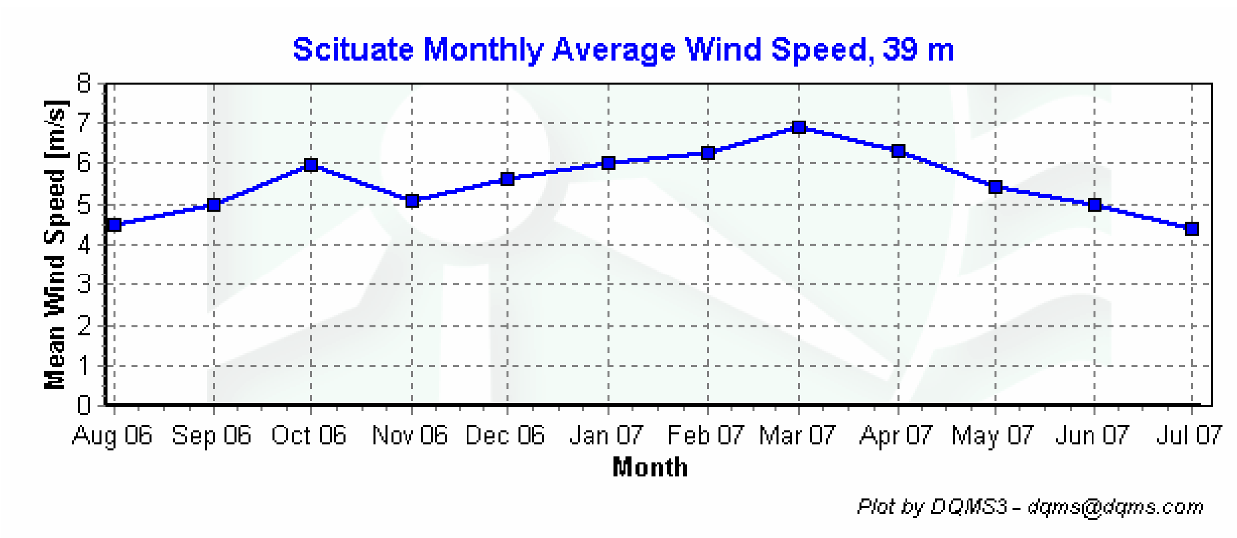

Figure 4 – Monthly Average Wind Speeds, August 1, 2006 – July 31, 2007

Diurnal Average Wind Speeds

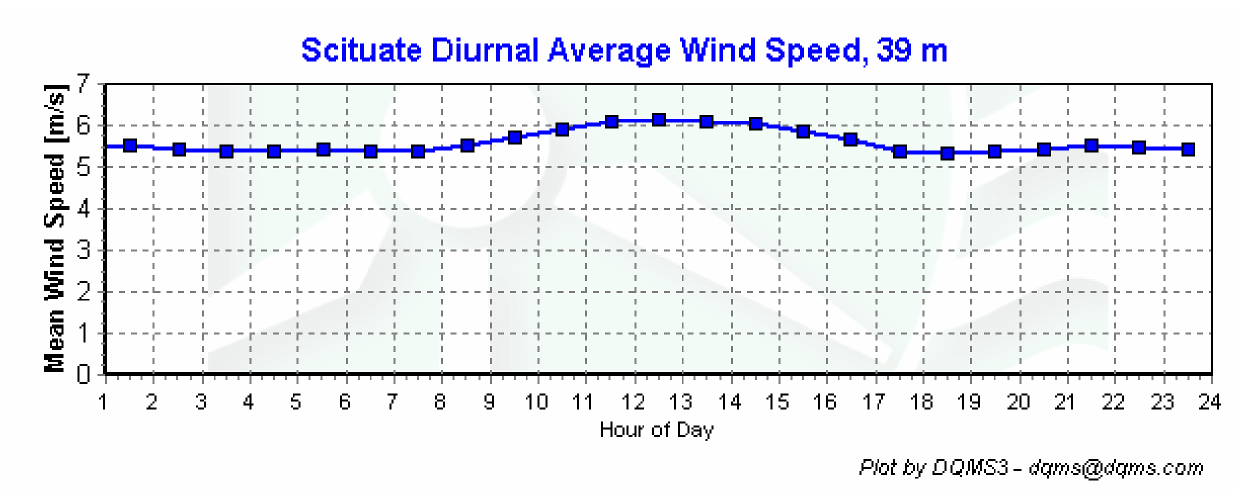

Figure 5 – Diurnal Wind Speeds, August 1, 2006 – July 31, 2007

Turbulence Intensities

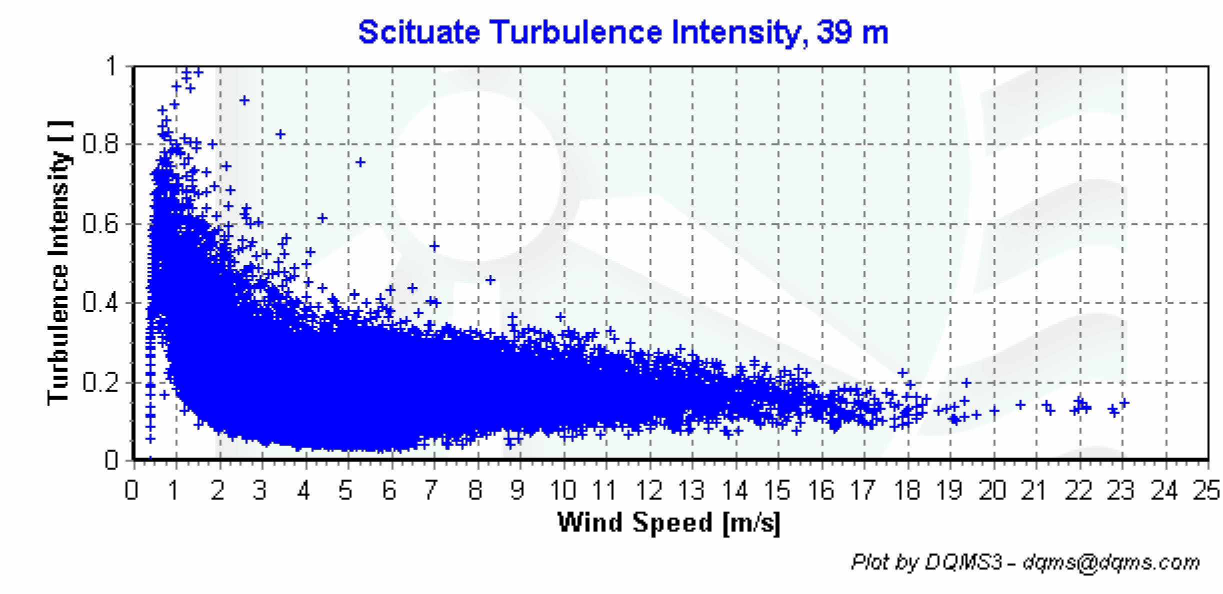

Figure 6 – Turbulence Intensity vs. Wind Speed, August 1, 2006 – July 31, 2007

Wind Roses

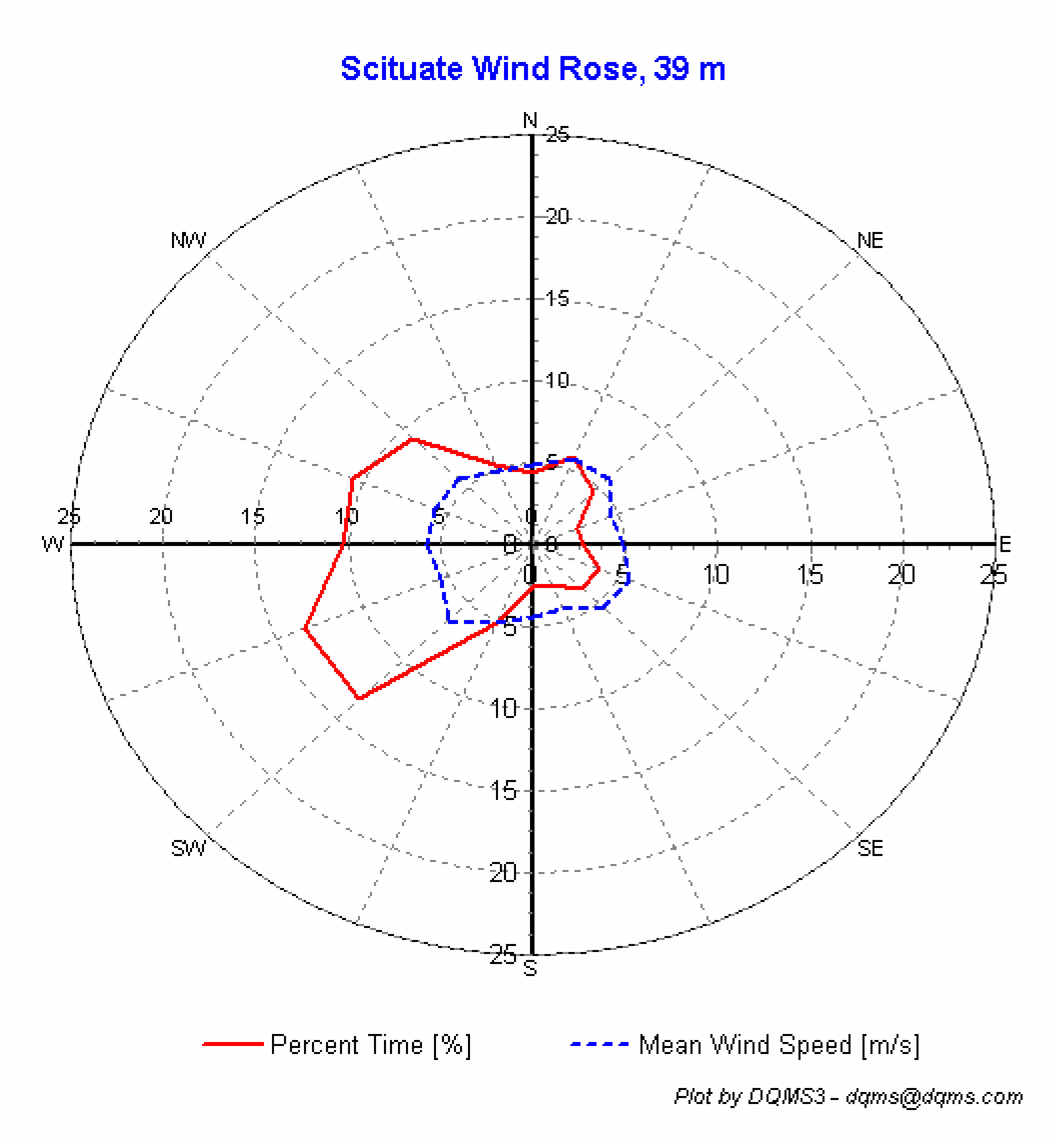

Figure 7 – Wind Rose, August 1, 2006 – July 31, 2007

SECTION 6 - Significant Meteorological Events

There were no extreme meteorological events throughout the year. This observation is based on the absence of any extreme fluctuation in the mean wind speed data as seen in the time series plot (Figure 2).

SECTION 7 - Data Collection and Maintenance

The following maintenance/equipment problems occurred during the report period:

- During the raising of the tower the anemometer boom facing 290 degrees at the 39 m level was slightly bent after being caught in a tree. No adverse affect on the data is apparent when comparing the data from the two anemometers at the 39m anemometer height.

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 [%]	99.75
Net Data Recovered [%]	99.50

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.

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

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.

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

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 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*.

APPENDIX A - Sensor Performance Report

Test Definitions

TestOrder	TestField1	TestField2	CalcField3	TestType	Factor1	Factor2	Factor3
1				TimeTest Insert	0	0	0
4	Etemp2aDEGC			MinMax	-30	60	0
5	Etemp2SDaDEGC			MinMax	0	1	0
10	Anem39aMS			MinMax	0	90	0
11	Anem39bMS			MinMax	0	90	0
12	Anem30aMS			MinMax	0	90	0
13	Anem30bMS			MinMax	0	90	0
14	Anem10aMS			MinMax	0	90	0
20	AnemSD39aMS			MinMax	0	4	0
21	AnemSD39bMS			MinMax	0	4	0
22	AnemSD30aMS			MinMax	0	4	0
23	AnemSD30bMS			MinMax	0	4	0
24	AnemSD10aMS			MinMax	0	4	0
30	Vane39aDEG			MinMax	0	359.9	0
31	Vane30aDEG			MinMax	0	359.9	0
32	Vane10aDEG			MinMax	0	359.9	0
50	Turb39zNONE			MinMax	0	2	0
51	Turb30zNONE			MinMax	0	2	0
52	Turb10zNONE			MinMax	0	2	0
60	Wshr0zNONE			MinMax	-100	100	0
200	VaneSD39aDEG	Anem39yMS	MinMaxT	0	100	100	10
201	VaneSD30aDEG	Anem30yMS	MinMaxT	0	100	100	10
203	VaneSD10aDEG	Anem10aMS	MinMaxT	0	100	100	10
400	Anem39aMS	Anem39bMS	CompareSensors	1	0.25	3	0
401	Anem30aMS	Anem30bMS	CompareSensors	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
Etemp2aDEGC	57594	57450	99.75	0.333	0	0	99.747
Etemp2SDaDEGC	57594	57450	99.75	2.333	0	0	99.726
Anem39aMS	57594	57450	99.75	0	29	8.167	99.363
AnemSD39aMS	57594	57450	99.75	0	29	0	99.448
Anem39yMS	57594	57450	99.75	0	29	0	99.448
AnemSD39yMS	57594	57450	99.75	0	29	0	99.448
Vane39aDEG	57594	57450	99.75	0	29	0	99.448
VaneSD39aDEG	57594	57450	99.75	2.667	29	0	99.42
Anem30aMS	57594	57450	99.75	0	22.167	0.333	99.516
AnemSD30aMS	57594	57450	99.75	0.167	22.167	0	99.517
Anem30yMS	57594	57450	99.75	0	18.333	0	99.559
AnemSD30yMS	57594	57450	99.75	0	18.333	0	99.559
Vane30aDEG	57594	57450	99.75	0	22.167	0	99.519
VaneSD30aDEG	57594	57450	99.75	1.5	22.167	0	99.503
Anem10aMS	57594	57450	99.75	0	25.333	0	99.486
AnemSD10aMS	57594	57450	99.75	0	25.333	0	99.486
Vane10aDEG	57594	57450	99.75	0	25.333	0	99.486
VaneSD10aDEG	57594	57450	99.75	13.833	25.333	0	99.342
Total	1036692	1034100	99.75	20.833	400.667	8.5	99.501

APPENDIX B - Plot Data

Wind Speed Distribution Data

Wind Speed m/s	Percent
0.5	1.59
1.5	4.18
2.5	8.34
3.5	14.95
4.5	18.16
5.5	16.52
6.5	11.66
7.5	8.37
8.5	6.05
9.5	4.12
10.5	2.48
11.5	1.48
12.5	0.87
13.5	0.51
14.5	0.28
15.5	0.2
16.5	0.12
17.5	0.06
18.5	0.02
19.5	0.02
20.5	0
21.5	0.01
22.5	0.01
23.5	0
24.5	0

Monthly Average Wind Speed Data

Date	Average wind speed m/s
Jul-06	5.01
Aug-06	4.49
Sep-06	5.01
Oct-06	5.95
Nov-06	5.1
Dec-06	5.64
Jan-07	6.03
Feb-07	6.25
Mar-07	6.93
Apr-07	6.31
May-07	5.44
Jun-07	4.99
Jul-07	4.38

Diurnal Average Wind Speed Data

hr	Average wind speed m/s
0.5	5.46
1.5	5.5
2.5	5.45
3.5	5.38
4.5	5.36
5.5	5.42
6.5	5.38
7.5	5.39
8.5	5.53
9.5	5.72
10.5	5.9
11.5	6.09
12.5	6.12
13.5	6.08
14.5	6.05
15.5	5.86
16.5	5.64
17.5	5.39
18.5	5.32
19.5	5.37
20.5	5.44
21.5	5.5
22.5	5.48
23.5	5.48

Wind Rose Data

Direction deg	Percent	Speed
0	4.38	4.84
22.5	5.78	5.71
45	4.63	5.77
67.5	2.55	4.6
90	2.75	4.87
112.5	3.82	5.61
135	3.73	5.37
157.5	2.63	4.27
180	2.59	4.41
202.5	5.11	5.2
225	13.29	6.49
247.5	13.38	5.44
270	10.32	5.7
292.5	10.55	5.74
315	9.19	5.69
337.5	5.29	4.93