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# Salem: SODAR-Based Wind Resource Assessment

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December 24, 2008

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# Executive Summary

This report summarizes the wind data collected at the South Essex Sewerage District (SESD) facilities in Salem, Massachusetts using one of the Renewable Energy Research Laboratory's (RERL) two SODAR (Sonic Detection and Ranging) units for the purpose of wind resource assessment.

From February 22nd to March 26th and from July 1st to September 5th, wind speed and direction were measured at the SESD facility in Salem, MA (42°31'45"N, 70°52'27"W ). During the second deployment period the SODAR ceased collecting data twice, once due to a noise complaint shutdown and once due to a power supply problem. The SODAR pulse output level was set at 50% throughout the two deployment periods due to concerns about noise nuisance at nearby residences. This resulted in lower amounts of valid data collected.

Wind data collected at Thompson Island in Boston Harbor since 1998 was used as a reference site and a Measure-Correlate-Predict (MCP) algorithm was used to predict long-term wind speeds at the SESD site. The Thompson Island met tower is located at 42° 18' 56" N, 71° 0' 40" W and the anemometer is mounted at 40 m.

After conducting the MCP analysis, the predicted wind speeds were adjusted to account for the bias in the SODAR data caused by vector averaging effects as well as by volume averaging effects. Long-term average wind speeds were predicted at a range of heights (30 m to 160 m). The following table shows the predicted wind speeds and the expected range of uncertainty from 80 m to 120 m at the SESD facility. It is estimated that there is a 68% chance that the mean wind speeds are between the minimum and maximum values shown in the table. The uncertainty ranges stated below include all of the significant sources of uncertainty. The predicted P90 wind speed is also shown which represents the minimum average wind speed that can be expected with 90% confidence.

| Height [m] | Predicted wind speed [m/s] | Minimum [m/s] | Maximum [m/s] | P90 wind speed [m/s] |
|---|---|---|---|---|
| 80 | 6.03 | 5.30 | 6.76 | 5.40 |
| 90 | 6.24 | 5.50 | 6.99 | 5.60 |
| 100 | 6.54 | 5.69 | 7.38 | 5.80 |
| 110 | 6.66 | 5.76 | 7.56 | 5.88 |
| 120 | 6.91 | 5.98 | 7.83 | 6.10 |

At the SESD site, the estimated wind speed, according to the AWS Truewind Navigator (a successor to the New England Wind Resource Map), is 5.95 m/s at a height of 80 m and 6.23 m/s at a height of 100 m [1]. The wind speeds predicted by SODAR analysis are different than that of the AWS Truewind Navigator but it is well within the uncertainty band.

An uncertainty analysis was conducted and each source of significant error was quantified and accounted for. These sources of errors included the error of the SODAR, the uncertainty of the MCP analysis and inter-annual variability. The uncertainty ranges stated above include all of the significant sources of uncertainty.

Finally, using four representative turbines and their power curves, along with the predicted wind distribution, capacity factors were estimated at their respective hub heights. The capacity factor is defined as the actual annual wind energy output divided by the rated wind turbine output. The table below summarizes the predicted capacity factors.

| Turbine | Rated Power [kW] | Hub Height [m] | Capacity Factor | | Capacity Factor with losses | |
|---|---|---|---|---|---|---|
| | | | Predicted wind speed | P90 wind speed | Predicted wind speed | P90 wind speed |
| Fuhrlaender | 250 | 50 | 0.14 | 0.09 | 0.11 | 0.07 |
| Vestas V52 | 850 | 49 | 0.14 | 0.09 | 0.10 | 0.07 |
| Siemens/Bonus | 1000 | 60 | 0.16 | 0.12 | 0.12 | 0.09 |
| GE 1.5 xle | 1500 | 80 | 0.29 | 0.23 | 0.23 | 0.17 |

## Introduction

As electricity prices continue to increase and with growing concerns of global warming, renewable energy sources are steadily burgeoning in popularity. Currently, the most economical renewable source for electricity generation is wind energy. Since Eastern Massachusetts is home to an abundant source of wind, many towns and communities are actively pursuing the installation of wind turbines. When evaluating the viability of a wind turbine installation, one of the most important parameters is the wind resource at the site. This report summarizes the wind resource assessment carried out by the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts, Amherst for the South Essex Sewerage District in Salem, MA.

The traditional method of collecting wind data is through the use of cup anemometers mounted on meteorological (met) towers. The maximum height for a typical met tower is 50 m. Therefore the estimated wind speeds must be extrapolated up to higher heights when estimating the wind resource at heights of interest for wind energy. With the increasing size of modern wind turbines and higher hub heights, this traditional method leads to an increase in uncertainty and is therefore becoming less desirable.

SODAR (Sonic Detection and Ranging) offers an alternative approach to estimating wind speed. As will be explained in a subsequent section, SODAR measures wind speed by emitting high frequency acoustic waves and recording the Doppler shift of the reflected signal. The wind speed is calculated at a range of heights (from 30 m to 160 m). SODAR can therefore provide more information about the wind resource at a site than a typical met tower assembly.

From February 22nd to March 26th and from July 1st to September 5th, 2008, RERL's SODAR console unit collected wind data at the SESD facility in Salem, MA. The unit was shut down between July 19th and July 30th due to a noise complaint from a nearby resident. Data was also not collected between August 17th and August 25th due to a problem with the power supply. This report presents the measured data that was obtained during this time and the results of the data analysis. Wind data collected at Thompson Island in Boston Harbor was used with the SODAR data to estimate the long-term wind speed at a range of heights (30 m to 160 m).

## Outline of Report

Prior to discussing the data collected at the SESD facility, an overview of SODAR operation is given. The basic functionality of SODAR is discussed and the filters used to determine valid data are presented. Also, some of the limitations of SODAR are identified. These include the effects of echoes caused by ground clutter (i.e. trees, buildings, etc.) and the inability to measure wind speed during precipitation.

Following this, the data analysis methodology is explained. Since ground clutter may contaminate SODAR readings, filters are introduced to eliminate questionable data. Also, since gaps will exist in the SODAR data, due to data filtering and precipitation, long term wind data must be used in conjunction with the Measure-Correlate-Predict (MCP) algorithm to determine long term average wind speeds at the SODAR site over a range of heights.

After the methodology has been presented, the location and duration of data collection at the SESD facility is discussed and a summary of the data is presented.

The results from the MCP analysis using the SODAR data and the long-term data are then presented. The long-term predictions are adjusted to account for vector and volume averaging effects. An uncertainty analysis is also conducted. All significant sources of errors are discussed and included in the overall uncertainty of the predicted wind speeds. Next, capacity factors based on various wind turbine power curves are estimated for their respective hub heights. Finally, a summary and discussion of the results are given as well as some concluding remarks.

## Overview of SODAR Operation and Data Filtering

### *SODAR Operation*

The SODAR trailer unit owned by RERL is an ART Model VT-1. This is described as a monostatic (it emits and receives the signal from the same location) phased-array SODAR. High frequency acoustic waves (~4500 Hz) are emitted from the SODAR in three consecutive directions: one in the vertical direction (W) and two in directions orthogonal in the surface plane, approximately 17 degrees from vertical. The horizontal wind speed components, U and V, are calculated from the two orthogonal tilted beams. After each signal is emitted, a portion of the acoustic energy is backscattered due to fluctuations of the refractive index of air and is returned to the SODAR at some shifted frequency. The SODAR measures the reflected signal and calculates the shifted frequency at each height (from 30 m to 160 m at 10 m intervals). This shift in frequency is called the Doppler shift.

The Doppler shift refers to the change in frequency from a moving source as measured by a fixed observer. The amount of this apparent frequency shift is directly related to the velocity of the moving source (i.e. wind speed). Therefore, after every chirp, the SODAR calculates the wind speed in the direction of the beam at each specified height (range gate). The default range gate heights are from 30 m to 160 m at 10 m increments. The wind speeds are then averaged in each direction (U, V and W) over a ten-minute interval and the average vector wind speed and wind direction are determined at each range gate.

$$Note : Vector\ Wind\ Speed = \sqrt{(U\ Speed)^2 + (V\ Speed)^2}$$
$$where\ U\ Speed\ and\ V\ Speed\ are\ corrected\ for\ Vertical\ Speed\ (W)$$

It should be noted that the SODAR measurement differs slightly from an anemometer measurement. The SODAR measures the instantaneous wind speed components and then averages them to determine the vector wind speed. Anemometers measure the instantaneous wind speed (i.e. U and V components are indistinguishable) and the average scalar wind speed is calculated. The scalar wind speed is typically 1 – 2 % higher than the vector wind speed.

In addition to wind data, the SODAR also records the ambient temperature, the precipitation and the wind speed as measured by an anemometer mounted on a ~3 m-high pole.

## *SODAR Data Filters and Data Quality Checks*

This section describes the SODAR data filtering that was applied to the data at both the pre-processed and post-processed stages. The main function of these filters was to remove spurious data caused by high levels of ambient or electrical noise and to ensure good quality data.

### Pre-processing SODAR Filtering

When the SODAR collects data, there are four initial criteria that must be met in order for the data to be considered valid. First, the signal-to-noise ratio (SNR) is calculated at each height and if it is found to be below the user-defined minimum then the data is discarded. Next, the amplitude of the signal is calculated and the data is removed if it is below the minimum allowed amplitude.

The third criterion is called the consensus check. Once the ten-minute interval is complete, there will be about 150 data samples (Doppler shifts) in each direction. The average Doppler shift is calculated in each direction and if, over that time interval, a data sample has a Doppler shift beyond the range of the average Doppler shift plus or minus the “consensus” (the default is 100 Hz), then the data point is removed.

Finally, if, over the ten-minute interval, there is less than the minimum percent of valid data points (the default is15%) then the data for that ten-minute interval is considered invalid and is removed from the data set [5].

## Echo Rejection Algorithm

In addition to the pre-processing SODAR data filtering described above, the manufacturer has included an optional echo rejection algorithm which is designed to minimize the effect of echoes caused by ground clutter. This option was enabled throughout the SODAR operation at SESD facility.

Ground clutter is defined as trees, buildings, bushes or any stationary object surrounding the SODAR that could reflect the signal at a zero Doppler shift. When echoes occur in this way, the measured wind speed is biased low since the SODAR will interpret the zero Doppler shift as zero wind speed. Echoes from ground clutter impact the lower range gates more significantly than the higher range gates.

Ideally, the SODAR should be situated in an area void of ground clutter. When this is not possible, however, there are several steps that can be taken to minimize the effect of ground clutter. First, if the SODAR is oriented in such a way to direct the SODAR beams away from the ground clutter, the degree of echo contamination is lessened. Also, it has been found that if the SODAR can be raised to a higher elevation (for example, to the roof of a building) then the echoes have less of an impact. Finally, if ART's echo rejection algorithm is employed then the negative bias caused by echoes is greatly reduced.

The echo rejection option is a built-in function in the ART Model VT-1s and can be enabled at the user's discretion. The algorithm works by comparing the amount of spectral energy at the zero Doppler shift to spectral energy at other frequencies. If there is sufficient energy at a frequency other than the zero-shift, then the wind speed is calculated at this frequency and the energy at the zero-shift is ignored. It has been found in previous data sets that the echo rejection option is very effective at lessening the effects of ground clutter contamination.

Ground clutter could not be avoided at the SESD site, the concrete surfaces of the buildings in the facility are very strong sound reflectors. During the first period of SODAR deployment, the SODAR was aligned so as to minimize the potential for noise nuisance to nearby residences. This resulted in a higher occurrence of echoes and subsequently a higher amount of rejected data. The alignment of the SODAR for the second deployment period was corrected to reduce the potential of echoes and this reduced data invalidation due to echoes. Unfortunately, this caused an increase of noise at a nearby residence and the SODAR was realigned to the same direction as during the first deployment which thus increased echoes.

## Post-processing SODAR Filtering

Once the wind speeds had been measured by the SODAR, additional filters were applied to the data. These filters were designed by comparing SODAR measurements to anemometer readings and determining appropriate cut-offs for removing erroneous data. These filters included the following:

- Maximum W turbulence intensity (W speed / Vector Wind Speed)
- Maximum U and V turbulence intensity (U or V speed / Vector Wind Speed)
- Minimum and maximum W wind speed (normalized by vector wind speed)
- Noise filter
- Shear filter

**Turbulence Intensity Filters**

The maximum W turbulence intensity used in the filtering was 0.4 and the maximum U and V turbulence intensity applied was 0.9. These values have shown to remove invalid measurements while retaining the majority of good data.

**Vertical (W) Wind Speed filter**

Minimum and maximum normalized W wind speeds were also defined based on comparisons between SODAR and anemometry data. The minimum and maximum values used in the filtering algorithm were –0.12 and 0.16, respectively.

**Noise filter**

At past sites, there have been occurrences of extraneous noise entering the system which can contaminate the SODAR signal. The noise filter was designed to remove these erroneous data averages.

The noise algorithm compares the calculated wind speed at each height to the wind speed measured by the anemometer (mounted on a 3 m pole). At each time step, the average difference between the SODAR (at each height) and the anemometer are calculated using the measured differences from the most recent five time steps. If the difference, at that time step, is greater than the average difference plus 4 m/s, then the data is discarded.

$$(Avg\ Difference)_{height} = \left( \frac{(Diff_{t-5} + Diff_{t-4} + Diff_{t-3} + Diff_{t-2} + Diff_{t-1})}{5} \right)_{height}$$

$$If\ (Diff_t)_{height} > (Avg\ Difference + 4)_{height}\ Then\ Discard$$

**Shear filter**

Finally, a shear filter was applied to the data. This filter was developed after it was observed that, even after applying the other filters, a significant amount of scatter existed when plotting SODAR versus anemometer data. It has been found that at sites where ground clutter is present, echoes tend to contaminate the signal and bias the wind speed low, particularly at lower range gate heights. It has also been observed that at higher heights, the returning signal has a lower amplitude and it becomes increasingly difficult for the SODAR to accurately distinguish signal from noise.

Based on these observations, the shear filter was designed with the following algorithm:

1) The average wind speed is calculated at 70 m, using wind speeds at 60, 70 and 80 m. This is called the true wind speed at 70 m.
2) It then compares the wind speed at every height to the true 70 m wind speed.
3) The shear power law exponent, alpha, is calculated at each height using the 70 m wind speed as the datum. The following equation shows the wind shear power law expression where U is wind speed [m/s], z is height, $z_r$ is the reference height and α is the power law exponent.

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

4) If alpha is greater than the user-defined maximum shear exponent then the data point is removed
5) If alpha is less than the user-defined minimum shear exponent then the data point is removed.
6) If the 60 m or 80 m data point had been deleted due to shear, then the 70 m data point is also removed.

When designing this filter, it had to be decided what alpha limits should be specified. To answer this question, several tall tower data sets were analyzed. The power law exponent, alpha, was calculated at each ten minute interval between the lower and upper height for each of the tall tower data sets. For each data set, day and night histograms were calculated and the minimum alphas were selected such that 2.5% of the alphas were less than the minimum. The maximum alphas were defined at an alpha where approximately 2.5% of the alphas were greater. Table 1 lists the five tall tower sets and the range of acceptable alphas. As shown, for more complex and forested terrain, the range of acceptable alphas are relatively wide. Conversely, the range of acceptable alphas is much narrower for the offshore tower (Cape Wind). This trend is logical since more wind shear will be present (i.e. higher alpha) when more obstacles are present to slow down the wind. For the SESD data set, the alpha limits based on the Hull WBZ tall tower were used in the shear filter since it is the one with the most similarity to the site at SESD.

**Table 1: Summary of Tall Tower Alpha Limits**

| Site | Site Description | Day Alpha Minimum | Day Alpha Maximum | Night Alpha Minimum | Night Alpha Maximum |
|---|---|---|---|---|---|
| Nantucket, MA | Coastal | -0.2 | 0.7 | -0.3 | 0.8 |
| Hull WBZ, MA | Coastal / Complex terrain | -0.5 | 0.8 | -0.3 | 0.9 |
| Hatfield, MN | Onshore: flat with no trees | -0.5 | 0.9 | -0.5 | 1.1 |
| Isabella, MN | Onshore: forested | -0.3 | 1 | -0.5 | 1.2 |
| Cape Wind site, MA | Offshore | -0.2 | 0.6 | -0.2 | 0.6 |

### *SODAR Operation during times of precipitation*

Since the SODAR measures the speed of moving volumes encountered in the atmosphere, precipitation will usually lead to incorrect wind speed measurements. The effect of precipitation is most evident in the W (vertical) direction, since precipitation obviously falls in this direction. A precipitation gauge was mounted on the SODAR unit and the data acquisition control system ensured that SODAR data was not collected during times of precipitation.

## Data Analysis Methodology

The following section outlines the approach taken in analyzing the SESD SODAR data. Since the SODAR data alone was not sufficient to predict long-term wind speeds due to the limited data collection period and gaps in the data, an MCP algorithm was used with long-term anemometer data from Thompson Island to develop an estimate of the expected wind resource. The steps taken in analyzing the SESD data are described below.

**1) The MCP algorithm was used with wind data from Thompson Island as the reference site to predict long-term wind speeds.**

Measure-Correlate-Predict (MCP) is a technique used to predict the wind resource at a target site using long-term data at a reference site. The method used in this report is discussed in [4]. The site at SESD was the target site and the wind data measured at Thompson Island was used as the reference site. A relationship was developed between the target and reference site based on the ratio of the wind speed standard deviations. Based on this relationship, a predicted long-term wind speed at a range of heights at the SESD facility was found.

**2) The predicted long-term wind speeds were adjusted to account for the low-bias due to volume averaging.**

SODAR measurements tend to be lower than those of an anemometer and the reason for this is volume averaging. This will be explained in more detail later in the report. After MCP, the predicted wind speeds at all heights were adjusted to reflect the bias.

## Summary of Data Collection

### *Location and Duration of Data Collection Site*

On February 14th, 2008, RERL brought its SODAR console unit to the site at the SESD facility and began collecting data on February 22nd. Figures 1 and 2 show maps of the location of the SESD SODAR site. This site has residential areas close to the location of the SODAR and the noise impact of the SODAR is high on the minds of every interested party. The SESD management provided safe guards to ensure that the residences in the area are not affected by the operations of the SODAR and has an immediate response to any concerns raised by the residents.

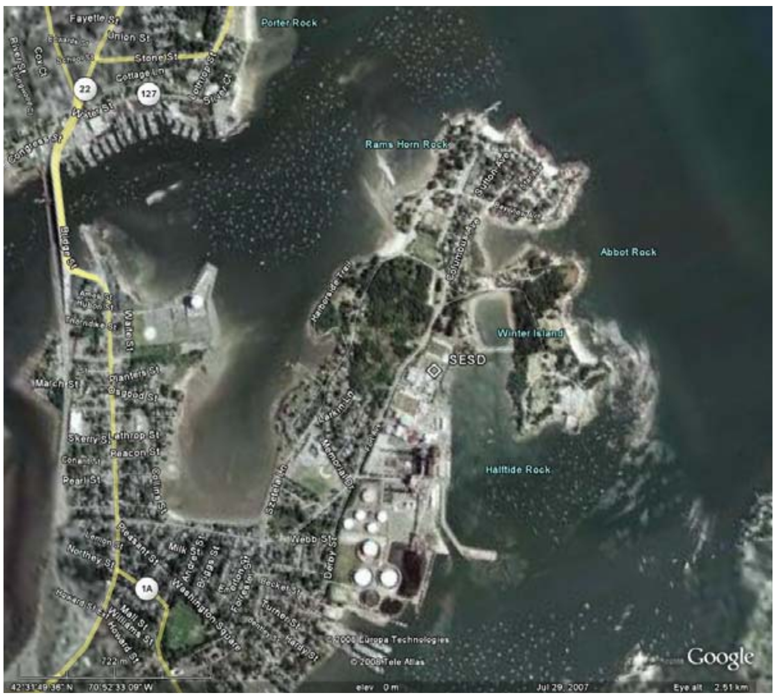


**Figure 1: Location of the SESD SODAR Site**


**Figure 2: Map of SESD SODAR Site (zoomed)**

After the SODAR data was processed, an MCP algorithm was used to estimate the long-term wind speed. The long-term data set used as the reference site was from a 40 m met tower where wind data has been collected since 1998. The distance from the SESD site to the Thompson Island met tower was 16 miles (26 km). Figure 3 shows a map of the Thompson Island met tower location.

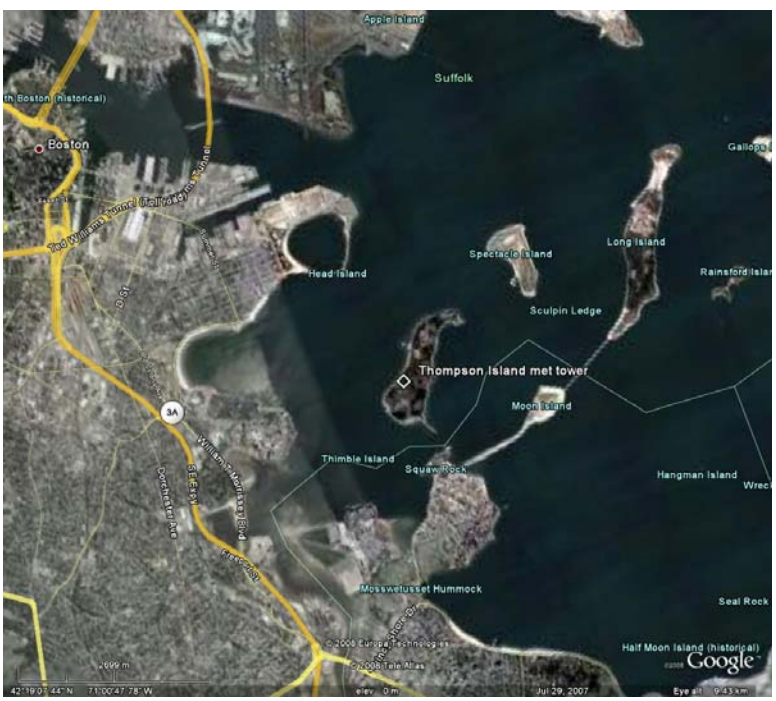


**Figure 3: Map of Long-term data location at Thompson Island**

## *Summary of Data Collection*

On February 14th, 2008 one of RERL's SODARs was brought to the SESD facility in Salem, MA to collect wind data. The unit was removed on March 26th and redeployed to the same location on June 25th until September 5th, 2008. During the second deployment period the SODAR ceased collecting data twice, once due to a noise complaint shutdown and once due to a power supply problem. The SODAR pulse output level was set at 50% throughout the two deployment periods due to concerns about noise nuisance at nearby residences. This resulted in lower amounts of valid data collected.

Figure 4 shows the SODAR at the SESD site.

**Figure 4: SODAR at the SESD facility in Salem, MA**

## Summary of the SESD data

The SODAR was placed at the SESD site from February 14th to March 26th and from June 25th to September 5th, 2008. Figure 5 shows the time series of the SODAR data at 30 m, 60 m and 90 m for the two time periods.

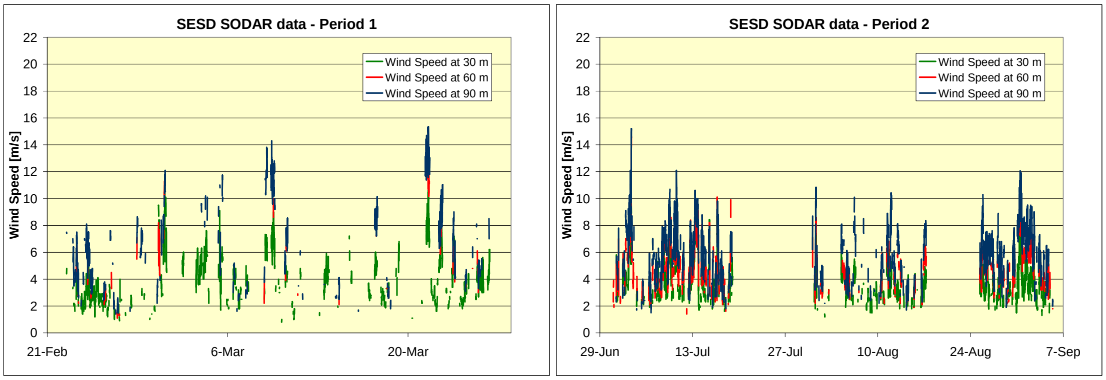


**Figure 5: SESD Time Series**

It can be seen from Figure 5 that the amount of data collected was not complete. This is due to the lower pulse output level set point necessitated by noise nuisance concerns. Echoes caused by the non-optimal direction of the SODAR, also necessitated by noise nuisance concerns, reduce further the amount of valid data collected during the first deployment period and the later part of the second deployment period.

Figure 6 depicts the percentage of valid data collected during this time after applying all filters.

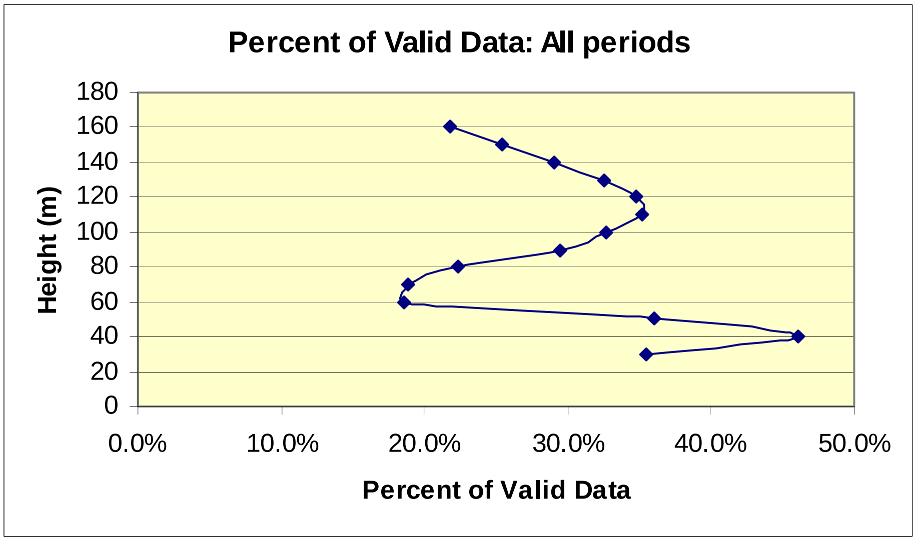


**Figure 6: Percent Valid Data for both time periods**

## *MCP Prediction for the SESD Site Using Thompson Island Data*

The MCP algorithm was carried out on data that has been filtered. The reference data used was from the 40-m meteorological tower located at Thompson Island in Boston Harbor (42°18'53"N, 71° 0'44"W). An anemometer is mounted at a height of 40 m and wind data has been collected since 1998. When conducting an MCP analysis, it is best to use full-years of long-term data therefore data from May 1998 to April 2008 were used.

After conducting the MCP analysis, the predicted wind speeds were adjusted to account for bias due to volume averaging. Volume averaging means that the SODAR measures wind speed over a volume for every height of interest (range gate). If the wind speeds vary significantly within that volume then the predicted wind speed can be skewed. This is of particular importance at sites with high wind shear. At such sites, the predicted wind speed will be biased low by a SODAR. The extent of the under-prediction is a function of height and of the power law shear exponent, alpha. At the SESD facility, the average alpha exponent was found to be 0.34. Using an in-house program coded in Visual Basic, the percent error was found at each range gate as shown in Table 2 below.

**Table 2: Volume Average Percent Error**

| Height | Volume Average Bias |
|---|---|
| 30 | -3.59% |
| 40 | -1.88% |
| 50 | -1.17% |
| 60 | -0.80% |
| 70 | -0.58% |
| 80 | -0.44% |
| 90 | -0.35% |
| 100 | -0.28% |
| 110 | -0.23% |
| 120 | -0.19% |
| 130 | -0.17% |
| 140 | -0.14% |
| 150 | -0.12% |
| 160 | -0.11% |

Long-term wind speed predictions were made at every height between 30 m and 160 m (at 10 m intervals) and were adjusted to account for volume averaging. Table 3 shows the predicted long-term wind speeds. The predicted Weibull parameters, k and c, are presented and their significance will be explained later in this section. The uncertainty of the MCP analysis is also shown in the table. This uncertainty is associated only with the MCP portion of the analysis and is not the overall uncertainty of the wind speed.

**Table 3: SESD Long-term Wind Speed Prediction Results**

| Height [m] | Corrected estimated wind speed [m/s] | Uncertainty of MCP [m/s] | Estimated *k* | Estimated *c* |
|---|---|---|---|---|
| 30 | 4.06 | 0.40 | 2.26 | 4.42 |
| 40 | 4.56 | 0.40 | 2.40 | 5.05 |
| 50 | 4.88 | 0.40 | 2.35 | 5.44 |
| 60 | 5.30 | 0.21 | 2.36 | 5.94 |
| 70 | 5.69 | 0.24 | 2.32 | 6.39 |
| 80 | 6.03 | 0.33 | 2.30 | 6.78 |
| 90 | 6.24 | 0.34 | 2.49 | 7.01 |
| 100 | 6.54 | 0.44 | 2.59 | 7.34 |
| 110 | 6.66 | 0.49 | 2.50 | 7.49 |
| 120 | 6.91 | 0.51 | 2.41 | 7.78 |
| 130 | 7.21 | 0.52 | 2.40 | 8.12 |
| 140 | 7.42 | 0.56 | 2.40 | 8.36 |
| 150 | 7.81 | 0.52 | 2.46 | 8.80 |
| 160 | 7.99 | 0.58 | 2.37 | 9.01 |

The predicted wind speed is shown for each height as well as the estimated standard deviation. The Weibull probability density function (PDF) parameters, k and c, were also estimated at each height. A PDF provides a statistical representation of the wind resource at a site. The *k* parameter is referred to as the shape factor and the *c* parameter is called the scale factor. The shape factor determines the shape of the peak in the PDF and the scale factor is related to the average mean speed. A typical value for the shape factor is 2.0 and a higher value implies that there is less variation in the wind speeds at the site.

$$Weibull\ PDF: P(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^{k}\right]$$

## *SESD - Uncertainty Analysis*

Throughout the process of estimating long-term wind speeds, several sources of error were introduced and must be accounted for. The following section describes each source of significant error, how the error was quantified and then compiled to determine the expected range of uncertainty. The end result is a range of wind speeds around the predicted mean wind speed that can be expected at the SESD facility. The percentage uncertainty values are the standard deviation divided by the mean value. In other words, the uncertainty range is representative of the expected standard deviation surrounding the predicted mean wind speed. Also, a P90 wind speed is given which represents the minimum average wind speed that can be expected at the SESD facility with 90% confidence.

The significant sources of uncertainty in this analysis included:

1) Uncertainty of SODAR Wind Speed, $\delta U_1$
2) Uncertainty of MCP Analysis, $\delta U_2$
3) Inter-annual Variability Uncertainty of Long-term Data, $\delta U_3$

All the error sources (%) were combined into one equivalent uncertainty using the following equation:

$$\delta U = \sqrt{\delta U_1^2 + \delta U_2^2 + \delta U_3^2}$$

## Uncertainty of SODAR Measurement ($\delta U_1$)

The first source of error that was considered was the uncertainty of the SODAR. The manufacturer of the SODAR claims that the horizontal wind speed measurements have an accuracy of ± 0.25 m/s and the vertical wind speed is accurate to ± 0.04 m/s (5). Based on the relationship between the horizontal and vertical wind speed components, the overall uncertainty in the SODAR measurement is ± 0.282 m/s. At each range gate, the SODAR wind speed uncertainty of ± 0.282 m/s was converted to a percentage uncertainty (i.e. % uncertainty = (0.282 / Mean Wind Speed) x 100).

## Uncertainty of MCP Analysis ($\delta U_2$)

The MCP algorithm estimates the long-term wind speed at a target site based on the relationship of the wind speeds at the target site and a reference site. In this case, the target site was the SESD SODAR and the reference site was the Thompson Island met tower. In the algorithm, a standard deviation was determined which quantified the uncertainty in the predicted long-term wind speed at the target site. An uncertainty was determined at each height at the SESD site and this was representative of the uncertainty in the MCP analysis (4).

## Inter-annual Variability Uncertainty of Long-term Data ($\delta U_3$)

The next source of uncertainty is the inter-annual variability uncertainty, which arises since the wind speed at a given site will vary from year to year. Typically, 20 years of data is considered to be sufficient to capture all inter-annual variability. With a shorter data set, there is uncertainty about whether the predicted wind speed is in fact representative of the long-term wind speed at that site. To quantify this error, the following equation can be used (2):

$$\delta U = \frac{6\%}{\sqrt{N}}$$

$$where: N = Length\ of\ Data\ Set\ in\ Years$$

Since 10 years of data from the Thompson Island met tower was used in this analysis, the inter-annual variability uncertainty is 1.9 %.

## Summary of Uncertainty Analysis

Table 4 shows the predicted wind speeds at the site at the SESD facility along with the range of expected wind speeds incorporating all the error sources. The predicted P90 wind speed is also shown at each height which represents the minimum average wind speed that can be expected with 90% confidence.

**Table 4: SESD Predicted Wind Speeds, Expected Ranges and Expected P90 Wind Speed**

| Height [m] | Predicted wind speed [m/s] | Total uncertainty [%] | Total uncertainty [m/s] | Min [m/s] | Max [m/s] | P90 wind speed [m/s] |
|---|---|---|---|---|---|---|
| 30 | 4.06 | 18.64 | 0.76 | 3.30 | 4.82 | 3.40 |
| 40 | 4.56 | 16.78 | 0.77 | 3.80 | 5.33 | 3.90 |
| 50 | 4.88 | 15.78 | 0.77 | 4.11 | 5.65 | 4.21 |
| 60 | 5.30 | 11.12 | 0.59 | 4.71 | 5.89 | 4.79 |
| 70 | 5.69 | 11.15 | 0.63 | 5.06 | 6.33 | 5.14 |
| 80 | 6.03 | 12.07 | 0.73 | 5.30 | 6.76 | 5.40 |
| 90 | 6.24 | 11.92 | 0.74 | 5.50 | 6.99 | 5.60 |
| 100 | 6.54 | 12.92 | 0.84 | 5.69 | 7.38 | 5.80 |
| 110 | 6.66 | 13.53 | 0.90 | 5.76 | 7.56 | 5.88 |
| 120 | 6.91 | 13.38 | 0.92 | 5.98 | 7.83 | 6.10 |
| 130 | 7.21 | 13.01 | 0.94 | 6.27 | 8.15 | 6.39 |
| 140 | 7.42 | 13.30 | 0.99 | 6.43 | 8.41 | 6.56 |
| 150 | 7.81 | 12.11 | 0.95 | 6.86 | 8.76 | 6.99 |
| 160 | 7.99 | 12.73 | 1.02 | 6.97 | 9.01 | 7.10 |

Figure 7 shows the predicted wind shear profile at the SESD facility along with the expected range of uncertainty. The error bars represent a 68 % uncertainty (i.e. one standard deviation of a normal distribution). One can then estimate with 68 % confidence that the long-term wind speed at a given height will fall within the error bars.

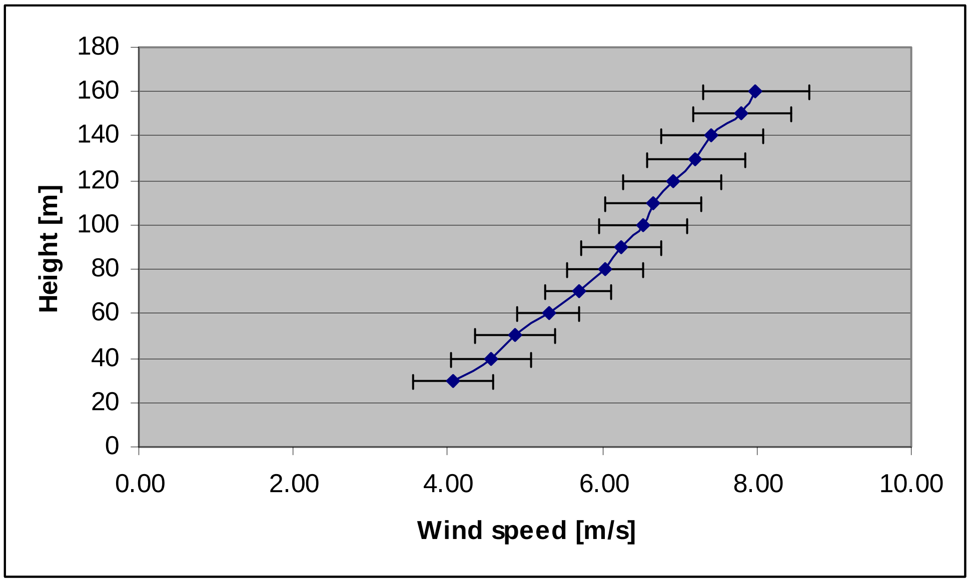


**Figure 7: SESD: Wind Shear Profile with Uncertainty Range**

## *Capacity Factor Calculation*

Finally, using the predicted mean wind speeds, the expected capacity factor was calculated for a few turbines of different rated power at their respective representative hub heights. The capacity factor is defined as the actual annual wind energy output divided by the rated wind turbine output.

The power curve used in the capacity factor calculation is shown in Figure 8.

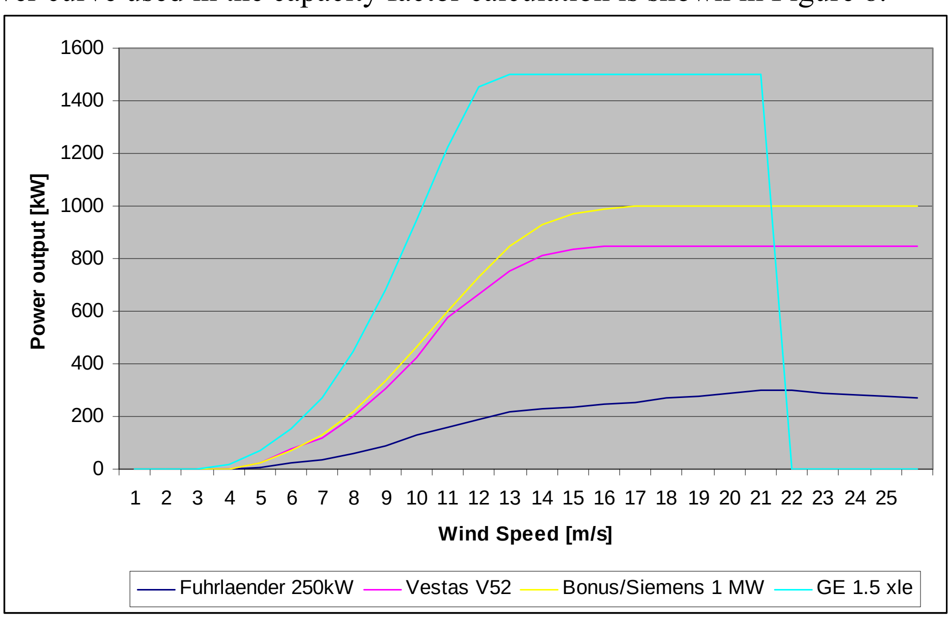


**Figure 8: Wind Turbine Power Curves**

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. 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 the turbines and hub heights as listed in Table 5 below together with the predicted long term mean wind speed as calculated previously. 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 predicted power production was then multiplied by the expected losses that account for maintenance and icing. It was assumed that the loss factors due to maintenance and icing were each 0.95 and the combined loss factor was therefore 0.9025 (i.e. $0.95^2$). Finally, the capacity factor is then calculated from:

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

where $P_{rated}$ is the rated capacity of the turbine.

Table 5 shows the predicted capacity factors at the respective hub heights for each of the turbines.

**Table 5: SESD Facility Capacity Factor Prediction**

| Turbine | Rated Power [kW] | Hub Height [m] | Capacity Factor | | Capacity Factor with losses | |
|---|---|---|---|---|---|---|
| | | | Predicted wind speed | P90 wind speed | Predicted wind speed | P90 wind speed |
| Fuhrlaender | 250 | 50 | 0.14 | 0.09 | 0.11 | 0.07 |
| Vestas V52 | 850 | 49 | 0.14 | 0.09 | 0.10 | 0.07 |
| Siemens/Bonus | 1000 | 60 | 0.16 | 0.12 | 0.12 | 0.09 |
| GE 1.5 xle | 1500 | 80 | 0.29 | 0.23 | 0.23 | 0.17 |

# Summary and Discussion of Results

One of RERL's SODARs was brought to the SESD facility in Salem , MA and began collecting data from February 22nd 2008 until March 26th and then again from July 1st until September 5th 2008. During the second deployment period the SODAR ceased collecting data twice, once due to a noise complaint shutdown and once due to a power supply problem. The SODAR pulse output level was set at 50% throughout the two deployment periods due to concerns about noise nuisance at nearby residences. This resulted in lower amounts of valid data collected.

Long-term wind speed data collected at Thompson Island in Boston Harbor was then used as the reference data in MCP. The long-term wind speed was then estimated and adjusted to account for vector and volume averaging effects at each height. The wind shear was examined to be about 0.34

An uncertainty analysis was conducted and the expected range of long-term wind speeds was determined at each height. The estimated long-term wind speeds are shown in the Table 6, along with the expected range of uncertainty and the P90 wind speed.

**Table 6: Predicted Wind Speeds and Ranges of Uncertainty**

| Height [m] | Predicted wind speed [m/s] | Min [m/s] | Max [m/s] | P90 wind speed [m/s] |
|---|---|---|---|---|
| 30 | 4.06 | 3.30 | 4.82 | 3.40 |
| 40 | 4.56 | 3.80 | 5.33 | 3.90 |
| 50 | 4.88 | 4.11 | 5.65 | 4.21 |
| 60 | 5.30 | 4.71 | 5.89 | 4.79 |
| 70 | 5.69 | 5.06 | 6.33 | 5.14 |
| 80 | 6.03 | 5.30 | 6.76 | 5.40 |
| 90 | 6.24 | 5.50 | 6.99 | 5.60 |
| 100 | 6.54 | 5.69 | 7.38 | 5.80 |
| 110 | 6.66 | 5.76 | 7.56 | 5.88 |
| 120 | 6.91 | 5.98 | 7.83 | 6.10 |
| 130 | 7.21 | 6.27 | 8.15 | 6.39 |
| 140 | 7.42 | 6.43 | 8.41 | 6.56 |
| 150 | 7.81 | 6.86 | 8.76 | 6.99 |
| 160 | 7.99 | 6.97 | 9.01 | 7.10 |

The expected wind speed at the SESD facility at 100 m is 6.54 m/s and there is a 68% level of confidence that the average wind speed will be between 5.69 and 7.38 m/s.

Finally, using four representative turbines and their power curves, along with the predicted wind distribution, capacity factors were estimated at their respective hub heights. The capacity factor is defined as the actual annual wind energy output divided by the rated wind turbine output. Table 7 summarizes the predicted capacity factors at heights of 60 m and 80.

**Table 7: Summary of Estimated Capacity Factors at the SESD facility**

| Turbine | Rated Power [kW] | Hub Height [m] | Capacity Factor | | Capacity Factor with losses | |
|---|---|---|---|---|---|---|
| | | | Predicted wind speed | P90 wind speed | Predicted wind speed | P90 wind speed |
| Fuhrlaender | 250 | 50 | 0.14 | 0.09 | 0.11 | 0.07 |
| Vestas V52 | 850 | 49 | 0.14 | 0.09 | 0.10 | 0.07 |
| Siemens/Bonus | 1000 | 60 | 0.16 | 0.12 | 0.12 | 0.09 |
| GE 1.5 xle | 1500 | 80 | 0.29 | 0.23 | 0.23 | 0.17 |

Although every effort was made in accurately measuring and predicting the wind speeds at the SESD site, it is noted that the predictions stated in this report should be treated as estimates only. The predictions made in this report should serve only as a guide when determining the economic feasibility of a wind turbine installation.

# References


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