

Feasibility Study for Marblehead, Massachusetts

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FEASIBILITY STUDY: MARBLEHEAD, MASSACHUSETTS

INTRODUCTION

This report outlines the possibility of installing wind energy in Marblehead Massachusetts. The study reviews issues related to installing wind energy including possible turbine locations, the wind resource, turbine options, estimated power production, economics and public acceptance hurdles.

BACKGROUND

Town of Marblehead

Marblehead is located on the northern shores of Massachusetts. It has a population of about 20,000 and covers 4.5 square miles, which includes a peninsula (the *Head*) and a small island to the east (the *Neck*). The Head and Neck are connected by a causeway, which encloses Marblehead Harbor. To the west of the peninsula is Salem Harbor. A map of Marblehead in relation to the rest of Massachusetts is shown in Figure 1.

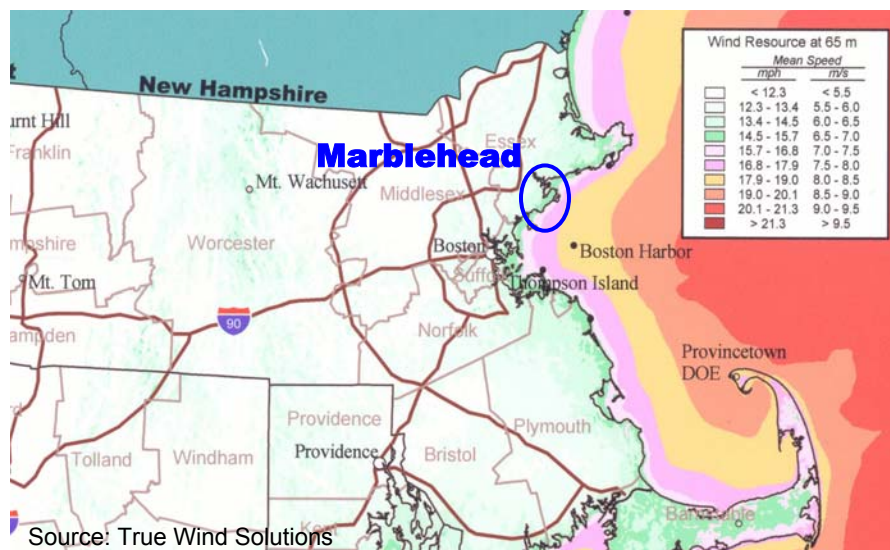


Figure 1. Location of Marblehead on Wind Resource Map

Marblehead has a peak electric demand of 25,500 kW and consumes approximately 105 GWh per year. Distribution lines are rated at 4,160 volts, with 13kV transmission lines. Most circuits are designed at 1 to 1.5 MW. Several diesel generators distributed around the town provide 6 MW of peak generating capacity. The Salem Harbor Power Station is the primary supplier of electricity to the area.

Interest in Wind Power

Recently, the Salem Harbor Power Station, a coal-fueled power plant located about 2 miles to the northwest of Marblehead, was declared one of the five dirtiest power plants in Massachusetts and the dirtiest plant operated by Pacific Gas & Electric [Greenpeace, 2003]. Massachusetts Governor Mitt Romney has threatened shutdown of the facilities if federal emissions standards are not met by October 2004 [TheBostonChannel.com, 2003].

Marblehead was highlighted in the April 2003 issue of Boston Magazine as ranking low on the list of healthiest towns in Massachusetts. It states, "This North Shore community scores well on safety, with a low violent crime rate and high public safety spending... What's unexpected are the sky-high rates of asthma and some types of cancer, which researchers at the Harvard School of Public Health attribute to pollution from the Salem Harbor Station power plant" [Blanding, 2003].



Figure 2. Salem Harbor Power Station As Seen From the Cell Tower

In response to pollution-related health concerns such as this, the citizens group HealthLink was formed in Marblehead. HealthLink is involved in public education, corporate responsibility, regulatory hearings, and solid waste clean up. In actively seeking solutions to energy-related pollution, HealthLink is investigating renewable energy options.

In addition, the Marblehead Municipal Light Department (MMLD), a town-owned municipal utility, became interested in the potential economic benefits of wind energy and the ability of wind to diversify their energy portfolio after the successful wind turbine installation in Hull, MA [Manwell et al, 2003].

Role of the Renewable Energy Research Lab

In 2001, HealthLink requested the services of the Renewable Energy Research Lab (RERL). After discussing the potential benefits and challenges of wind energy with Marblehead representatives, the decision was made to analyze the feasibility of a wind project. With the assistance of MMLD, permits were obtained to mount wind-monitoring equipment on top of an existing cellular tower located at the town landfill. RERL has collected over a year of data from this site.

Feasibility Study Results

Based on the year of wind data collected at Marblehead, the results of the feasibility study are presented below. The study consists of six parts:

- 1) Description of the potential wind turbine site(s)
- 2) Description of the available wind resource
- 3) Initial candidate turbine choices
- 4) Estimation of energy production
- 5) Preliminary economic evaluation
- 6) State regulation or public acceptance hurdles
- 7) Series of recommendations

DESCRIPTION OF POTENTIAL WIND TURBINE SITES

As Marblehead is densely populated, siting of a wind turbine is a critical issue. Two possible wind turbine locations are investigated in this paper: the town landfill and the public beach parking lot, as described below. Due to the land constraints of both sites, only one machine is considered for either location. A computer generated wind energy resource map of Southern New England has been made by TrueWind Solutions. The section of the map around Marblehead is shown in Figure 3.

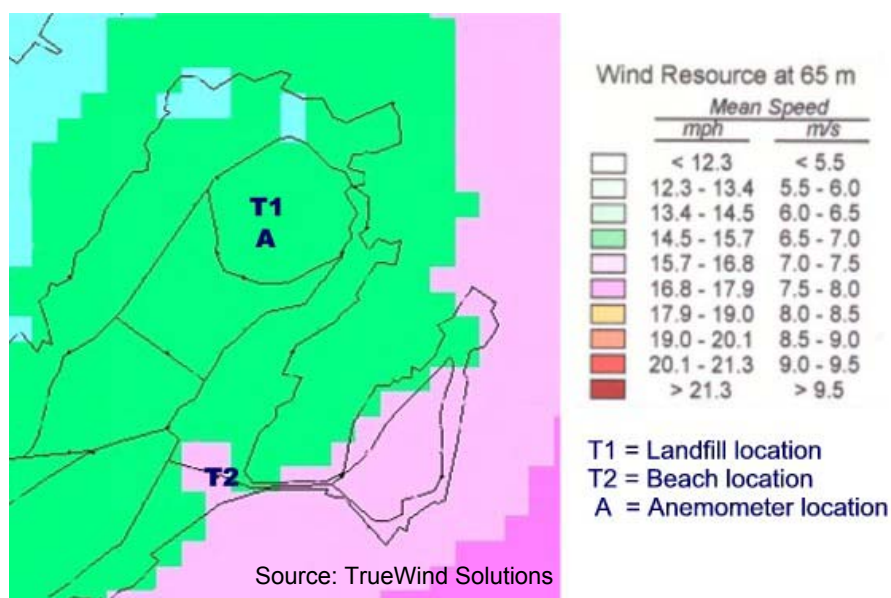


Figure 3. Wind Resource Map of Marblehead, MA

Town Landfill: The anemometry equipment is currently located on a cell tower on the edge of the landfill. A 13kV transmission line goes through the property. Also at the site are diesel generator sets, an old incinerator plant, and a water tower. Soil instability may make a turbine foundation more expensive. The wind map indicates that at the landfill site the average wind speed at a height of 65 meters (213 feet) above the ground is in the 6.5 to 7 meters per second range.



Figure 4. Landfill Site as Viewed from Top of Cell Tower

Public Beach: The public beach is located to the southwest of the causeway connecting Marblehead Neck and Head. The exact wind potential at this site is unknown, but the wind map in Figure 3 suggests that the beach site could have a wind resource anywhere from 6.5 to 7.5 m/s winds at a 65-meter height. A turbine could be located in the southwest corner of the parking lot. In the area are a powerhouse, playground, several homes, and the harbor, which houses many pleasure craft.



Figure 5. Beach Site as Viewed from the Causeway

Other sites that were discussed with Marblehead representatives, but not explored in detail in this report include:

Middle School: The wind potential at this site is not known and would need to be explored. The turbine could be used as an educational tool. A 13kV transmission line is nearby.

Water Tower / Tioga Way: Although at a high elevation, there is little space to site a turbine. The water tower would also disrupt the wind from certain directions.

Offshore: A possible solution to inland constraints is to install the turbine(s) offshore. However, offshore sites would require an undersea cable, at a rough price of \$1 million per mile. To make an off-shore development economically feasible, the project would need to be at least 10 MW in size. This is beyond the scope of Healthlink's current interest, but should be kept in mind for future projects.

Conclusions on Wind Turbine Sites

Two possible wind turbine locations will be investigated in this report: the town landfill and the public beach parking lot. Due to the land constraints of both sites, only one machine can be placed at either location.

MEASURED WIND RESOURCE

On March 1st, 2002, wind resource monitoring equipment was installed atop the 55-meter (150-foot) cell tower at Marblehead's landfill. It consisted of a primary and secondary pair of anemometers and wind vanes, along with a data acquisition unit. A specially designed pole and base was needed to mount the equipment on the tower. A crane was provided by Marblehead Municipal Light Department to lift equipment and crew to the top of the tower. The monitoring tower and equipment are shown in Figures 6 and 7.



Figure 6. Wind Monitoring Tower



Figure 7. Wind Monitoring Equipment at Top of Tower

The data loggers are programmed to sample the wind speed every second and record the average 10-minute wind speed, standard deviation, maximum and minimum values. These ten-minute averages are periodically sent to RERL to be inspected for completeness and accuracy. For this report, the 10-minute averages were converted to hourly averages, which are more manageable for energy calculations.

Quality Control and Data Verification

Two sets of anemometers and wind vanes were used to measure wind speed and direction at the Marblehead site. Redundant equipment is used to ensure that measurements are accurate and to serve as a back-up. Given the sensitivity of the power potential to wind speed, it is important that even small sources of error are identified and corrected.

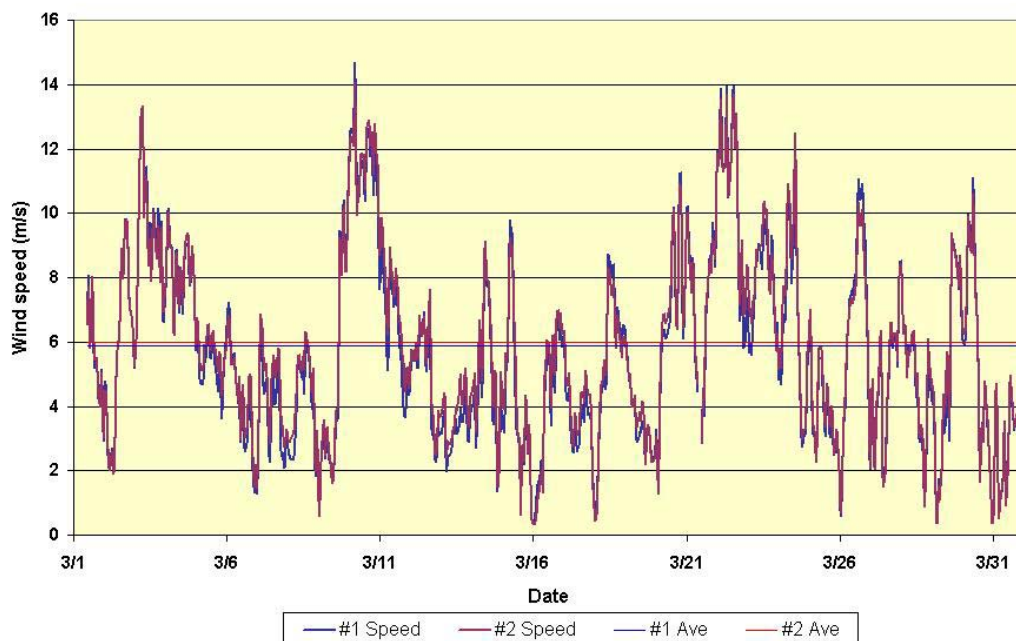


Figure 8. Hourly Wind Speeds Recorded by Each Anemometer in March

A comparison of wind speeds between the two anemometers shows slightly different averages, with Anemometer #1 generally recording lower speeds than Anemometer #2, as shown in Figure 8. The readings also have a directional effect, as shown in Figure 9. The wind rose shows that the Anemometer #1 and #2 track quite closely, except in the NW quadrant. When winds come from this direction, Anemometer #1 indicates a lower wind speed than #2. The anemometers are identical NRG #40G, which typically have far less unit-to-unit variation than seen here.

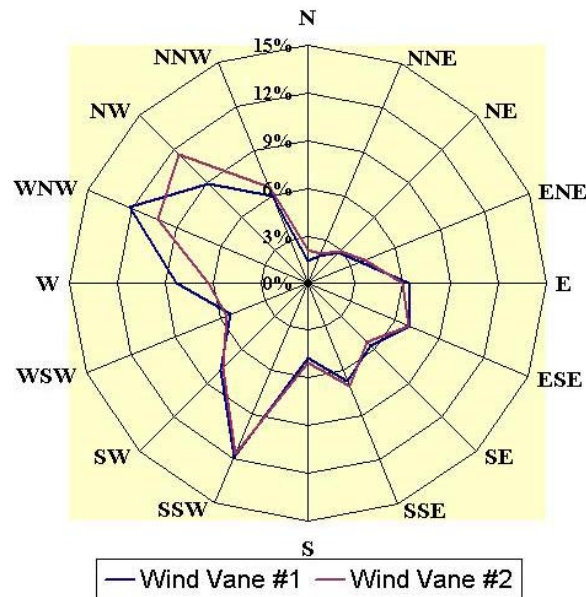


Figure 9. Wind Rose Recorded by Each Wind Vane for March 2002

Figure 10 shows the layout of the equipment at the top of the tower. Anemometer #1 and Vane #1 are located near the mounting pole, which is a small boom 14 inches length. Anemometer and Vane #2 are mounted on a 3-foot boom to the West-North-West. Comparing this configuration to the wind rose, it can be seen that Anemometer #1 and Vane #1 are in the wake of the #2 sensors when winds come from the primary wind direction. Therefore, the #1 sensors do not accurately record wind speeds from the West-North-West. A test done in the University of Massachusetts open-air wind tunnel qualitatively confirmed this expectation. Therefore, the data collected from the #2 sensors are determined to be less biased and are used throughout this report.

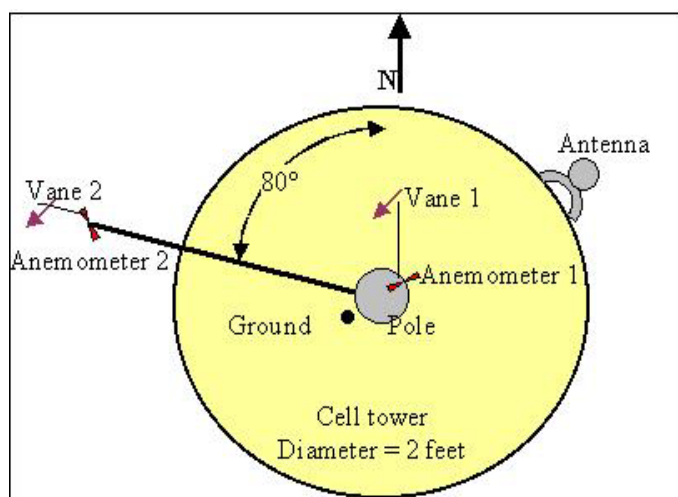


Figure 10. Aerial View of Layout of Equipment at Top of Tower

Some data collection problems were encountered. Most of these occurred in April and were able to be corrected remotely without much loss of data. During the summer, short dropouts of data became a fairly frequent occurrence, possibly as the result of electrostatic discharge (ESD). In late July, a lightning strike damaged the logger. These events resulted in a total loss of 31.5 hours for the summer. A site visit to repair the logger was made on August 2, 2002. The data card and two SIM (analog to digital converter) cards were replaced. In addition, surge absorbers were wired into the anemometers to increase resistance to future ESD damage. These adjustments have minimized data dropouts. Figure 11 lists the percent of missing data for each month. This results in a total data recovery rate of 97%.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.0%	0.0%	0.3%	8.3%	1.1%	12.2%	8.7%	4.8%	0.1%	0.0%	0.0%	0.0%

Figure 11. Percent of Data Missing for Each Month

In order to make hourly predictions of energy production throughout the year, any missing data in hourly wind speeds, due to either sensor failure or the removal of erroneous data, was approximated. Gaps were filled using a statistical technique developed by the University of Massachusetts based on the short-term fluctuations in the wind and diurnal trends. Wind speeds were generated that would closely match expected values without changing the average wind speed or standard deviation of the data set. Figure 12 shows where synthesized data is used to fill gaps in the raw data. A curve is fitted to the complete data set to show the general annual wind speed trend.

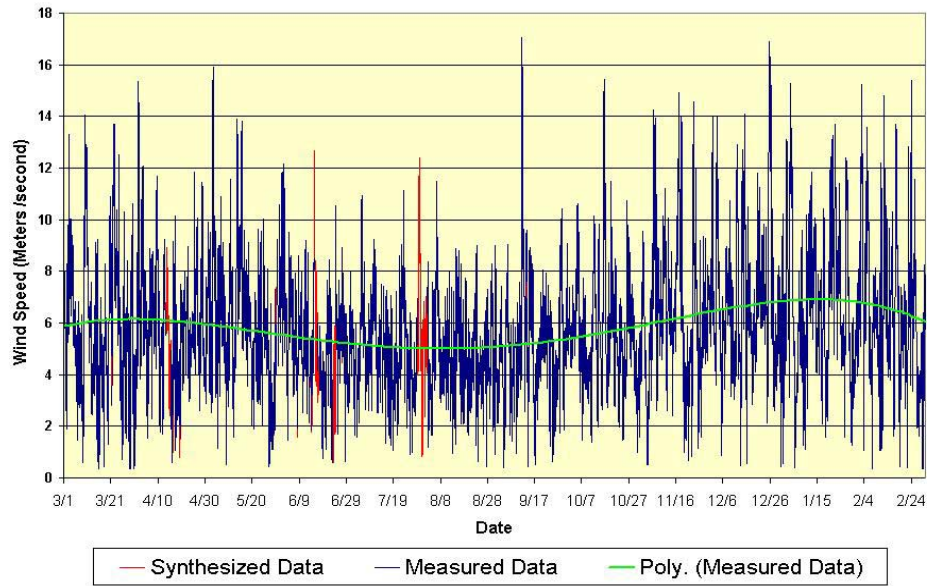


Figure 12. Annual Hourly Wind Speeds in Marblehead Including Gap Fill

Calculations performed in this report use the complete hourly data set, including synthesized gap-fill data, from March 1, 2002 through March 1, 2003.

Wind Characteristics

The hourly data is used to determine parameters that characterize the wind resource in Marblehead, as shown in Table 13.

Average Wind Speed	5.84 m/s	13.1 mph
Max Wind Speed	17.1 m/s	38.3 mph
Min Wind Speed	0.35 m/s	0.78 mph
Standard Deviation	2.54	5.68

Table 13. Measured Wind Speed Characteristics for Marblehead

Wind speeds for the year are grouped into bins to form a probability histogram, shown in Figure 14. The histogram illustrates how often a particular wind speed is likely to occur throughout the year. As shown, the most probable wind speed is approximately 4.5 meters per second, while average wind speeds of over 15.5 meters per second rarely occur.

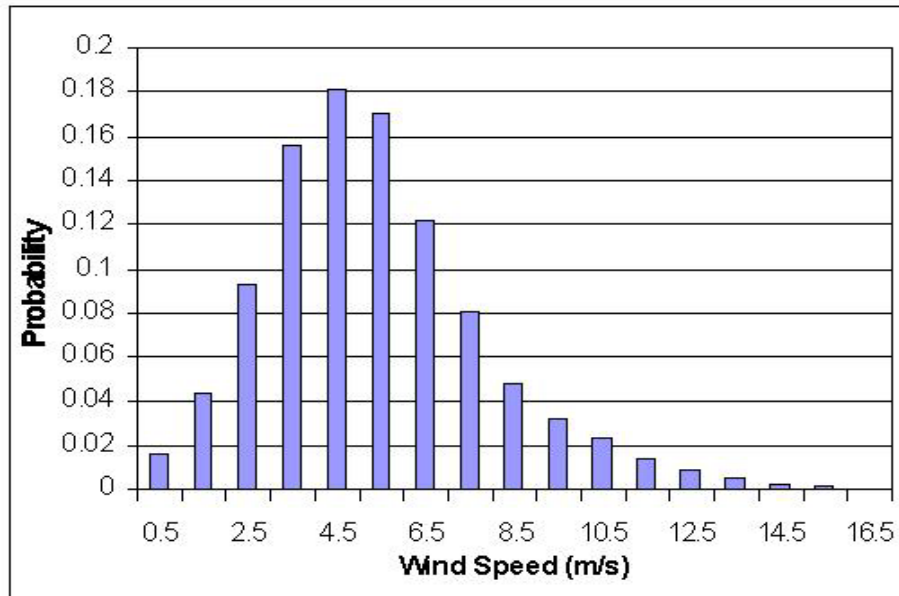


Figure 14. Histogram of Marblehead Wind Speeds

Turbulence intensity is a measure of the “gustiness” of a wind resource. It is a dimensionless number defined as the standard deviation of the wind speed divided by the average wind speed. Lower turbulence intensity numbers are better for two reasons. First, a turbine blade can more efficiently extract energy from a ‘smooth,’ less turbulent wind. Second, high turbulence increases loads on a turbine, which can result in increased maintenance costs over the life of the machine. Typical turbulence intensity numbers range from a low of 0.09 in an offshore location to over 0.30 on a mountain ridge. The measured average turbulence intensity value of 0.22 is relatively high.

The change in wind speed throughout the day is shown in Figure 15. As shown, the winds are relatively steady throughout the day. They are strongest during the daylight hours, peaking in the afternoon at approximately 6.8 m/s.

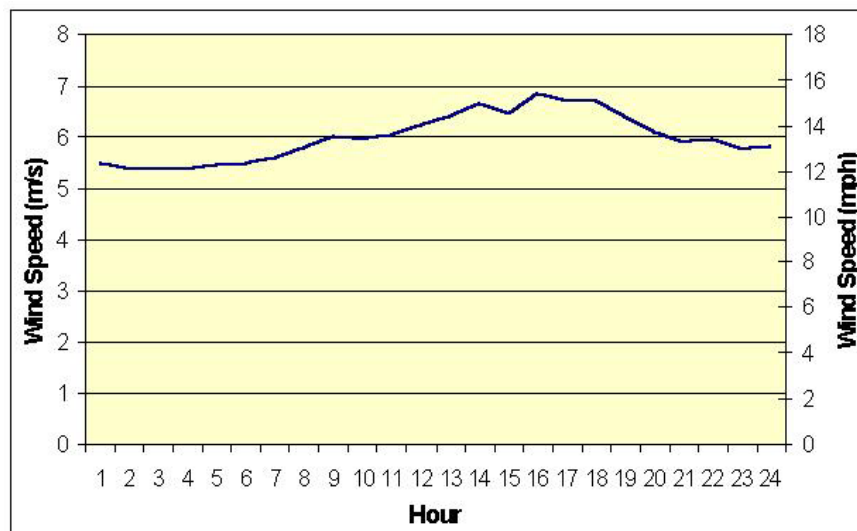


Figure 15. Diurnal Wind Speeds for Typical April Day

A wind energy rose, or plot of wind direction as a function of time, is shown in Figure 16. As indicated in Figure 16, the primary wind direction is from the Northwest.

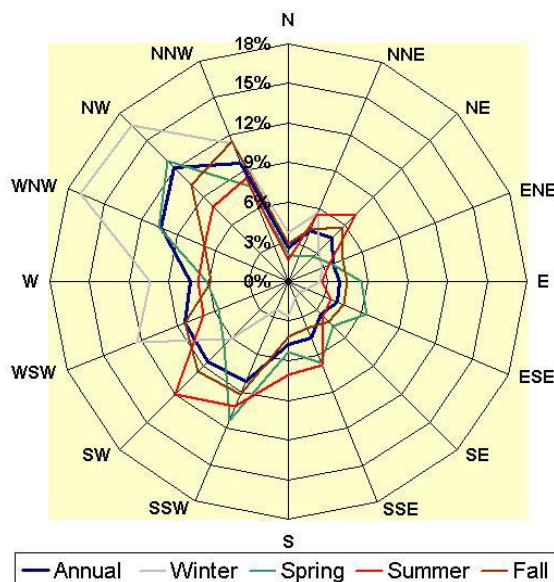


Figure 16. Seasonal and Annual Wind Rose for Marblehead

WIND RESOURCE PREDICTIONS

Estimation of Hub Height Wind Speeds

In order to make useful predictions about the feasibility of a wind project in the area, some modifications to the wind data file must be made. Wind speed generally increases with height. Thus, a turbine on a higher tower will produce more energy than the same machine on a shorter tower. The data was collected at a height of 55 meters (180 ft). To determine the energy production of the various candidate turbines, the wind speed distribution at each turbine hub height, or wind shear, must be calculated. The data collected at Marblehead did not include a measure of the wind shear; therefore, the *log law* mathematical model must be used to estimate changes in wind speed with height. An explanation of this model is provided in Appendix 1.

In this model, a surface roughness length of 0.30 is used at the landfill site to adjust all hourly wind speed data to what would be expected at each possible wind turbine hub height.

Estimating Long Term Wind Speeds

In addition to the height adjustment, a modification is made to account for variations in annual wind speed trends. The year when data was collected could have been an unusually windy or unusually calm year. If this wind speed alone was used to predict power production over the next 20 or 30 years, calculations could drastically over or under estimate performance. A Measure-Correlate-Predict (MCP) method is used to predict long-term wind speeds based on short-term measurements. Short-term measurements are taken at the proposed turbine location and compared to long-term measurements available at a nearby location. In this report, five years of wind speed data from Logan International Airport in Boston were compared to the one year of

Marblehead data. It was determined that the average annual wind speed at the landfill location is 5.70 m/s, which is slightly slower than the measured 5.84 m/s. Therefore, all of the hourly wind speeds were adjusted downward by a factor of 0.976 to reflect a lower long-term average wind speed.

The results of both the height and long-term adjustments are shown in Figure 17. The adjusted average of 5.70 m/s at a 55-meter height is a fair to moderate wind speed for power production. Wind speeds are expected to increase with increased wind turbine hub heights. Therefore, taller turbines will likely produce more electricity.

Tower Height (m)	55	60	65	70	75	80	90
Wind speed (m/s)	5.70	5.81	5.90	5.98	6.04	6.13	6.26

Figure 17. Long-Term Average Annual Hourly Wind Speed at Hub Height

Estimating Wind Speeds at Beach Location

At the beach site, the smooth surface of water will tend to slow the wind to a far lesser degree than it would going over land, resulting in lower surface roughness values. This effect has been observed at other sites monitored by RERL [Ellis, et. al. 1998-1999]. However, the primary wind direction is from the northwest, so during the majority of the year, winds will be coming from over the land, not the ocean. A preliminary analysis in the WindFarm® software program [ReSoft Ltd], which uses topographical information to determine wind flows, shows that the beach site has a wind resource very similar to the landfill site. The wind resource map shown earlier suggested that the beach site may have a higher average wind speed, but without taking measurements at the site, it is difficult to make an accurate prediction. Therefore, in this report it is assumed that any difference in energy production between each site is negligible.

Conclusions of Wind Resource Predictions

The year of measured wind speed data has been modified to adjust for long-term wind characteristics and various wind turbine hub heights. The long-term wind speeds are slightly slower than the year that was recorded, with an annual average of 5.7 m/s at a 55-meter height. This is a fair to moderate wind speed for power production. Wind speeds will increase with increased wind turbine hub heights. Therefore, taller turbines will produce more electricity.

The two possible wind turbine locations have approximately the same wind resource characteristics and thus have equal power-producing potential. Therefore, the same wind data file will be used to predict power production at each site based on various wind turbine models and hub heights.

CANDIDATE TURBINE CHOICES

The current wind turbine market has scaled up over the last decade to turbines in the 600 kW to 3.5 MW class. These modern turbine designs incorporate features that improve performance and lower operation costs. Advanced features on these machines can include: fiber optic control for better lightning and electromagnetic interference (EMI) protection, more modular designs that allow rotors to be optimized for low or high speed wind sites, reduced noise generation, direct drive gearless generators, and variable speed operation.

Candidate turbines were selected based on a number of criteria, including proven design concepts, established business presence in the U.S., operational reliability, and safety. Preliminary power production estimates were done to determine the capacity factor of each machine. Machines with capacity factors less than 16% were eliminated. Eight turbines from six companies made the initial screening. All selected turbines have the following characteristics:

Three bladed – Most modern wind turbines have two or three blades. Three-bladed turbines generally spin somewhat slower than two bladed turbines of an equivalent power rating.

Upwind rotor orientation – Blades may be oriented upwind or downwind of the tower. Blades that are downwind of the tower may be noisier due to sudden changes in airflow over the blades as they intersect a region of lower wind speeds behind the tower, known as tower shadow.

The candidate turbines differ from each other in a number of aspects:

Power rating – The rated power of a wind turbine is the power that the turbine will produce at a specified wind speed. The rated power is usually close to the maximum possible power output. In low winds the turbine will produce less than the rated power. Candidate wind turbines have a power range of 660 to 1.5 MW.

Dimensions – Turbines with a higher rated power have longer blades and consequently higher towers.

Power regulation – The power produced by the wind turbine depends in part on the method of regulation. In high winds the power must be regulated so that it remains close to the rated power for which the machine was designed. Stall-regulated machines are designed so that the blades become less efficient in high winds, limiting the power. Pitch-regulated machines actively change the angle of the blades to achieve optimum performance and ensure safe operation in above-rated wind speeds. This provides for more control, but is more complex mechanically.

Generator operation – Most wind turbine use induction generators that run at a (nearly) constant speed. Some machines use induction generators that can operate at two distinct speeds and power levels. The GE wind generators can operate at variable speed using additional power conversion equipment.

Selected turbines are listed in Figure 18. More complete specifications for each machine are listed in Appendix 2.

Manufacturer (Model)	Power Rating	Rotor Diameter	Tower Height	Power Regulation	Generator Operation
GE (GE1.5sl, 80)	1.5 MW	77 m	80 m	Pitch	Variable speed
GE (GE1.5sl, 65)	1.5 MW	77 m	65 m	Pitch	Variable speed
Vestas (V47)	660 kW	47 m	65 m	Pitch/OptiSlip®	2 speed
Vestas (V80)	1.8 MW	80 m	80 m	Pitch/OptiSlip®	2 speed
Nordex (N62)	1.3 MW	62 m	70 m	Stall	2 speed
NEG-Micon (NM72c)	1.5 MW	72 m	80 m	Active-Stall®	Constant speed
MADE (46/660)	660 kW	46 m	70 m	Stall	2 speed
Bonus (62/1300)	1.3 MW	62 m	60 m	CombiStall	2 speed

Figure 18. Characteristics of Candidate Wind Turbines

Conclusions on Candidate Wind Turbines

Eight potential wind turbine configurations, covering a range of manufacturers, power capacity, and tower heights, will be investigated in this report.

ESTIMATED POWER PRODUCTION

The long-term hourly hub height wind speeds are used with the power curves of each wind turbine to estimate the annual electricity they would produce. The power curve information, which is usually supplied by the turbine manufacturer, shows the predicted performance of the turbine at each wind speed. Power curves used in this report are listed in Appendix 2. Summing the power production for every hour of the year will give the maximum possible power production. These results are then decreased by 3 % to assume 97% turbine availability. New turbine installations have demonstrated availabilities up to 99%, and availabilities in excess of 95% are common on older, but well maintained wind farms [Micon 1998], so 97% appears a realistic, achievable goal. The yearly power production from each machine is shown in Figure 19.

GE1.5sl, 80m	GE1.5sl, 65m	Vestas V47	Vestas V80	Nordex N62	NEG-M72c	MADE (46/660)	Bonus (62/1300)
2,981,476 kWh	2,703,066 kWh	1,042,029 kWh	3,082,276 kWh	1,786,492 kWh	2,557,735 kWh	910,868 kWh	1,809,495 kWh
23.2%	21%	18.4%	19.9%	16%	19.9%	16.1%	16.2%

Figure 19. Estimated Annual Power Production and Capacity Factors

Conclusions on Estimated Power Production

The Vestas V80, which is the machine with the largest rated power (1.8 MW), will produce the most electricity, followed by the GE 1.5 MW machine. Both are on 80-meter

towers and are optimized for moderate wind speeds with their large rotor diameters. Of the smaller machines (less than 1 MW), the Vestas V47 out-performs the MADE 46/660.

ECONOMIC EVALUATION

The economics of the candidate turbines are compared against each other based on the value of the electricity produced, estimated turbine cost, installation cost, O&M costs, electricity cost inflation rate, general inflation rate, and the discount rate. Values used for each of these variables in the baseline economic analysis are described below, followed by a sensitivity analysis to evaluate the affects of variations in any assumed values.

Capital and Installation Costs

Turbine capital costs were either taken from published manufacturer's list prices or information supplied directly by the manufacturer. In cases where quoted prices were not available, general benchmark guidelines were used. The numbers assume a 'typical' installation, which includes a foundation, transformer, grid hookup, installation, transportation, roadwork, and remote monitoring equipment. The Marblehead installation costs may be more or less expensive depending on the exact details of the foundation, road design, grid hookup, etc. The prices are summarized in Figure 20.

Turbine Costs	GE1.5sl (80m tower)	GE1.5sl (65m tower)	Vestas (V47)	Vestas (V80)
Capital:	\$1,245,000	\$1,155,000	\$487,500	\$1,350,000
Installation:	<u>\$315,000</u>	<u>\$290,000</u>	<u>\$162,500</u>	<u>\$450,000</u>
Total:	\$1,560,000	\$1,445,000	\$650,000	\$1,350,000
Turbine Costs	Nordex (N62)	NEG-Micon (NEGM72)	MADE (46/660)	Bonus (62/1.3MW)
Capital:	\$950,000	\$1,125,000	\$581,625	\$1,145,625
Installation:	<u>\$250,000</u>	<u>\$375,000</u>	<u>\$193,875</u>	<u>\$381,875</u>
Total:	\$1,200,000	\$1,500,000	\$775,500	\$1,527,500

Figure 20. Project Costs

Annual Costs

Annual costs include maintenance and insurance. Routine maintenance consists of checking oil and seals and replacing components that are subject to normal wear, such as bearings. Some spare parts are usually kept on hand to replace common wear and tear items and keep turbine downtime to a minimum. Based on experience from wind turbine installations in Europe and California, it is estimated that operation and maintenance costs are 1.5% of the total installed turbine cost [Manwell, et al, 2003].

The cost of insurance is estimated to be 0.3% of installed cost, based on previous experience [Ellis, et al. 1999]. Therefore, the total annual costs for all turbines are assumed to be 1.8% of installed turbine cost.

Value of Electricity Produced

The value of electricity produced by the wind turbine depends on the market in which it can be sold and various production-based incentives. Renewable energy credits (REC),

which are based on the Massachusetts renewable portfolio standard, allow the environmental aspects of renewable energy to be sold in the competitive market. The Renewable Energy Production Incentive (REPI) is a federal incentive that is currently part of legislation but is subject to change over the 20 years of the project [MA DOER, 2001].

In this paper, it is assumed that the price of electricity for the municipal utility is \$0.05/kWh, the renewable energy credits can be sold at \$0.025/kWh, and the REPI is available at \$0.018/kWh. Therefore, the total revenue is taken as the sum of the market price of electricity and production incentives, or \$0.093/kWh.

Electricity Cost Inflation Rate, General Inflation Rate, and Discount Rate

Based on previous experience, a constant electricity cost inflation rate of 2.7%, a general inflation rate of 2.7%, and a discount rate of 4.25% is assumed over the life of the project [Ellis, et. al, 1999].

Baseline Turbine Life Cycle Ranking

A lifecycle cost analysis, using software developed at the University of Massachusetts [UMass Wind Energy Engineering Minicodes], has been performed for each of the machines. The life cycle code calculates the values described below:

Present value of total costs -- found from the annual costs, adjusted by inflation, discounted to the beginning of the first year, and summed to give a single value for the life of the project [Smith, 1973].

Levelized cost of energy -- the value, which if held constant over the life of the project, multiplied by the annual energy production, discounted back to the beginning of the first year, and then summed, would yield a value equal to the net present value of all the costs [Smith, 1973].

Net present value of savings -- the difference between the present value of the cost of obtaining energy from the normal supplier and the present value of the wind turbine costs. The cost of energy is adjusted by the inflation rate and discounted as appropriate in determining the total net present value [Smith, 1973].

Simple payback period -- found from the first cost of the project divided by one year's annual revenue less that year's expenses. Loan interest rates, inflation rates, and the discount rate are not considered. The first cost of the project is the turbine capital cost plus installation cost [Smith, 1973].

Based on previous experience, Figure 21 lists the assumptions that are used in all baseline life cycle analysis. The economic life of the project is equal to the manufacturer's design life for each turbine. The non-financed portion of the first cost is assumed to be made at the beginning of the first year. All annual expenses and receipts are assumed to occur at the end of each year.

Economic Life	20 years
Down Payment	15%
Loan Interest Rate	7%
Discount Rate	4.25%
Electrical Inflation Rate	2.7%
General Inflation Rate	2.7%
Price of Electricity	\$0.093 /kWh
Loan Period	10 years

Figure 21. Baseline Values for Economic Analysis

Using these baseline values as input to the life cycle costing program, the candidate turbines were evaluated, and results are summarized in Figure 22.

Turbine Model	GE1.5sl (80m tower)	GE1.5sl (65m tower)	Vestas V47	Vestas V80	Nordex N62	NEG-Micon M72	MADE46	Bonus1.3
Installed Cost	\$1,560,000	\$1,445,000	\$650,000	\$1,800,000	\$1,200,000	\$1,500,000	\$775,500	\$1,527,500
Present Value of Total Costs	\$2,228,052	\$2,063,805	\$928,355	\$2,570,829	\$1,713,886	\$2,142,358	\$1,107,599	\$2,181,634
Levelized Cost of Energy (\$/kWh)	\$0.056	\$0.057	\$0.067	\$0.063	\$0.072	\$0.063	\$0.091	\$0.091
Net Present Value of Savings	\$2,528,083	\$2,248,203	\$733,920	\$2,346,105	\$1,135,976	\$1,937,813	\$345,444	\$704,924
Simple payback (years)	6.3	6.4	7.6	7.1	8.3	7.1	11.0	10.8

Figure 22. Baseline Economic Evaluation

The GE1.5sl (80-meter tower) wind turbine has the shortest simple payback of 6.3 years and lowest levelized cost of energy (\$0.056), followed by the NEG-Micon and Vestas V80, each with a simple payback of 7.1 years and levelized cost of energy of \$0.063.

Sensitivity Analysis

To determine the relative sensitivity of the outputs to the initial assumptions, the UMass life cycle costing program was re-run with one of the turbines, the Vestas V47, which was evaluated to be in the middle of the pack. The range of input values was varied, but only by one parameter at a time, for the price of electricity, discount rate, electricity inflation rate, general inflation rate and initial system cost (to determine effects of subsidy or bidding changes to first cost). Results are summarized in Figures 23 – 27.

Price of Electricity	\$0.06	\$0.07	\$0.08	\$0.09	\$0.10	\$0.11
Capital Cost	\$487,500	\$487,500	\$487,500	\$487,500	\$487,500	\$487,500
Installed Cost	\$650,000	\$650,000	\$650,000	\$650,000	\$650,000	\$650,000
Present Value of Total Costs	\$928,355	\$928,355	\$928,355	\$928,355	\$928,355	\$928,355
Levelized Cost of Energy	\$0.067	\$0.067	\$0.067	\$0.067	\$0.067	\$0.067
Net Present Value of Savings	\$144,080	\$322,820	\$501,559	\$680,298	\$859,037	\$1,037,777
Simple Payback (years)	12.8	10.6	9.1	7.9	7.0	6.3

Figure 23. Effect of Changes in Price of Electricity (Vestas V47)

Discount Rate (%)	0.03	0.04	0.05	0.06	0.07	0.08
Capital Cost	\$487,500	\$487,500	\$487,500	\$487,500	\$487,500	\$487,500
Installed Cost	\$650,000	\$650,000	\$650,000	\$650,000	\$650,000	\$650,000
Present Value of Total Costs	\$995,490	\$941,120	\$891,881	\$847,154	\$806,407	\$769,181
Levelized Cost of Energy	\$0.064	\$0.066	\$0.069	\$0.071	\$0.073	\$0.075
Net Present Value of Savings	\$884,489	\$761,722	\$656,689	\$566,584	\$489,078	\$422,232
Simple Payback (years)	7.6	7.6	7.6	7.6	7.6	7.6

Figure 24. Effect of Changes in Discount Rate (Vestas V47)

General Inflation Rate	2%	4%	6%	7%	10%	12%
Capital Cost	\$487,500	\$487,500	\$487,500	\$487,500	\$487,500	\$487,500
Installed Cost	\$650,000	\$650,000	\$650,000	\$650,000	\$650,000	\$650,000
Present Value of Total Costs	\$915,230	\$955,861	\$1,007,646	\$1,038,715	\$1,158,842	\$1,268,063
Levelized Cost of Energy	\$0.066	\$0.069	\$0.073	\$0.075	\$0.084	\$0.092
Net Present Value of Savings	\$747,045	\$706,413	\$654,629	\$623,560	\$503,433	\$394,212
Simple Payback (years)	7.6	7.6	7.6	7.6	7.6	7.6

Figure 25. Effect of Changes in General Inflation Rate (Vestas V47)

Electricity Inflation Rate	-1%	0%	1%	2%	3%	4%
Capital Cost	\$487,500	\$487,500	\$487,500	\$487,500	\$487,500	\$487,500
Installed Cost	\$650,000	\$650,000	\$650,000	\$650,000	\$650,000	\$650,000
Present Value of Total Costs	\$928,355	\$928,355	\$928,355	\$928,355	\$928,355	\$928,355
Levelized Cost of Energy	\$0.067	\$0.067	\$0.067	\$0.067	\$0.067	\$0.067
Net Present Value of Savings	\$248,905	\$359,985	\$484,791	\$625,205	\$783,375	\$961,750
Simple Payback (years)	7.6	7.6	7.6	7.6	7.6	7.6

Figure 26. Effect of Changes in Electricity Inflation Rate (Vestas V47)

Initial Installed Cost	10%	5%	-1%	-5%	-10%	-15%
Capital Cost	\$536,250	\$511,875	\$482,625	\$463,125	\$438,750	\$414,375
Installed Cost	\$715,000	\$682,500	\$643,500	\$617,500	\$585,000	\$552,500
Present Value of Total Costs	\$1,021,190	\$974,773	\$919,071	\$881,937	\$835,519	\$789,102
Levelized Cost of Energy	\$0.074	\$0.070	\$0.066	\$0.064	\$0.060	\$0.057
Net Present Value of Savings	\$641,084	\$687,502	\$743,203	\$780,338	\$826,755	\$873,173
Simple Payback (years)	8.5	8.1	7.5	7.2	6.8	6.4

Figure 27. Effect of Changes in Installed Cost (Vestas V47)

In evaluating the sensitivity analysis the most important and most effected parameter is the net present savings. Changing each parameter affects the savings as follows:

- Price of energy: a \$0.01 change has a 13% effect on payback period and 26% effect on the net present savings.

- Discount Rate: a 14.3 % change has a 13.7% effect on the net present savings.
- General Inflation Rate: a 14.3% change has a 4.7% effect on the net present savings.
- Electrical Inflation Rate: a 25% change has a 18.5% effect on the net present savings.
- Initial Installed Cost: a 5% change has a 6.3% effect on the net present savings.

Project Risk Analysis

A final run of the life cycle cost program was performed to determine the value of each variable that will produce a net savings approximately equal to zero. This will indicate at what point the Vestas V47 turbine becomes uneconomical to operate. The zero savings values, along with the baseline values, are listed in Figure 28, and are described below.

	Zero Savings Value	Baseline Assumption Value	Percent Change in Baseline Assumptions
Price of Electricity	\$0.052	\$0.093	44%
Discount Rate	26%	4.3%	609%
General Inflation Rate	17%	2.7%	618%
Electricity Inflation Rate	-4%	2.7%	240%
Initial Cost	79%	100%	21%

Figure 28. Values that Produce No Net Savings (Vestas V47)

The initial cost is by far the easiest factor to control, through the competitive bidding process and pre-construction site testing. If formal quotes exceeded the estimated costs by 21% for any unforeseen reason the project can be terminated.

A change in the cost of electricity has a large effect on the projects economic potential. The total price of electricity to bring the project to zero savings is shown to be \$0.052. The baseline price of electricity includes the production tax credits and green certificates. Without these incentives, the price of electricity would be \$0.05/kWh and the project will not earn any money. The availability of the production tax credit and green certificates need to be further assessed before continuing with the project.

The general inflation rate change required to render the Vestas V47 uneconomical is 14% over the assumed inflation rate of 2.7 %. It is unlikely that inflation could increase this substantially without intervention from the Federal Reserve.

The electrical inflation rate change required to eliminate any net savings, is the only one that would have to decrease to a negative value. While not impossible, the expected trend is that the cost of energy is expected to increase.

The required upward change of 21.7 % in the discount rate would most likely occur only if the Federal Reserve raised interest rates substantially to deter inflationary pressures. However, a rate increase of this magnitude seems very unlikely.

It should be noted that the Vestas V47 is the third lowest ranked turbine out of a possible eight in the baseline case, with a net savings of \$733,920. All other higher-ranking machines would each have a larger range before they would produce a net savings of zero.

Conclusions on Economics

The GE1.5sl (80-meter tower) wind turbine has the shortest simple payback of 6.3 years and lowest levelized cost of energy (\$0.056), followed by the NEG-Micon and Vestas V80, each with a simple payback of 7.1 years and levelized cost of energy of \$0.063.

The GE 1.5 on an 80-meter tower has the highest net present value of savings (\$2,528,083), followed by the Vestas V80 (\$2,346,105). Therefore, the GE 1.5sl machine installed on an 80-meter tower appears to be the best economic value.

Rebates, grants, and financing resources are also available for renewable energy projects in Massachusetts, such as a Renewable Portfolio Standard and the Renewable Energy Trust Fund (created through a system benefits charge). These sources may further improve the economics of a wind project in Marblehead; however, investigation of these options is beyond the scope of this report.

PUBLIC ACCEPTANCE HURDLES

The installation of a new wind turbine involves a number of environmental, regulatory, grid interconnection, and public acceptance issues. Issues related to permitting are beyond the scope of this report. These can be addressed in more detail once economic and public acceptance hurdles have been overcome. Public acceptance hurdles include visual impact, noise, avian interaction, and electromagnetic interference, each of which is addressed below.

Visual Impact

In order to have unobstructed access to winds, turbines must be placed on tall towers and be located in open areas. When placed in an urban setting such as Marblehead, wind turbines become highly visible structures.

Public perception of wind turbines on the landscape can vary greatly. Individuals will react differently to the surrounding environment and changes in the landscape, making it very difficult to reach public agreement on a wind project. The general consensus is that a wind turbine should be unobtrusive in character. The visual appearance of a wind turbine depends on its apparent size, color, number of blades and tower type. Modern wind turbines, with smooth conical towers, aerodynamic nacelle, and light colors, are based on popular aesthetic design principles [Gipe, 2002].

Photo simulations are used to present accurate representations of a proposed wind turbine in a particular location to help facilitate discussions on a wind project's impact on the landscape. A number of visualizations were created of both the landfill and beach sites in Marblehead.

Photographs were taken at various vantage points throughout Marblehead, and locations of each were documented using a Global Positioning System. Using dimensions of each wind turbine and digital elevation maps (DEM) from MassGIS [Massachusetts Geographic Information System], the software program WindFarm [ReSoft Ltd] was used to superimpose a turbine in the proper location and the proper scale on each photo. Figure 32 shows an aerial photograph of the locations of the proposed wind turbines and the viewpoints where the photos were taken. Figures 30 through 35 on the following pages show photo simulations of the turbines from the various viewpoints listed in

Figure 32. Note that other structures appearing on the landscape include the cell tower and the exhaust stacks from the Salem Harbor Power Station.



Figure 29. Locations of Proposed Wind Turbines and Photo Simulation Viewpoints



Figure 30. Visualization of Landfill Site (T1) from Across Marblehead Harbor (V1)



Figure 31. Visualization of Landfill Site (T1) from Across Marblehead Harbor (V1)



Figure 32. Visualization of Landfill Site (T1) from Across Marblehead Harbor (V2)



Figure 33. Visualization of Landfill Site (T1) from the North (V4)



Figure 34. Visualization of Beach Site (T2) from the Causeway (V3)



Figure 35. Visualization of Beach Site (T2) from the Causeway (V3)

Noise

Sound generated from the proposed wind turbine is an important issue because of the densely populated area and central location of the potential wind turbine sites. The detection of noise is a function of the sound levels emitted by the turbine itself, the location of the listener, and the background sound levels (Danish Wind Turbine Mfg., 1998). In this section estimates for the sound from the candidate turbines are presented. In order to help the reader understand the noise issues, Appendix 3 includes an explanation of the basics of sound and sound measurements.

The Massachusetts Department of Environmental Protection (DEP) regulates noise emissions as a form of air pollution [Mass DEP, 1999]. These regulations include two requirements. First, any new broadband sound source is limited to raising noise levels no more than 10 dB(A) over the ambient baseline sound level. Based on non-linear effects of adding sound levels, the effective legal rise limit is 9.5 dB(A). Second, “pure tones”, defined by the DEP as an octave band or less in the frequency band of generated sound, may be no greater than 3 dB(A) over the adjacent octave bands. These readings are measured at the property line or at any inhabited buildings located within the property.

Baseline Sound Level: The ambient baseline is defined as the sound level that is exceeded 90% of the time, sometimes referred to as the L_{90} level. A noise study was performed previously in Marblehead at a residential location, which resulted in a background noise level measurement of 32 dB(A). Therefore, according to state regulations, the installation of a wind turbine cannot result in background sound levels exceeding 41.5 dB(A).

Distance to Locations of Interest: For the landfill location the distance to the nearest residence is 108 meters. For the beach location, the distance to the nearest residence is 78 meters. These distances are based on available maps.

Source Sound Levels: In order to calculate noise levels heard at different distances, the reference sound levels, or sound power levels, need to be determined. The sound power level should be thought of as the effective acoustic power being radiated, and is not the actual sound level heard. There are standard tests in place for turbine manufacturers to test sound power levels generated by their machines. These tests are performed at wind speeds of 8 m/s and result in a sound power level ranging from 98 dB to 102 dB for the turbines investigated. To be conservative, a sound power level of 102 dB is assumed for all noise calculations.

Noise Propagation Model: Sound propagation is a function of the source sound characteristics, directivity, height, distance, air absorption, reflection and absorption by the ground and nearby objects and weather effects, such as changes of wind speed and temperature with height. A model is used to estimate sound propagation [Rogers, 2002]:

$$L_p = L_w - 10\log_{10}(2\pi R^2) - \alpha R$$

Where L_p is the sound pressure level (dB) a distance, R (m), from a noise source radiating at a power level, L_w (dB), and α (estimated at 0.005 dB(A) per meter) is the frequency-dependent sound absorption coefficient. This noise propagation model is shown in Figure 36, using the sound power level (L_w) of 102 dB, along with the legal noise increase limit.

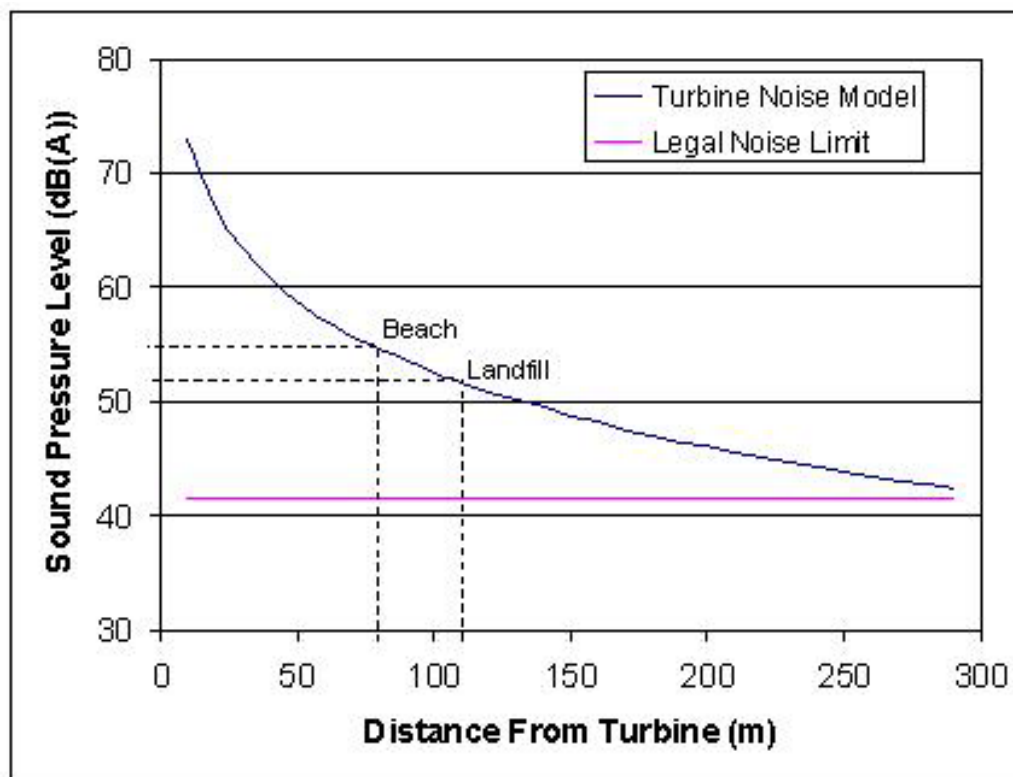


Figure 36. Model of Noise Emitted From a Wind Turbine ($L_w = 102$ dB)

Perceived sound pressure levels from the candidate turbines at the locations of interest can be deduced from Figure 36 as 52 dB(A) for 108 meter distance at the landfill and 55 dB(A) for the 78 meter distance at the beach. Based on this model, a turbine generating 102 dB(A) will be eliminated from the selection possibilities.

A detailed noise study is needed at the specific locations of concern to accurately assess the sound levels. The measurements will be a costly test and a study should only be performed in the event that all other obstacles have been overcome.

Avian Issues

An environmental impact study on the local bird population may be required. Unless the turbine is sited along an avian flyway or a nesting area, this is typically not a major concern. The tubular towers that are recommended will have less impact on bird populations than a lattice tower as the former lacks perching sites that might otherwise attract birds.

Electromagnetic Interference (EMI)

Early wind turbine designs were reported to have affected the reception of TV broadcasts. While some early wind turbine designs did have problems with EMI, they were often due to the materials used to make the blades, namely conductive metals. None of the machines in this study use metal blades, but rather a layered epoxy and matrix design consisting of wood, carbon fiber, or fiberglass. The small quantity of metal used for lightning protection and bolting to the hub does not appear likely to cause reception problems.

Conclusions on Public Acceptance Hurdles

Any wind turbine model at any tower height will be visible on the landscape as viewed from across the Marblehead Harbor and in the immediate vicinity of the machine. However, foliage and the hilly landscape will obscure the view of a wind turbine from most vantage points throughout the Head. The existing 55-meter cell tower is not visible from many points along the streets of Marblehead.

In order to accurately assess the impact of increased sound levels in the area, a more detailed study and measurements are needed. An environmental impact report that includes migratory patterns of birds should also be performed.

RECOMMENDATIONS

Turbine recommendation

The wind turbine that produces the most electricity at the lowest cost is the GE 1.5 MW machine on an 80-meter tower. If a smaller turbine is desired, the Vestas V47 660 kW machine on a 65-meter tower is recommended.

Site recommendation

The town landfill site and the public beach parking lot site would produce approximately the same amount of electricity. The landfill site will have less of a visual impact and may be preferable.

AREAS OF FURTHER INVESTIGATION / CONTINUED SUPPORT

If the community decides to move forward with a wind project based on the findings in this report, a number of predevelopment tasks remain to be completed.

A more detailed analysis of the sound levels at turbine operating conditions will be needed to verify that any sound generated by a wind turbine will be within legal limits. A comprehensive environmental impact report, which includes the impacts on the air, water, land, and wildlife in the area, is required. A geotechnical study should also be performed.

The Marblehead Municipal Light Department would be leading the siting and permitting process. Since they are a municipal utility, a power purchase agreement would not need to be negotiated. Depending on the scope of the project, RERL would assist in developing a request for bids from turbine manufacturers or direct the participant to a commercial developer.

GLOSSARY

- Active Pitch** – A power regulation method used in some wind turbines whereby an actuator will rotate the blade to control lift.
- Availability** – The fraction of time that the turbine is available to operate.
- Broadband** – A non-discrete type of sound, covering a large frequency interval.
- Cut-in wind speed** – The minimum wind speed needed for the turbine to produce a useful amount of power. It is also called the startup wind speed.
- Cut-out wind speed** – The continuous wind speed at which a turbine shuts down to limit overloading of system components.
- Induction Generator** – is an essentially constant speed device that transmits power through induction between the rotor and stator. It consists of a rotating transformer secondary (the rotor) and a stationary primary (the stator). An emf (electro-magnetic force) is induced when the rotor moves past the stator windings.
- L₉₀** – The level that is exceeded 90% of the time, the standard used by the DEP to set ambient noise levels.
- Nacelle** – The bedplate upon which the gearbox, generator, brake and controls are mounted. Located at the top of the turbine tower, where it is connected to the tower by a bearing.
- Octave** – A frequency interval equal in range to eight notes on a standard musical scale.
- Passive Pitch** – A power regulation method used in some wind turbines that adjusts the blade pitch using aerodynamic and other loads, but without using a powered actuator.
- Pitch** – A change in the orientation of an airfoil relative to the incident wind caused by rotating the blade.
- Power Factor** – A measurement of the phase difference between the voltage and current. A power factor of 1.0 is ideal. Lower values result in greater losses in the electrical system.
- Rated wind speed** – The wind speed at which a wind turbine first produces its rated power.
- Rotor orientation** – The designed location of the rotor while the turbine is operating relative to the tower and incoming wind. Depending on the design, this may be either upwind or downwind of the tower.
- Soft Start** – A device to limit the initial current draw when starting the turbine. It reduces startup loads and excess heat generation in the generator windings.
- Survival wind speed** – The maximum wind speed for which a non-operating wind turbine is designed to withstand.
- Stall** – An aerodynamic condition on an airfoil characterized by high drag and low lift. Used in power regulation of wind turbines by making the blades less efficient as the wind speed increases.

APPENDIX 1. WIND SHEAR

Wind speed generally increases with height. Thus, a turbine on a higher tower will produce more energy than the same machine on a shorter tower. To determine the wind speeds at the various turbine heights, the wind speed distribution, or wind shear, must be determined. If this information is not collected with the anemometry equipment, a mathematical model must be used to estimate changes in wind speed with height. Wind speed changes with height are often represented by the *log law* relationship:

$$V = V_0 \times \frac{\ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H_0}{z_0}\right)}$$

where,

- V_0 = Reference velocity (measured with anemometer)
- H_0 = Height where measurements were taken
- H = Height of the tower where the wind speed is sought
- V = Resultant wind speed at height H
- z_0 = Surface roughness length

The surface roughness length characterizes the roughness of the ground terrain. Table X shows ranges of typical values of z_0 for various types of terrain.

Terrain Type	z_0 (meters)
Calm open sea	0.0002
Snow surface	0.003
Lawn grass	0.008
Rough pasture	0.01
Crops	0.05
Few trees	0.10
Many trees, few buildings	0.25
Forest and woodlands	0.5
Suburbs	1.5
City with tall buildings	3.0

Table X. Values of Surface Roughness Length for Various Types of Terrain

As an example, if the anemometer measured a wind speed of 5.0 m/s at a height of 55 meters, and the surface roughness length is assumed to be 0.3 meters, then the wind speed seen by a wind turbine on an 80-meter tower would be calculated as follows:

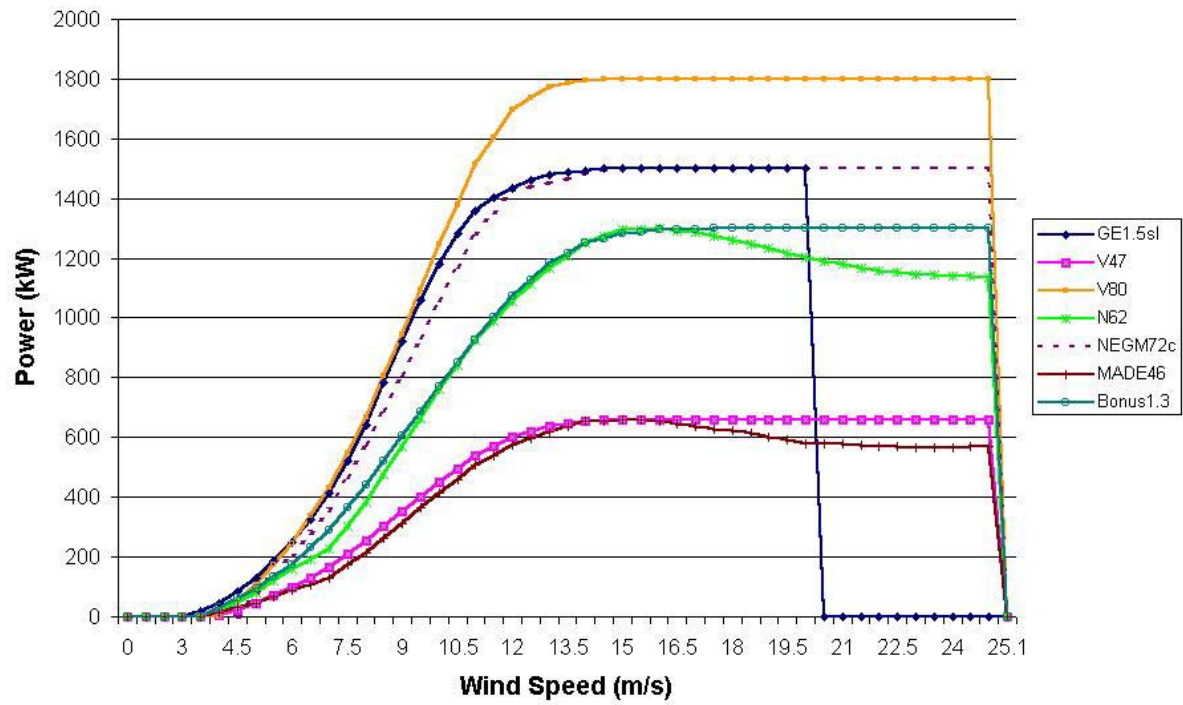
$$V = 5 \times \frac{\ln\left(\frac{80}{0.30}\right)}{\ln\left(\frac{55}{0.30}\right)} = 5.36 \text{ m/s}$$

Although the anemometer recorded a wind speed of 5 m/s, power production from a wind turbine is based on 5.36 m/s.

APPENDIX 2. CANDIDATE TURBINE SPECIFICATIONS

Turbine Model	GE (GE1.5sl)	GE (GE1.5sl)	Vestas (V47)	Vestas (V80)	Nordex (N62)	NEG-Micon (NEGM72c)	MADE (46/660)	Bonus 1.3 MW, 60 Hz
Generator Power	1500 kW	1500 kW	200 / 660 kW	1800 kW	250 / 1300 kW	1500 kW	660 kW	250 / 1300 kW
Generator Speed (rpm)	Variable	Variable	1,500-1,650	1,800- 1,980	1,000 / 1,500			1800 / 1200
Power Regulation			Pitch/ OptiSlip®	Pitch/ OptiSlip®	Stall	Active-stall®		CombiStall
Rotor Diameter			47 m	80 m	62 m	72 m	46 m	62 m
Rotor Speed (rpm)	10 – 18	10 – 18	26/ 20	15.5 / 16.8	12.8 / 19.2	17.3	25.5 / 17	13 / 20
Blade Material					GRP	Fiberglass, epoxy, carbon fiber, PE		Fiberglass
Survival Wind Speed					55 m/s	55 m/s		
Brake System (aerodynamic)	Blade pitch	Blade pitch	Feathered	Pitch settings	Pivotable blade tips	Hydraulic blade pitch adjustment	Airbrakes at blade tip	Full span pitching
Brake System (mechanical)	Hydraulic disk	Hydraulic disk			Hydraulic disk brake	Hydraulic disk brake	Disk brake	Spring loaded disk brake
Tower Type	Conical tubular	Conical tubular		Tubular	Tubular, conical	Tubular, conical	Tubular, conical	Tapered tubular
Tower Material	Steel	Steel			Steel, epoxy coating	Steel	Steel	
Tower Height	80 m	65 m	65 m	78 m	69 m	80 m	58.5 m	60 m
Price			\$650,000 installed		\$1,200,000 installed	\$1,500,000 installed		

Power Curves for Candidate Turbines



APPENDIX 3. SOUND

Sounds are characterized by their magnitude (loudness) and frequency. There can be loud, low frequency sounds; soft, high frequency sounds and loud sounds that include a range of frequencies. The human ear can detect a very wide range of both sound levels and frequencies, but it is more sensitive to some frequencies than others. Because of the wide range of sound pressure to which the ear responds, sound levels are generally measured on a logarithmic scale, using units of decibels, or dB. The dB scale measures the sound intensity over a range of frequencies. A weighing factor, designated (A), accounts for the sensitivity of the human ear at those frequencies. Thus, the dB(A) scale measures, on a logarithmic scale, the magnitude of sounds that the human ear can hear. The dB(A) scale has the following characteristics:

The threshold of audibility (laboratory conditions) is 1 dB(A)

The threshold of pain is 130 dB(A)

Doubling the energy of a sound source corresponds to a 3 dB(A) increase

A 3 dB(A) increase is considered to be a just noticeable sound increase to an observer under field conditions

A 6 dB(A) increase is equivalent to moving half the distance towards a sound source

A 10 dB(A) increase corresponds to a subjective doubling of a perceived noise and is a tenfold increase in the energy of a sound source

From the comments above it can be seen that decibels do not add numerically as linear measures of other physical things do. Figure 1 shows how to add the decibels of two noise sources within 12 dB(A) of each other. If adding two sound sources together, one being 9.5 dB(A) louder than the second, the resultant is approximately 10 dB(A) louder than the second source.

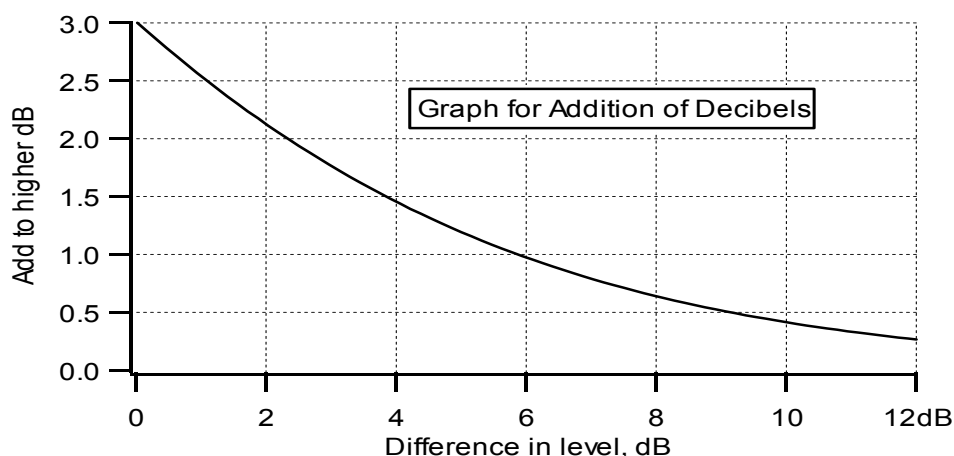


Figure 1. Addition of Two Sound Levels.

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