  

Energy, Environment and Society (5.92)

Student Project Results

Disclaimer

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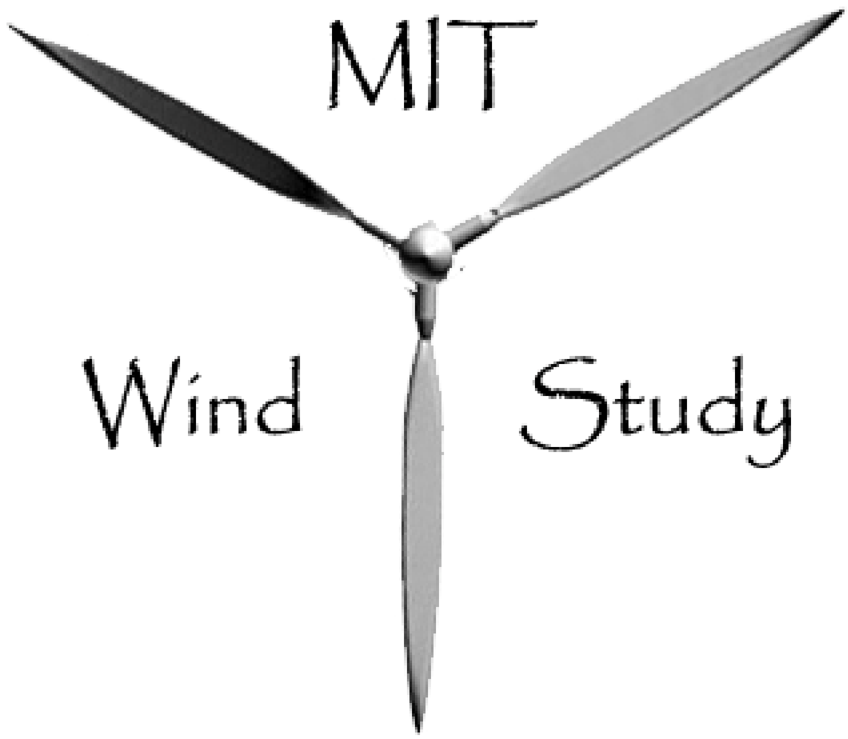

Wind Study: Feasibility Study and Recommendations for Implementing Wind Power on MIT's Campus

5.92 Energy, Environment, and Society

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Executive Summary

The purpose of this project was to assess the viability of small scale wind power as a means for Massachusetts Institute of Technology (MIT) to economically reduce its usage of dirty, non-renewable energy. We find that, although most of campus is a sub par resource, some wind sites offer the potential to produce electricity at half of the current utility cost. The results of this study concluded that if a Skystream 3.7 turbine were placed on top of Eastgate Graduate Housing it could supply electricity for as low as $0.08 per kWh and would have a payback period within its lifetime. Carbon offsets at all sites however are unsurprisingly small compared to MIT's enormous carbon emissions, per year they would offset approximately 10 seconds worth of MIT carbon emissions. Additionally, we find overwhelming support from the MIT undergraduate community in support of on-campus wind power and carbon emission reductions.

One of the greatest concerns with this project was its ability to be accepted by the MIT campus as a whole. Would people be willing to see wind turbines on top of buildings? With the creation of a campus survey, the team was able to ascertain that not only would people be willing to see wind turbines, but they also would like to see MIT lower its greenhouse gas emissions. We created a personal opinion survey and sent it to both graduate and undergraduate dorms. We had responses from over 200 students. Also, this study has had a tremendous amount of support from MIT faculty and facilities, so there will be few problems with that aspect of implementation.

Overall, since MIT's goal is to reduce emissions in a cost effective way, we recommend on-campus wind power as a viable option. Its implementation sets precedent for MIT, helps publicize successful implementation of renewable technologies, and provides educational opportunities for future students.

Introduction

Recently Susan Hockfield, President of MIT, declared that the university would be pursuing a “walk the talk” stance in reference to the energy crisis and carbon emissions. The reasoning being that MIT shouldn’t only research and recommend solutions to climate change; it should *itself* be involved in carrying those solutions out. Since the President’s announcement, the Institute has created classes, like 5.92 “Energy, Environment, and Society”, to investigate alternative sources of energy for the MIT campus, ramped up publicity about climate change and possible solutions, and intensified research efforts in relevant areas.

First and foremost, where exactly does MIT get its electricity? MIT receives its energy from two places. A large portion is produced by the 20MW cogeneration plant, while a smaller portion by the utility company NSTAR. The cogeneration plant burns natural gas and oil to generate both heat and power at extremely high efficiencies. NSTAR is a retail power distribution company, and it receives its power from coal (10%), natural gas (25%), residual oil (19%) and the remainder from hydropower nuclear and solar.[1]

The next consideration is how to reduce this consumption of carbon intensive electricity. Obviously efficiency upgrades and conservation efforts are of the utmost importance. It cannot be stressed enough how far simple efficiency or awareness improvements can go. One can easily understand how conservation of one kWh (turning off ten 100 watt light bulbs for an hour) is not only free (in fact its profitable) and 100% efficient, but requires much less economic and environmental costs than attempting to produce one kWh by means of combustion of natural gas (a process that is at best 30% efficient). However, once these behavioral and efficiency modifications have reached their maximum benefit, what is the next step?

[1] Power MIT.

The implementation of wind turbines on campus buildings is one such novel method of clean energy generation which may be the next step. Consequently, this report hopes to determine and quantify the effectiveness of "clean" wind energy on the MIT campus in an unbiased manner. Using a cost benefit analysis approach, the report will maintain an overarching philosophy that these turbines must make economic sense and have a payback time within their lifetime. In other words, the turbines must not simply be purchased as fancy- but ineffective- gadgetry. Both MIT's budget and reputation would be damaged if this kind of assessment is side-stepped. In addition to the cost benefit analysis, this report will also discuss non-economic, educational, social, and environmental benefits of installing such a system. All this will be performed in the hopes of reinforcing MIT's new "Walk the Talk" campaign.

Background on Wind Power and Small Scale Wind

There are large-scale wind farms being built all over the US and even close to MIT. The first large scale wind project in the Massachusetts area is Hull. This was also the first commercial wind turbine on the eastern seaboard.[2] This groundbreaking project consists mainly of Hull 1, a 660kW turbine, and Hull 2, a larger 1.8MW turbine. Dubbed Hull "two and a half" a small, 2.4kW Skystream 3.7 which can turn 360°, has recently been installed as well.[3]

The origins and development of such a revolutionary turbine go back several years. In 2005 National Renewable Energy Lab, Department of Energy, along with Southwest Wind Power put together a project with a goal "to reduce the lifecycle cost of energy to 10-15cents/kilowatt-hour in Class 3 wind resources by 2007".[4] Through this project the ***Storm*** turbine was designed with aesthetics, sound, and price in mind. Designed to be as unobtrusive

[2] Manwell, 635.
[3] Hull.
[4] D. Calley et al, 3.

and more economically feasible for the average home, ***Storm*** was not the final small-scale wind turbine to be developed by Southwest. Southwest continued to develop the small-scale turbine, improving upon it in every respect: aesthetics, sound, cost. By testing various blade designs, they tried to balance the aesthetics and noise issues while still producing an affordable machine that can generate power in low wind speeds.[5] Eventually, they attained their goal with the production of the Skystream 3.7.

There are many different types of turbine styles to consider. **Figure 1** below shows examples of each variation. The axis of rotation is one aspect which varies. Some, such as the Savonius and Darrieus rotate around a vertical axis, while the Skystream 3.7 and the AVX100 rotate around a horizontal axis.

Horizontal axis turbines can also be upwind or downwind machines. Upwind machines are actively, meaning motor-controlled, or passively, meaning the blade design facilitates without a motor, rotated to face the direction the wind is coming from. Downwind are actively or passively rotated in the direction towards which the wind is blowing.[6]

Another major distinction in turbine styles are lift and drag type turbines. Lift type use an airfoil, just like airplane wings, to create lift to turn the blades and generate power. Drag type turbines can generate power in lower wind speeds than lift type, and they can generate power with wind from any direction, but their theoretical efficiency is much lower than that of lift type turbines.[7]

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[5] Calley, 3.
[6] Danish Wind Energy Association.
[7] Danish Wind Energy Association.

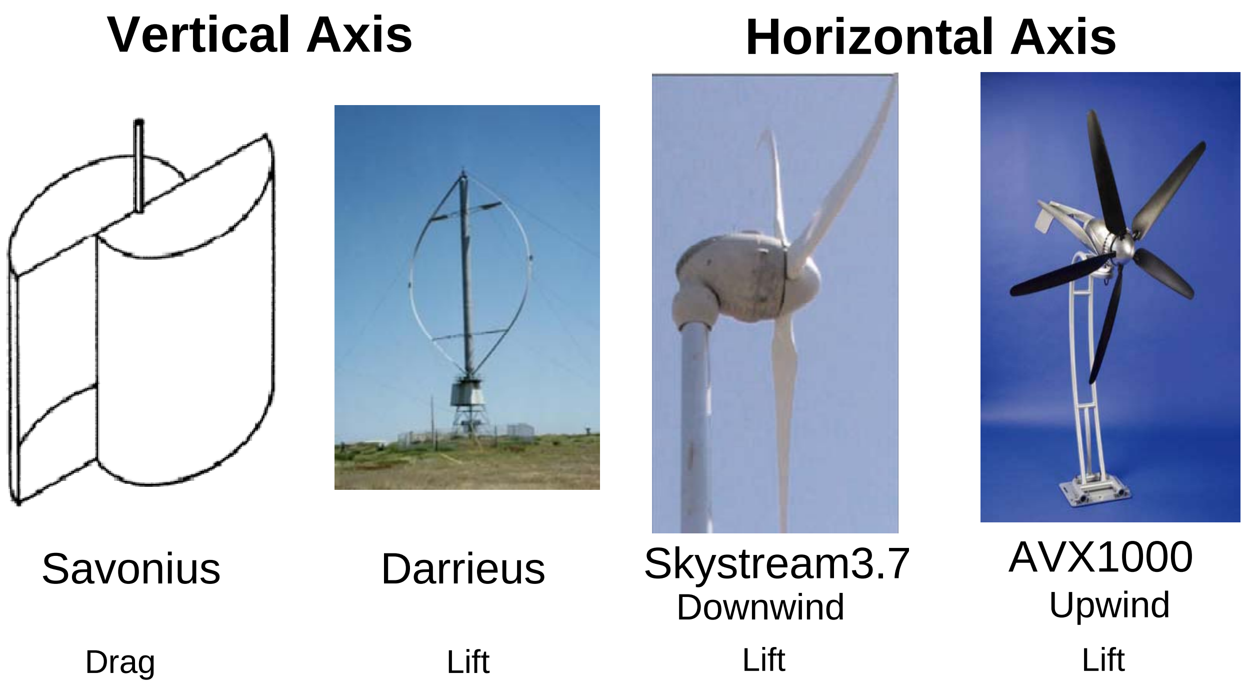

Figure 1. Different wind turbine styles.

After witnessing the development of the ***Storm***, it is not surprising that even with high winds the power output and effectiveness depends largely on the turbine used to procure the power. Thus an assessment of different turbines in the context of our sites was necessary in order to quantify economic feasibility of wind generation at MIT. Specifically, the two turbines compared in this report are the Skystream 3.7 and theAeroVironment AVX1000.

The AeroVironment, which is also quite revolutionary, was invented by AV specifically to make the best use of the increased wind speed of the updraft, coming up off the face of the building. Thus these turbines were designed be placed along the edge, or parapet, of the building. In contrast, the Systream was not designed for rooftop use, and it more generally makes use of horizontal wind from any direction.

Besides these two projects, what defines small scale wind? The American Wind Energy Association defines small-scale wind as turbines that produce 100 kW or less.[8] These are also classified as microgeneration technology.[9] They have primarily been used residentially to reduce electricity costs and carbon emissions. The usage of these small wind turbines is not widespread because they are a relatively new concept. Only until recently have manufacturers such as Southwest Windpower and AeroVironment intensified efforts to make viable, specialized small scale wind turbines. Additionally a few states, such as Massachusetts, have begun to see the potential in small scale wind and provide generous incentives for such installations.

Wind turbines in general are usually installed near bodies of water (sometimes *in* water), preferably in flat open spaces, at higher elevations where winds speeds tend to be higher and less turbulent. In an urban environment however, the wind resource at these locations is strongly affected by interference from surrounding buildings and wind shear, the turbulence caused by the updraft of the wind along the side of the building.

As a result, a potential site for urban wind cannot be analyzed in the same way as a site for a large-scale commercial wind farm. The variability of local wind speed in an urban environment is unpredictable because of turbulence factors. Using a wind map alone does not suffice for accurate wind speed or power predictions. A possible urban wind site needs to be analyzed on an extremely specific, local level.[10]

One of the first steps in installing a wind turbine system is sizing the electricity demand of the consumer. The size of this load depends on many factors, including the number of occupants, the number of electrical appliances, and lifestyle habits of the occupants.[11] This type

[8] AWEA, 4.
[9] Bahaj.
[10] Connors, Quinlan.
[11] Bahaj.

of analysis was not required because the electricity demand of MIT is so large (approximately 175,000 MWH annually[12]) relative to the power that could potentially be produced on campus by a 6 kW turbine system, that the wind system would only replace a small percentage of the electricity that MIT buys from NSTAR.

Additionally, wind speeds (and power production) peak in winter which matches the energy profile of many places whose energy demand increases in winter due to heating.[13] Furthermore, Connors indicates in his paper, “Offshore Wind Power in the Northeast: Estimating Emissions Reductions”, that the peak power generation of wind turbine coincides with the winter induced switch to the dirtiest of the fossil fuels, coal.[14] In such respects, wind power has great advantages.

Although there is an abundance of information on wind power in general, there has been little conclusive research done on the effectiveness and feasibility of wind turbines in an urban environment. Encraft, a renewable energy consulting firm in the United Kingdom, is conducting the Warwickshire Wind Trial of domestic roof-mounted wind turbines. Twenty turbines will be mounted with wind speed anemometers and energy production export meters. The findings from this study will help Encraft's clients select the appropriate turbine model.[15]

Consumers who are looking into installing a turbine face a lack of standardized, credible wind data. However, there is a wind resource rating system. Although it is technically incorrect to predict the wind resource of a site solely on the average wind speed[16], wind class is often used in the industry to predict the economic feasibility of a site. The Army Corps of Engineers follows

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[12] Power MIT.
[13] Bahaj.
[14] Connors.
[15] Sampson.
[16] This occurs because “most of the wind energy is available at wind speeds which are twice the most common wind speed at the site”. Specifically, it is fallacious to simply plug the average wind speed into a power function to determine average power. (Source) http://www.windpower.org/en/tour/wres/pwr.htm

particular criteria for citing wind farms. For onshore privately funded wind farms to be economically feasible, wind class should be class 4 or better. For offshore sites, this classification must be class 5 or better because of higher transmission costs.[17] The Hull wind turbines installed on land in Hull, MA are in a class 3 wind resource[18], and Cape Wind, the proposed wind farm offshore of Cape Cod, MA, is in a class 5 wind resource[19]. **Figure 2** below shows the wind power classification for different regions in Massachusetts.[20] The key in the lower left corner gives the wind power classes and the corresponding wind speeds and densities. Interestingly, our report shows how small scale has the potential to be economical in wind classes as low as 2. Rather than look down upon small scale wind for its seemingly low annual kWh's, we believe that the relative efficiency and ability to be economical at relatively low wind speeds is impressive.

[17] ESS Group, Inc.
[18] Hull.
[19] USDOE Massachusetts Wind Resource Map.
[20] USDOE Massachusetts Wind Resource Map.

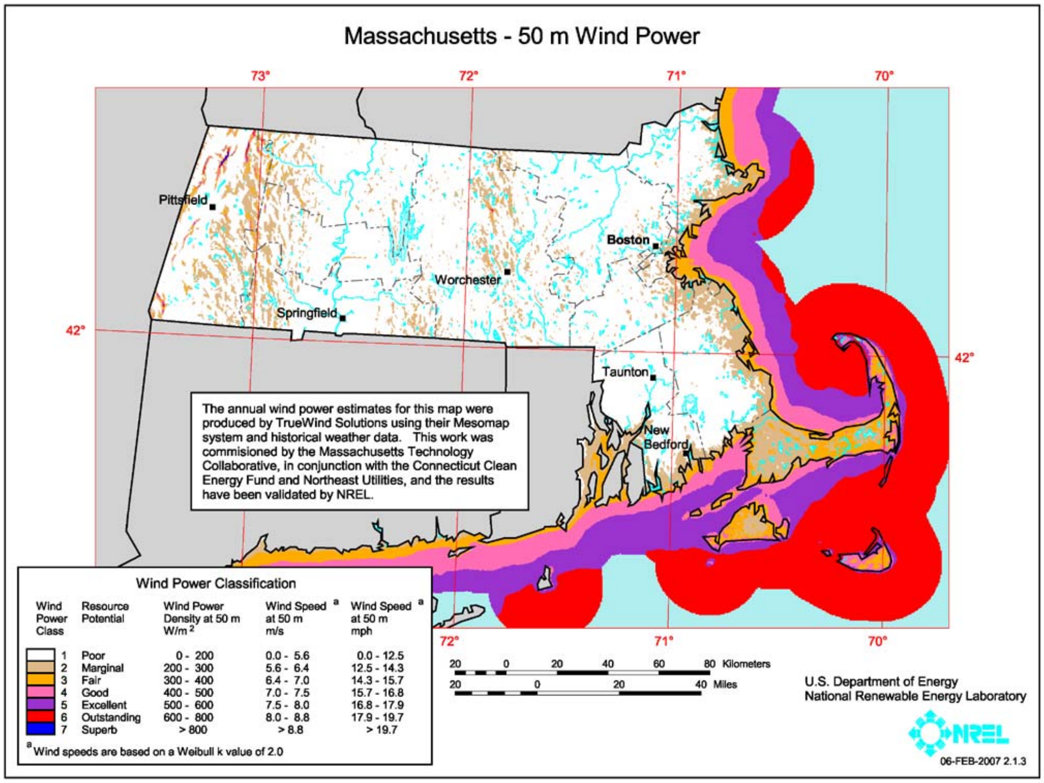

Figure 2. Massachusetts Wind Power Classification at 50m.

There are big plans for small-wind's future. A twenty year roadmap was drawn up in 2002 by a collection of small-wind turbine companies outlining their market potential, barriers, action plan, and strategy. By 2020, they estimate that small-wind turbines could generate 3% of America's energy demand.[21]

Methodology

Interviews

At the beginning of the project, names of several contacts, ranging from professors to wind experts, were given as possible sources of information. The first goal was to meet with as

[21] AWEA, 4.

many experts as possible to learn how to perform the research using robust, proven, and efficient methods.

Patrick Quinlan, an expert on wind power, was among the first interviews. His expertise and position as Director of Wind Systems at Second Wind helped provide invaluable knowledge with regards to wind assessment and data collection techniques. Additionally, Heidi Nepf from MIT's Environmental Engineering department provided ideas about campus airflow around buildings. Last, Stephen Connors from MIT's Lab for Energy and Environment contributed greatly to the development of our methodology.

A trip to Hull, a town off the coast of Massachusetts, was arranged later in the semester to gain further understanding about larger scale wind turbines and the public opinions that go along with such projects. Also, AeroVironment's Director of Global and Strategic sales, Jeff Wright, was able to provide information regarding the AVX1000 and AV's wind site feasibility methods.

Turbine Selection

There were a few options for turbines to analyze, both vertical and horizontal axes, lift and drag style, as well as a range of efficiencies and different performances in different wind speeds. Two turbines were analyzed and used as references when setting up our data collection equipment.

Southwest Windpower's Skystream 3.7, shown in **Figure 3**, was one of the turbines chosen. Its integrated design, 360° wind-tracking capability, successful use at Hull, MA, and efficiency make it a good fit for the resource available on top of MIT's roofs. It has a 12ft diameter and is a downwind, horizontal-axis, lift type turbine that produces a maximum of

2.4kW.[22] It also has an integrated inverter in the nacelle of the machine, shown in **Figure 4**. Designed with the goal in mind to make wind power viable at low wind speeds (averages speeds of 10mph), many see the Skystream 3.7 as a breakthrough in wind technology. Despite its advantages, the Skystream 3.7 is not specifically designed for urban uses, and has not been installed on rooftops before. It is pole mounted in its current design, meant to be installed with a concrete foundation in soil. If they were to be put on buildings, further research and/or engineering should go into designing a simple and safe method to roof mount the turbines.

Figure 3. Skystream 3.7.

Figure 4. Skystream's integrated AC inverter.

[22] Southwest Windpower.

The AeroVironment's AVX1000, shown below in **Figure 6**, is a very different turbine and was chosen for analysis based on Peter Cooper's (MIT Facilities Manager, Sustainability Engineering & Utility Planning) request, its urban specific design, and its pleasing aesthetics. As will turnout to be quite important later in the analysis, the AVX1000 only has a 60° turning capability. It also has a 5-foot 6-inch diameter, operates upwind, and has a maximum power production of 1kW.[23] These turbines are made to be installed as systems of six or more along the roofline of a building. According to AV, it was specially designed to be placed above the shear zone where updraft causes an increase in wind speed about two to three feet above the top edge of a building which can produce up to 15%-40% more power.[24] **Figure 5** shows the wind flow around a building and the wind shear effect on top of a building parapet, and **Figure 6** shows an AVX1000 turbine that would be installed on the roofline of a building.

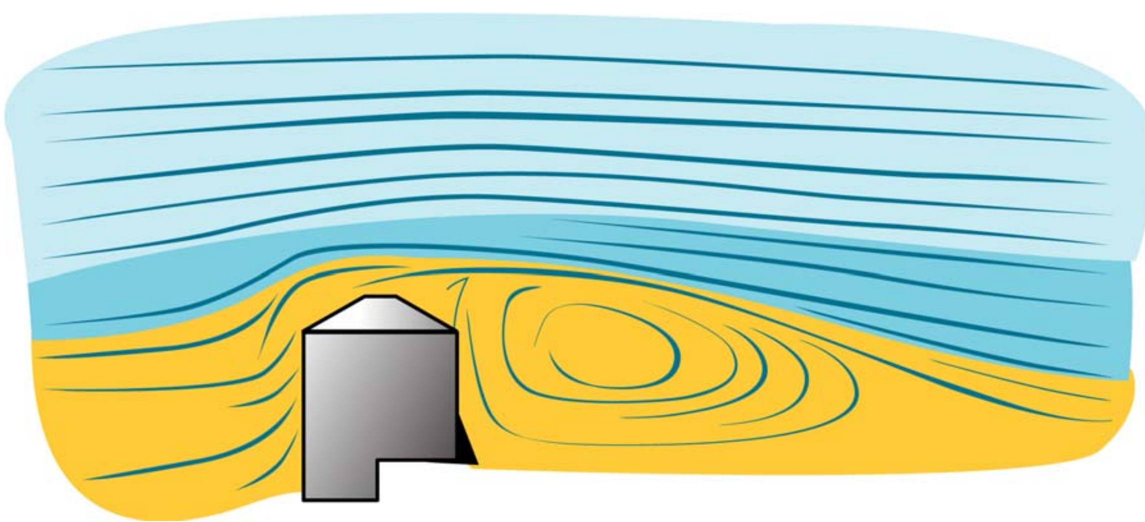

Figure 5. Diagram from AV proposal illustrating wind shear effect on the top of a building parapet.

[23] Wright.
[24] Wright.

Figure 6. AVX1000.

Measurement

Site Selection and Set-up

Team wind selected seven sites across MIT's campus after discussion with the aforementioned experts and preliminary qualitative assessment of several buildings. We chose the sites based on their height, shielding from other buildings, ease of roof access for installation, historical regulations, and visibility of the river. The sites were 36, 14, E51, W20, W61, E55, and W8 (see Appendix A for a map).

On each building, an anemometer (wind speed measurement device) was placed towards the center of the building at an elevated height and an anemometer with both wind speed and direction measurement capabilities was placed at the edge of the building. Despite the myriad of possible placement combinations, our final set up was related to the two turbines we had decided to analyze.

Location of anemometers and direction sensors was determined by mimicking the approximate location of where the AVX1000 and Skystream 3.7 would be installed. AVX1000's direction specific design required that wind speed and direction sensors were placed at the edge of the buildings where the predominant wind would have a direct affect. A wind speed sensor was placed at a higher elevation in the center of buildings, simulating where the Skystream turbines would theoretically be placed. **Figure 21** has a diagram of an example of how the anemometers were set up.

Samples of wind speed and direction were taken every second and averaged and recorded every thirty seconds with Hobo data loggers. Measuring began on the 21st of March and continued until the 30th of April. However, due to technical issues, measurements were intermittent for some of the buildings.

Statistical Descriptive Analysis

Equipment failures limited the quantity and quality of our data, and in order to have a more accurate assessment of our data, any faulty or seemingly incorrect data had to be excluded from our final analysis. To get rid of said data, we developed an equation in Microsoft Excel to calculate the standard deviation of the wind speed during five minutes of measurements. If the standard deviation was greater than 10 or less than 0.1, the measurements were regarded as false. Later, the true or false readings were used to determine if other calculations, such as average wind speed and wind turbidity, should be calculated. The range for the standard deviation was constructed to eliminate either large spikes in wind speed, which is some cases were past 100 mph, and therefore not very likely, or to remove flat-line data, where the wind speed remained constant for long periods of time, again an unlikely scenario.

Correlation and Prediction

Recommendation by Stephen Connors led us to use a widely known and robust correlation method set forth by University of Massachusetts wind energy researcher, Dr. Jim Manwell.[25] The method allows months of data to be correlated with years of data by a comparison to a similar site with data recorded for the year one would like to predict. Beverly Municipal Airport, located about twenty miles northeast of Boston, MA, is a location with about thirty years worth of historical weather data and is a decent match for our purposes of correlation. Its similar geographic location (distance from the coast) and its availability of hourly observational data made it acceptable. A map showing where Cambridge and Beverly are located in relation to each other and the coast is available Appendix A. Logan International Airport was considered but disregarded for its unique placement on a peninsula. A closer location such as the Green Building would have been optimal both in data resolution and relevance; however, acquisition of this data proved to be difficult. We suggest that future analysis use the Green Building data for even more accurate results if the data is available.

The first step in the measure-correlate-predict (MCP) method was to calculate the standard deviation and average wind speeds for the Beverly data and at our own sites during the measurement period. **Equation 1** below is the correlation equation used in the Hull Wind II case study where he proved it to be a very accurate method.[26]

Equation 1. Correlation.

$$\hat{y} = (\mu_y - (\sigma_y / \sigma_x)\, \mu_x) + (\sigma_y / \sigma_x)\, x$$

$\hat{y}$ is the wind speed that is predicted, x is the wind speed at the airport at the historical time, and σ and μ are the standard deviation and average wind speed, respectively, for the airport

[25] Rogers.
[26] Manwell.

and campus building for the measured time period. Using this equation, we could predict what the wind speed at any of our sites would have been at any time in the past 15-30 years.

Power Analysis

Equation 2 below is the wind power equation. The amount of power that can be converted into mechanical energy by a turbine is proportional to the swept area of the turbine blades, the density of the air, and the cube of the velocity of the wind. Obviously, the velocity cubed is the most important part of the power equation. A small increase in the wind velocity will greatly increase the power. We used this equation to understand how wind velocity is related to the power output of a wind turbine.

Equation 2. Wind Power.

$$P = A\frac{1}{2}\rho_{air}{v_{wind}}^{3}$$

Betz's Limit is the theoretical efficiency of the conversion of wind power into mechanical energy by any turbine. The limit is 16/27 or 59%.[27] This limit exists because the wind is slowed down or braked as it passes through the turbine blades. There is no way that a turbine could be 100% efficient and convert 100% of the wind power into mechanical energy because this would mean that the wind behind the blades has been stopped and is going at 0 mph. It is also an impossibility for wind to pass through the turbines blades and no wind power be converted, so the limit resides in between the two scenarios. The Betz limit is an ideal limit, so no turbine reaches the full efficiency of this limit.

[27] Danish Wind Industry Association.

Technical Feasibility

Data Summary and Analysis

Wind Speed

One simple and easy to compare wind statistic is the mean (average) wind speed. Our analysis of the wind resource shows that most of our sites, except for Eastgate, qualify as Class I wind sites, meaning that their average wind speeds are less than 9.8 mph. Eastgate is a class II wind resource because its average wind speed is between 11.5 and 9.8 mph. **Figure 7** below is a graph of the average wind speeds at each site. These blue averages were measured by our anemometers that were place at the edge of each roof. The red averages are the predicted average wind speeds that we calculated when we correlated our own data with the historical data from Beverly. The confidence interval[28] on each of these has an error bar ranging from ±2% to ±6% of the predicted wind speed.

[28] The error bars indicate means that we are 95% sure that the average wind speed lies between the error bars.

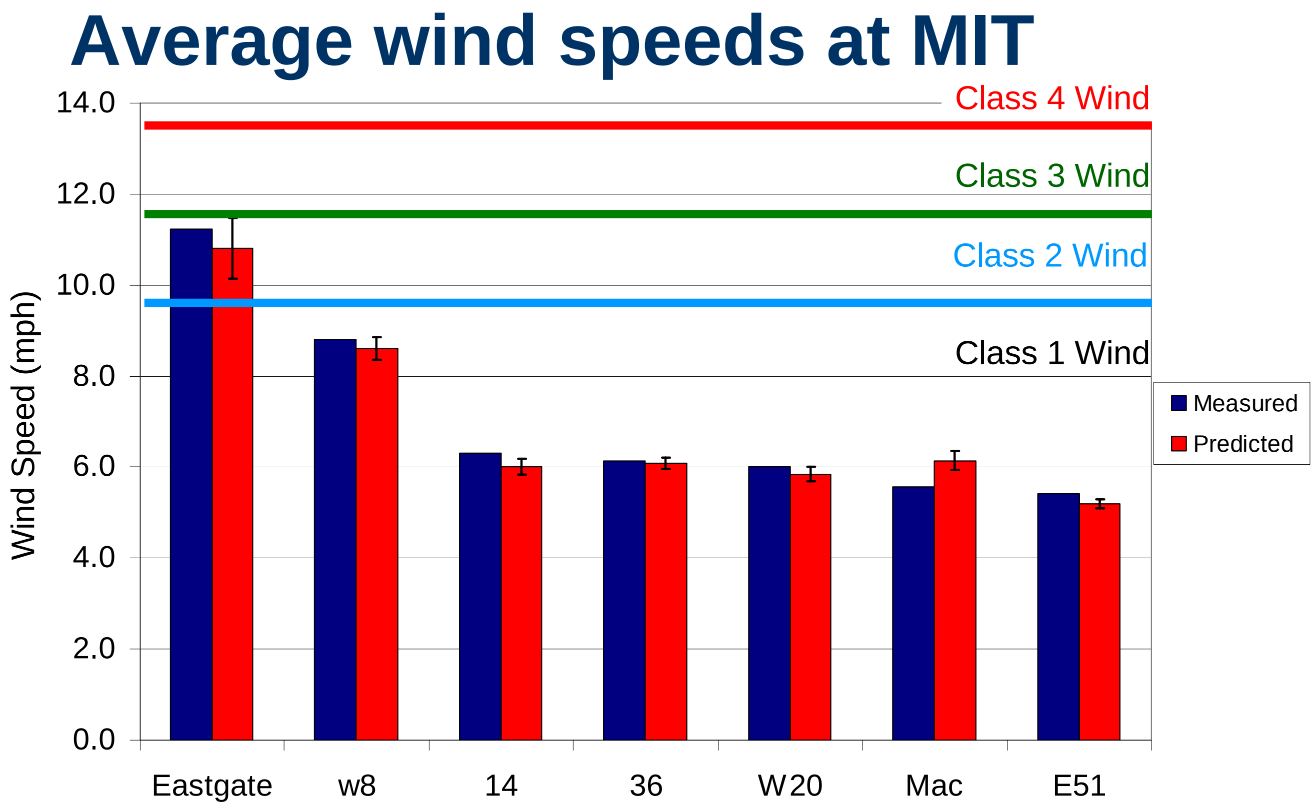

Figure 7. Average predicted and measured wind speeds and classification.

Another industry used method that more accurately describes the wind speed distribution of a wind site is a Weibull distribution. The Weibull distribution takes wind speed frequency data (i.e. 500 data points at 1mph, 600 data points at 2mph…) and fits a smooth probability distribution curve to it.

Typically the average wind speed will be slightly to the right of the peak (mode) of the Weibull. **Figure 8** below shows the characteristic shape of the Weibull distribution for the wind data from the edge anemometer at Eastgate. **Table 1** below gives our own measured Weibull k shape parameters and historical k shape parameters from AWS TrueWind for each site. The measured and historical vary because the historical k values are calculated from data taken over a longer time interval, at least a whole year, while ours are calculated from data from only a month.

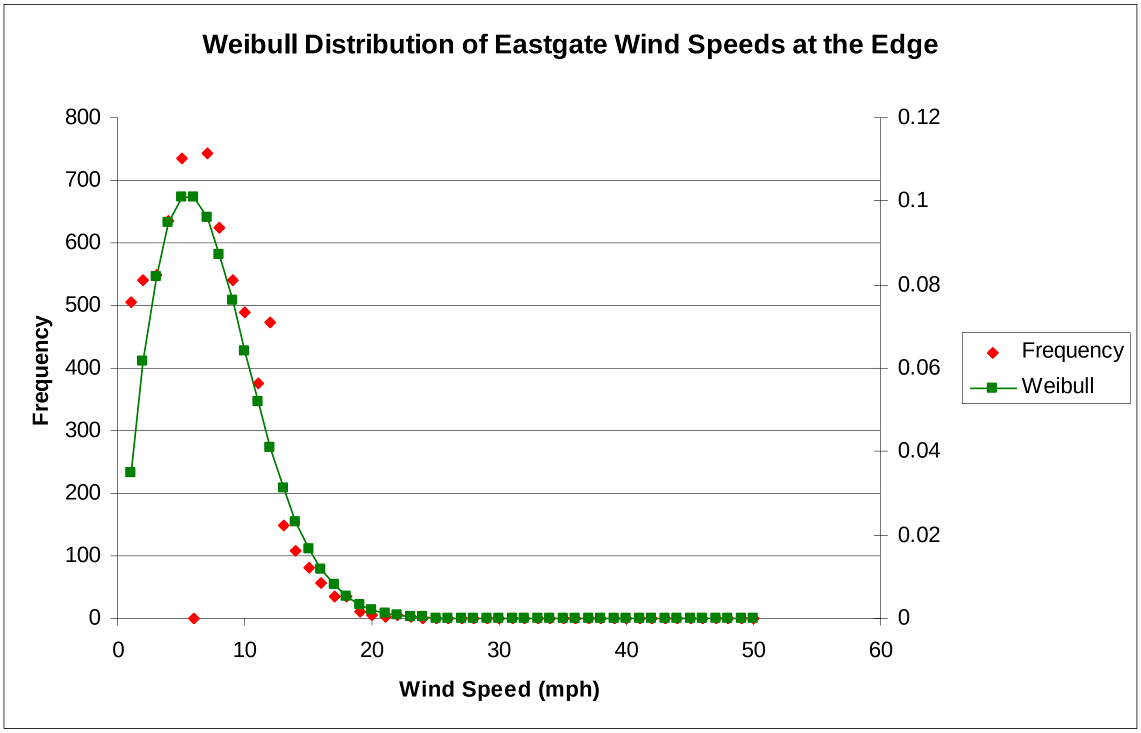

Figure 8. Sample Weibull curve from data from Eastgate edge anemometer.

Table 1. Measured and Historical Weibull k shape parameters.

Building	Measured k Edge	Historical k[29]
14	2.7	2.16
36	1.5	2.16
E51	1.9	2.17
Eastgate	2.1	2.17
Mac	1.7	2.16
w8	1.7	2.16
W20	2.6	2.16

[29] AWS TrueWind

Because of the nature of Weibull distributions, many statistics such as the mean, mode, variance, and skewness, can be calculated from the k shape factor and the **λ** scale factor.[30] An additional benefit of Weibull distributions is that the manufacturers of Skystream provide spreadsheets that allow one to predict annual average kWh's simply with average wind speed and Weibull k shape factor. This quick approximation method was used to compare to our actual energy production values.

Wind Direction

Because the AVX1000 only has a 60° yaw, the direction of the wind has a large affect on the type and placement of the wind turbines. To determine the predominant wind direction for each site we took a histogram of the wind directions and made a radar graph, or rose plot, of the frequencies. The radar graph shows visually the general wind direction. Wind direction is a very site specific parameter. Although the buildings are all within one square mile from each other, the direction of the wind varies greatly at each. Because we would expect the predominant wind direction to be roughly the same from site to site, this variation could be attributed to the fact that we only collected data for one month or possibly due to other unaccounted turbulent flows/shielding. **Figure 9** is a rose plot of the wind directions at Eastgate. The predominant wind direction is mainly from the South and Southwest. **Figure 10** is an historical wind direction rose plot for Eastgate from AWS TrueWind. The two rose plots correlate nicely; however, there is more distribution in the historical rose plot because it draws on data that was taken at least over one whole year, while our own measured rose plot relies on data from a much shorter time period. **Table 2** summarizes the average wind direction from each of our seven sites.

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[30] In Microsoft Excel c is used to represent the scale factor λ.

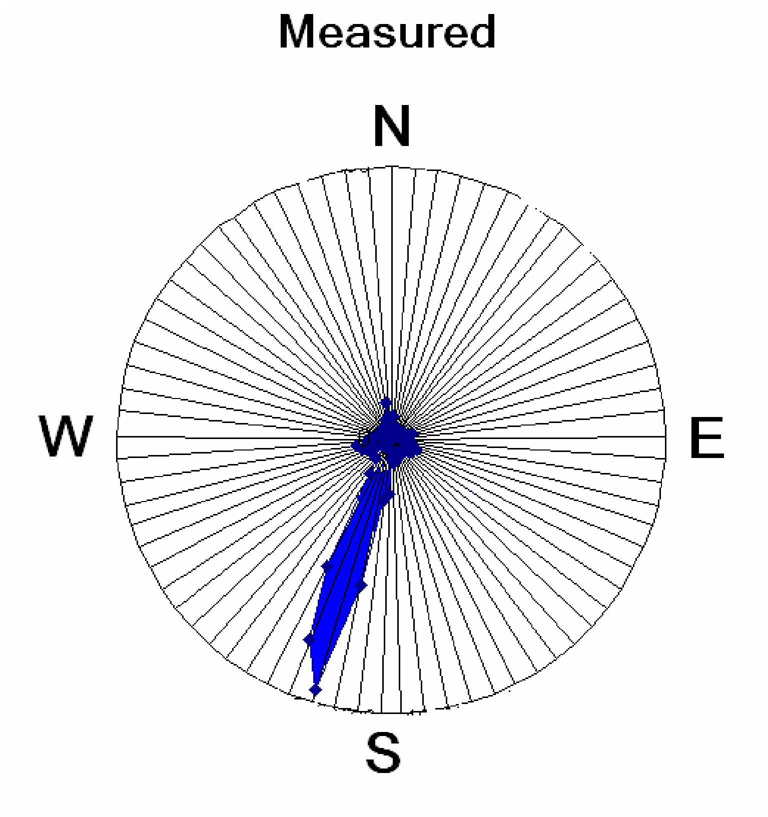

Figure 9. Rose plot of measured wind directions at Eastgate.

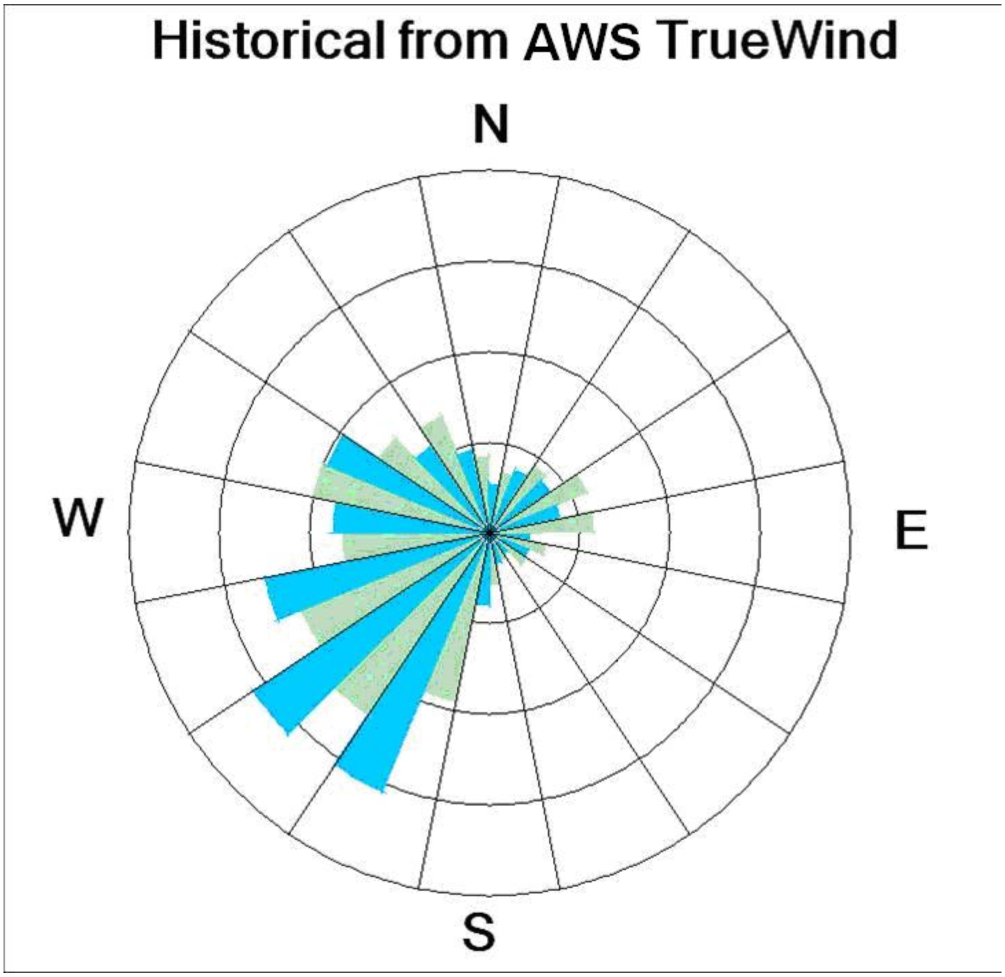

Figure 10. Historical rose plot of wind directions at Eastgate.[31]

Table 2. Measured predominant wind direction at our test locations.

Building	Measured Predominant Wind Direction (Degrees from North)
14	295.0
36	80.0
E51	205.0
Eastgate	205.0
Macgregor	20.0
W8	205.0
W20	280.0

[31] AWS TrueWind.

Economic Feasibility

Assumptions

Obviously, besides the wind related site specific considerations, there are many other factors that affect the feasibility of a wind turbine system. The lifetime, maintenance costs, price of electricity, emissions credits, and state and/or federal rebates and tax credits, all must be weighed in.

For the analysis, we assumed a constant cost of electricity of $0.15/kWh.[32] This electricity cost is the price that MIT currently pays NSTAR utilities to supply them with power.

For the purposes of a fair comparison between the turbine manufacturers, we decided to compare all wind systems at a 6 kW capacity.[33] The AeroVironment turbines are designed to be purchased as a 6 turbine, 6 kW system. Since each Skystream 3.7 turbine has a capacity of 2.4kW this meant comparing them as a two and a half turbine system. According to the owner's manual, "The Skystream is designed for 20 years of maintenance-free operation. All bearings and components were designed for a 20 year life at a site with an average annual wind speed of 19 mph (8.5 m/s)."[34] Despite this, annual owner performed checkups are recommended by the manufacturer. Although no owner's manual is available for the AVX1000, we assumed a similar nominal maintenance cost for the AV turbine. See **Table 16** and **Table 17** in Appendix E for additional information on turbine costs.

Additionally, rebates from the Massachusetts Technology Collaborative help make wind turbine purchases more viable. For small wind projects that are less than 10 kW, they provide rebate substantial rebates.[35] First the MTC provides a baseline rebate of $2.00 per installed

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[32] Cooper
[33] See **Error! Reference source not found.** in appendix for clarification
[34] Southwest Windpower, 30
[35] See **Error! Reference source not found.** in appendix for additional eligibility requirements.

Watt.[36] If the building is LEED certified, this rebate is increased by \$1.00 to \$3.00 per installed Watt. However, since none of the buildings we assessed were LEED certified, we used the baseline case of \$2.00/Watt. See **Table 14** in Appendix E for additional information on small scale rebates. For MTC grants on wind projects that are above 10 kW see **Table 15** in Appendix E.

MIT is involved in a NO_X trading scheme where they receive the current EPA market price of \$0.48 per pound.[37] Because MIT produces less than 25 MW of power and uses its own power, it is exempt from the carbon cap regulations that would have resulted in mandatory purchasing of renewable energy credits and/or alternative compliance payments.[38] Additionally, it does not participate in a SO_X emissions trading scheme.

Last, because the potential wind installation is defined as renewable energy, the electricity produced by the turbines could be sold as renewable energy certificates (RECs) to interested consumers. Although the revenue generated by these REC's was not taken into account in this analysis, future research could determine the exact price or monetary imbursement for the sale of the aforementioned certificates.

Power and Electricity Generation

Figure 11 shows the Betz Limit and the power that could potentially be produced from each of three different turbines in Watts per m^2. The Vestas V47 is an industrial turbine, the kind that would be installed in a large-scale wind farm. It is a 660 kW machine with a 154 ft

[36] MTC "*Small Renewables Initiative* Design & Construction REBATES", 1.
[37] Cooper.
[38] The Commonwealth of Massachusetts Executive Department, 1.

diameter.[39] We are not looking into the Vestas V47 as a viable option on campus. We just use it here as a means of comparison. The area swept by the blades of one AVX1000 turbine is 2.21m^2 [40], of one Skystream 3.7 turbine 10.87 m^2 [41], and of one Vestas V47 turbine 1735 m^2.

At lower wind speeds, between 0 and approximately 16 mph, all the turbines have about the same power output per m^2. Above that, however, the AVX1000 is the most efficient at producing power for the area swept by the blades. This, however, is just one means of comparison. It does not conclude that the AV system is the most efficient overall. As we will see later on, the AV system is not the most efficient when costs of the turbines and installations are factored in.

[39] Tenderland.
[40] Wright.
[41] Southwest Windpower.

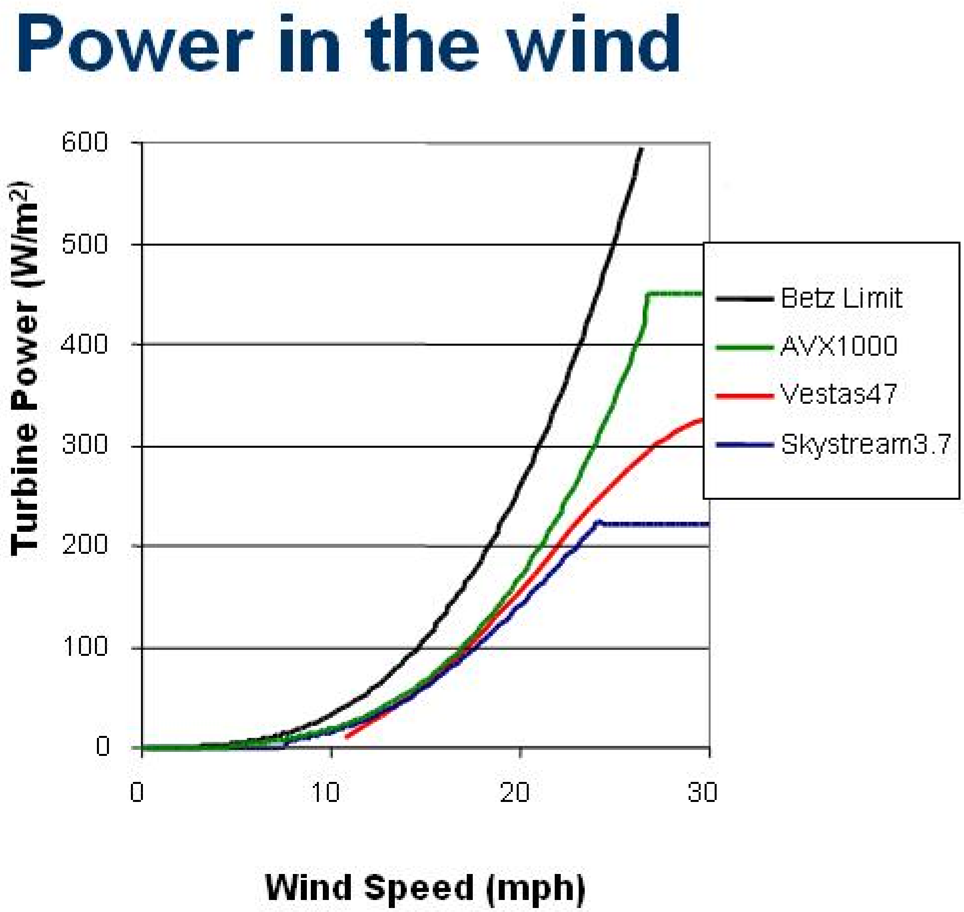

Figure 11. Power converted from the wind energy by each turbine in Watts per m^2.

Figure 12 takes a slightly different angle when comparing the two systems. It shows the superposition of both the Skystream 3.7 and AVX1000 power curves on the same graph. Both are normalized as 6 kW systems, which are approximately 2.5 Skystream 3.7 turbines and 6 AVX1000 turbines. At low wind speeds between 0 and 10 mph, the kind which are primarily present around MIT campus, both systems produce approximately the same power. Only when the wind speeds start getting higher above 10 mph do the powers curves diverge. At the same wind speed, the Skystream system will produce the more power than the AV system. The slope of the Skystream power curve is greater than that of the AV. Both systems level out at the same power output, 6000 Watts, but the AV system does so at a higher wind speed. Both systems discontinue power production at 60 mph because of safety concerns.

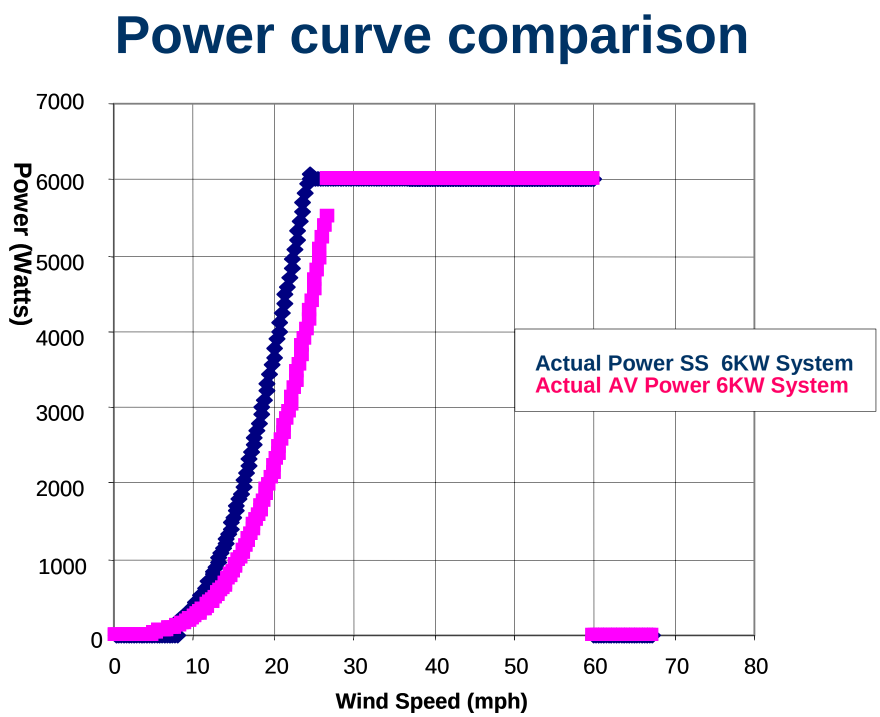

Figure 12. Power curve comparison of normalized Skystream and AV systems.

By correlating our own data to the historical data, we were able to predict what the wind speed at our sites would have been between 01/01/1990 and 03/31/2006. Under the assumption that the aforementioned time period accounted for seasonal and/or annual wind changes, we extrapolated the wind speed distributions an equal number of years forward. From that we calculated the mean, standard deviation, Weibull k and λ factors, for the wind speed. Next, because we correlated our data to hourly *observations* and not hourly averages, it was possible to plug these wind speeds directly into manufacturer power curves. After averaging these instantaneous powers and multiplying them by length of time of operation, we could determine the total and average annual electricity produced.

Below **Figure 13** shows the average annual kWh's produced by 6kW Skystream and 6kW AV systems on the two most feasible sites, Eastgate and W8. Under that in **Figure 14**, the same scenarios are shown but with the kWh's converted into dollars. As **Table 8** through **Table** 13 in the appendix demonstrate, the only economical option would be the use of a Skystream 3.7 on Eastgate's roof. Significantly, this scenario could produce electricity at $0.08/kWh, which is seven cents cheaper than MIT currently pays for its electricity.

On the other hand, no AeroVironment scenario comes close to being feasible. Even in the best scenario the AeroVironment has a payback of about 90 years.

One scenario that does come close to paying back is the Skystream placed on W8. As Appendix D in the appendix demonstrates, the payback period for this scenario would be about 27 years. Even at the upper bound[42] of our estimates, the least amount of time that this scenario would take to pay back is 24 years. However, if the price of electricity increased to $0.20/kWh or if Renewable Energy Credits could be sold for $0.05/kWh, this scenario would just pay itself off at the end of its 20 year life time.

As **Table 3** below shows, a Skystream system would produce electricity cheaper than either utility or solar panel system. Note that this occurs despite solar's larger per watt rebate.

[42] See Appendix section "Error Analysis" for details on confidence intervals and error bars.

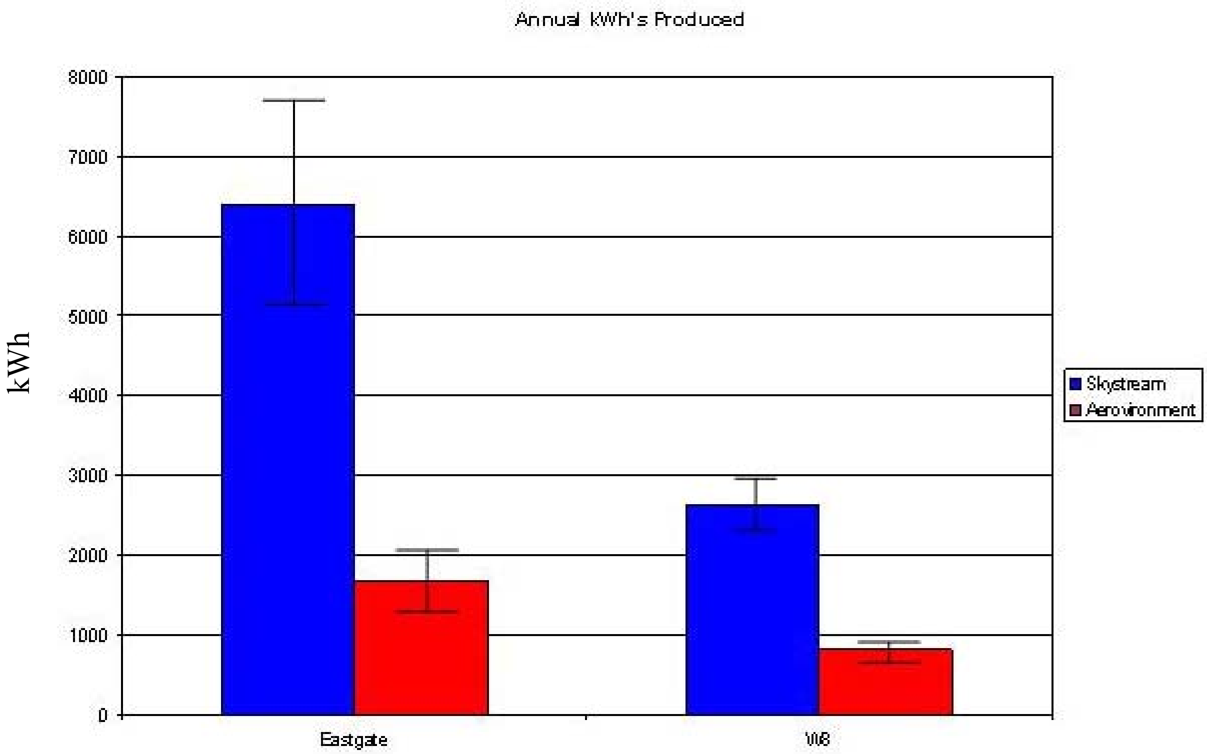

Figure 13. Graph showing predicted average annual kWhs produced by placement of turbines on Eastgate and W8.

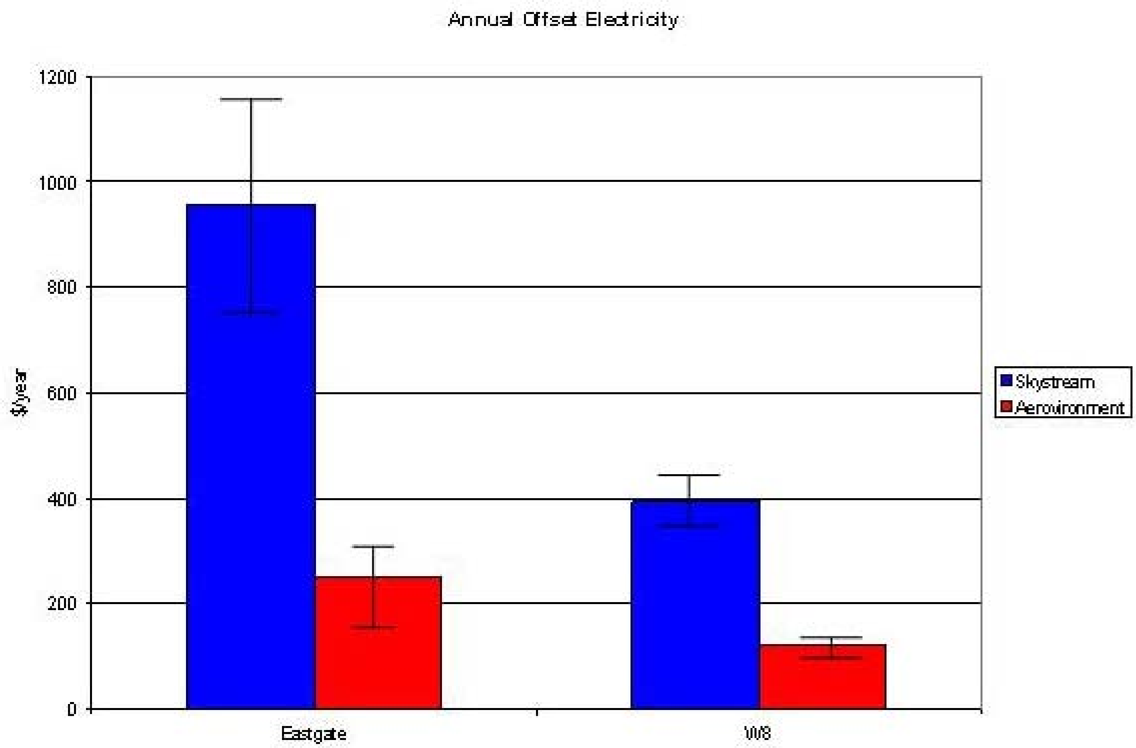

Figure 14. Average annual electricity offset in dollars per year

Table 3. Side by Side Comparison.

	Skystream 3.7	AeroVironment	BP Solar 6kW System
Total Installed Cost:	$19,975	$34,450	$51,000
Total Rebates:	$9000	$12,000	$18,000
Price per kilowatt hour:[43]	$0.08	$0.67	$0.23[44]

[43] Scenarios compared are on top of Eastgate: 6kW Skystream (two and a half turbines), 6kW AVX1000 (six turbines), and a 6kW BP solar array.
[44] Cost estimated by BP's "Solar Economic Estimator" http://www.bp.com/solarsavings.do?categoryId=3050495.

Social Feasibility

Any project that can have an influence a community must have the support of that community before it can be implemented. Common concerns with wind turbine installation include their affect on birds and bats as well as their visual and audio disturbances.[45]

Influence on Avian Life

An issue of concern with installing wind turbines is the effect they can have on birds in the area. However, many environmental groups, including both the National Audubon Society and Mass Audubon, have shown their support for wind turbines as a cleaner form of energy. In Mass Audubon's position statement on wind energy development, the group claims to support "responsible planning, permitting, and production of renewable energy resources including wind energy."[46] Responsible installation is largely defined by their placement in relation to the migratory path of birds or if the area is known for its avian life. Since the concept of putting turbines on top of buildings is relatively new, their affect on birds is still in question. However, it is believed that since MIT is not in the middle of any major migratory path, the effect on the birds in the area will be minimal. There is at least one hawk that nests on an MIT building. This may affect the implementation of a turbine if it is on or near that building.

Aesthetics

An important component of wind turbine installation is having support from the community. Common opinions claim turbines to be unsightly and loud. As such, it can be difficult to generate public support for such projects. As part of our analysis, a survey was conducted and given to the undergraduate students at MIT and 274 responses were received. The same survey was given to residents of Eastgate, or E55, one of our test sites, but

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[45] Firestone (2007).
[46] Clarke (2003).

unfortunately no responses were received from that group of people. The goal of the survey was to collect opinions about carbon emissions and wind turbine aesthetics. As shown in **Figure 15**, **Figure 16**, and **Figure 17** below, there was an overwhelming positive response to all of the questions, demonstrating that undergraduates at MIT support wind power.

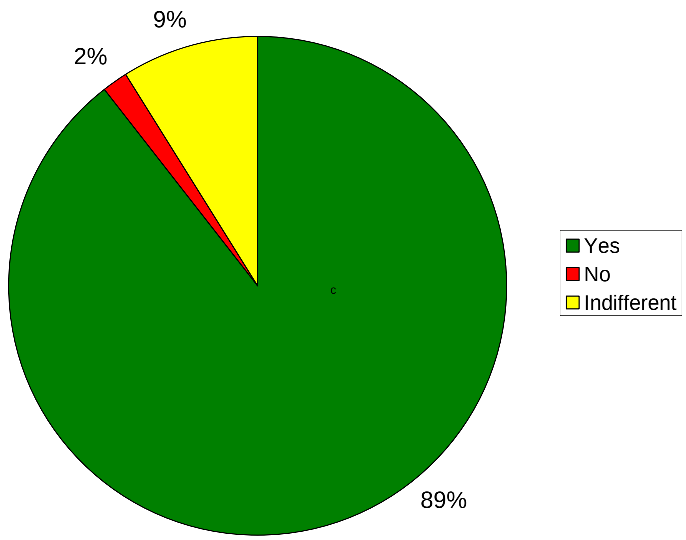

Figure 15. Do you think it is important for MIT to reduce its carbon emissions?

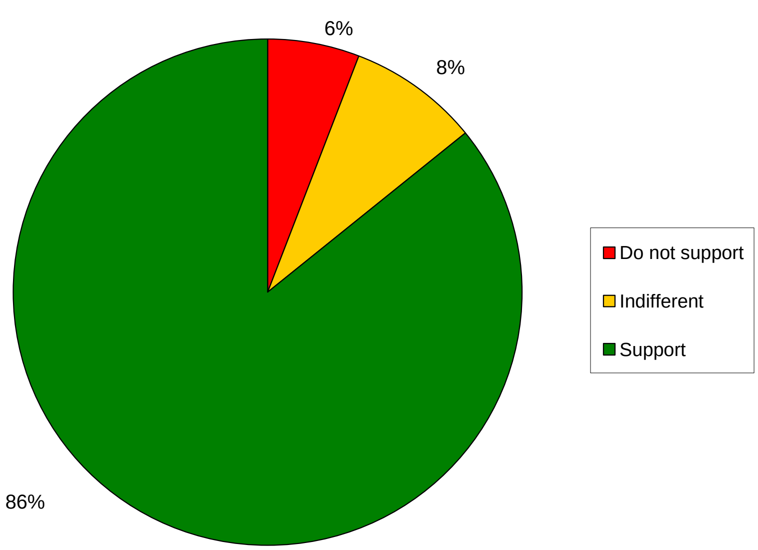

Figure 16. Do you support wind power?

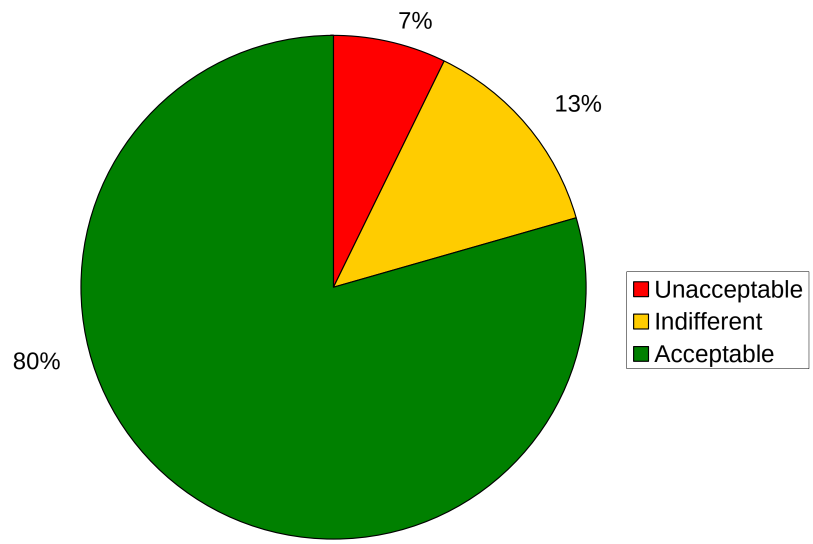

Figure 17. Is it acceptable to put a turbine on top of an MIT building?

These questions were asked to both get a general understanding of our audience and their interactions with wind power as well as their opinions. The high percentage of people supporting MIT's reduction of emissions is a positive sign for our project. Also, the fact that many people have seen turbines and still support their use implies that those who have seen them were not appalled and that an installation on MIT's campus might not be greeted with harsh aesthetics critics.

Hull, MA, a location on the coast of Massachusetts with two large scale turbines, has demonstrated a positive outlook on turbines within a community. In 2002, a 660 kW turbine was installed near the town's high school. After its installation, a survey was conducted to gather public opinions regarding the new turbine as well as possible implementation of multiple turbines. There was an amazingly positive response and 475 residents out of 499 surveyed supported the installation of more turbines. This demonstrates that perhaps some of the common beliefs about turbine aesthetics are not valid, and people do not mind having them near their homes.[47]

The survey was voluntary, so we may have suffered from voluntary response bias. But because of the short nature of the survey, we suspect that even unbiased/impartial students would have been willing to share their opinion.

Added social benefits

Implementing wind power at MIT is important for many reasons, including setting a precedent. If turbines on campus are quiet and aesthetically pleasing, then the public view and opinion of turbines could change for the better and trigger more widespread use of wind power. The mere fact we are even considering small scale wind may cause other universities, schools, and even homeowners to think about whether *their* own wind resource could be viable. The prospect that current or future students may be motivated by a successful wind installation to direct their efforts into energy/environment related field is not far fetched either. Last, with the changing global climate, the implementation of wind power helps MIT send the message to the rest of the world that it too does care strongly about reducing greenhouse gas emissions This sort of investment into renewable resources would illustrate just how willing MIT is to fulfill its "walk the talk" attitude.

Greenhouse gases

The amount of greenhouse gases offset was calculated after our power analysis was completed. The survey demonstrated that MIT undergraduates are concerned about carbon emissions; therefore, it was important to see how much CO_2 a turbine could offset. The graph

[47] Manwell et al (2003).

below assumes each system to have a 6 kW capacity. This is to make a fair comparison between the two turbines.

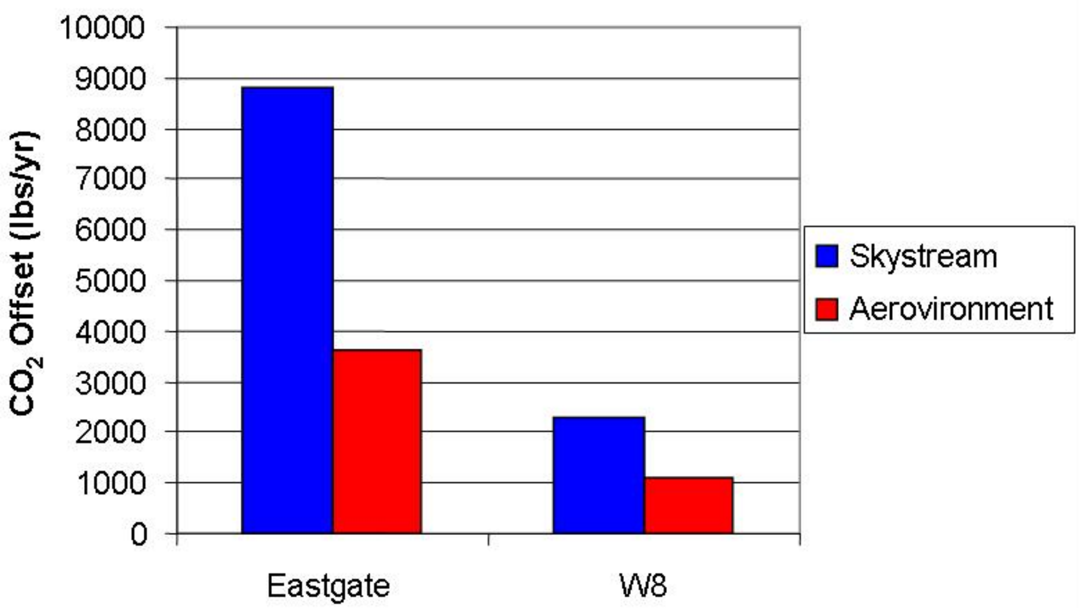

Figure 18. Pounds of carbon dioxide offset by using each turbine on the two most promising buildings.

From **Figure 18**, one can see that a Skystream on top of Eastgate would offset approximately 9000 pounds of CO_2 per year. MIT's overall CO_2 emissions add up to be 270,000 Tonnes per year, which translates to about 600 million pounds. Obviously, a single turbine would not impact the overall emissions a large amount, but it is important to realize that all the small projects that offset a small amount of carbon dioxide add up and make a cumulative difference.

Currently, there is no carbon tax or credit in place in the state of Massachusetts. However, there has been much talk about implementing such a system to reward those who make an effort to reduce their carbon dioxide emissions. **Figure 19** shows how a carbon tax could affect the payback time for a Skystream 3.7 on top of Eastgate. The highest value discussed to date is \$200 per ton of CO_2.

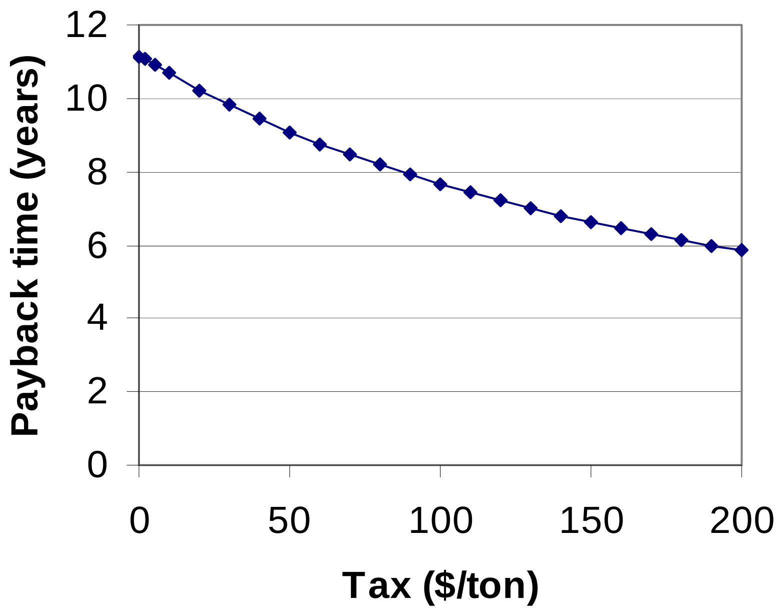

Figure 19. Payback versus a carbon tax or credit for a Skystream on Eastgate.

Recommendations

The analysis completed to date on this project shows that Eastgate is the best wind site of the seven tested buildings. Not only this, but placing a Skystream on top of Eastgate has a payback period within the turbine's lifetime. While the actual amount of energy produced or CO_2 offset might not be massive, it can provide a small amount of electricity for half the price of what MIT currently pays NSTAR for electricity. To put it in other words, by utilizing this type of technology, MIT would be making a profit for reducing its carbon emissions.

Also, of course, we suggest MIT look into larger scale renewable options. For example, Harvard University recently invested in the Cape Wind project, which is a proposed off shore commercial wind farm. Although MIT would be only be indirectly offsetting its own energy use, it would be directly supporting fledgling renewable energy initiatives by promoting such off-campus energy investments.

More to the core of this class, MIT's purchase of a wind turbine system contributes to its ability to be a learning laboratory. It allows students to conduct research as they learn. For example, one of the groups in this year's Environmental Engineering Design Lab designed and tested turbine that could generate power from the wind energy on a campus building's roof. If MIT were to install actual turbines on top of a building, they could be used as a teaching tool for such classes. Perhaps, through an MIT sponsored wind turbine competition, students could examine turbine mechanics and be challenged to design a wind turbine that could thrive in an urban small scale situation.

Most importantly, further research needs to be conducted. Limitations posed by this project forced us to limit our sites to only seven, yet there are a few other buildings across campus that would most likely be excellent wind resources, including 54 (the Green building) and Tang, a graduate resident hall. Further analysis should continue on the more promising sites of this study, including Eastgate and W8. Because of our short time interval, our data is neither ideal nor free from error. Consequently, a year-long analysis of these locations would raise the level of confidence for our calculations considerably.

Conclusion

Where can we find energy? It is well known that oil, and other fossil fuels store energy very efficiently. However, their supply up to this date, convenience, and accessibility has not come without cost. These energy sources have proven to be detrimental to the environment in the form of climate-warming gaseous byproducts such as carbon dioxide, nitrous oxides, sulfur dioxide. These gases enter the atmosphere and trap heat in the case of carbon dioxide or in the case of sulfur dioxide, cause acid rain. The damage to our atmosphere and biosphere can be irreversible and may have future consequences beyond our comprehension. Action must be taken immediately to reduce our reliance on these gases and their irrefutable deleterious effects. In addition to environmental impetuses, the increasingly uncertain nature of the global energy market and the dwindling supply of these fossil fuels call for immediate change. This is where renewable energy comes in to play. Not only are renewable energy resources clean but they are permanent and found all over the planet.

However, our group was interested in renewable energy at a very specific and important place- MIT. With the recent “Walk the Talk” campaign, the increasing momentum of the MIT energy initiative (MITei), and the overwhelming support for emissions reductions from students, now more than ever is MIT’s chance to improve its green image, support small scale renewable initiatives, and at the same time improve energy/climate change awareness. From the results of our survey, we would predict little resistance to implementing wind power on campus.

Regardless of what MIT decides, both energy efficiency modifications and avenues for new energy sources should be explored by the Institute. MIT is the leading technology school in the nation and by initiating renewable options on or off campus it would help set a precedent that others would be sure to notice.

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Appendix A

Site Setup

Figure 20. W8 Anemometer locations48.

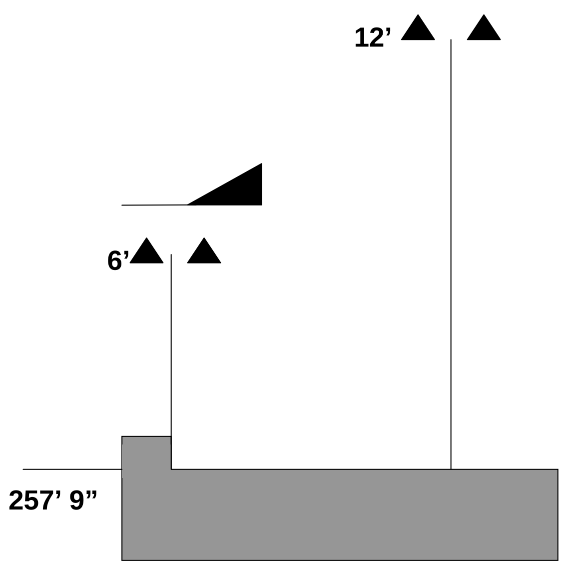

Figure 21. Heights of anemometers on Eastgate.

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[48] Picture modified from Google Earth.

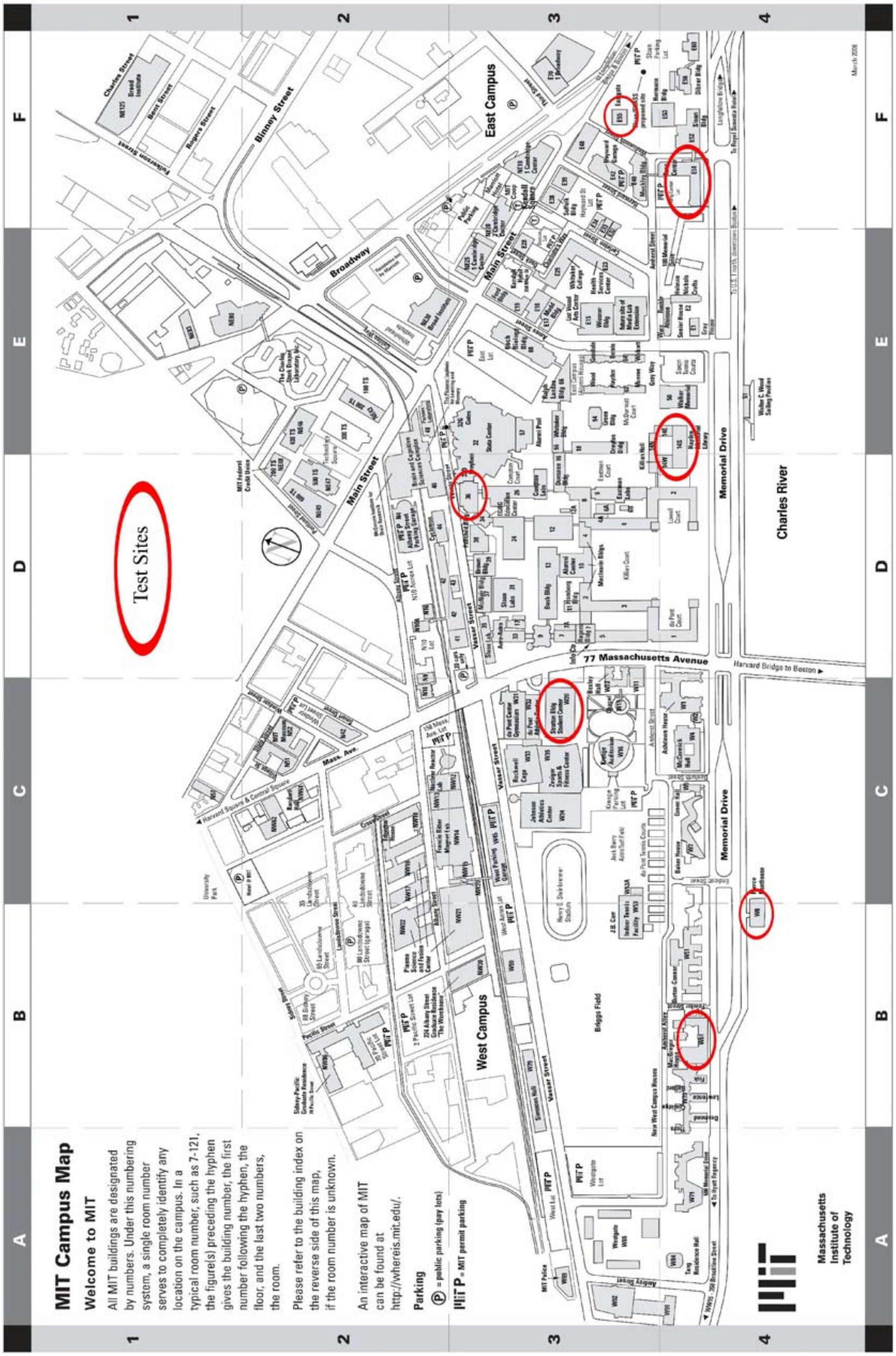

Figure 22. Building locations across campus.

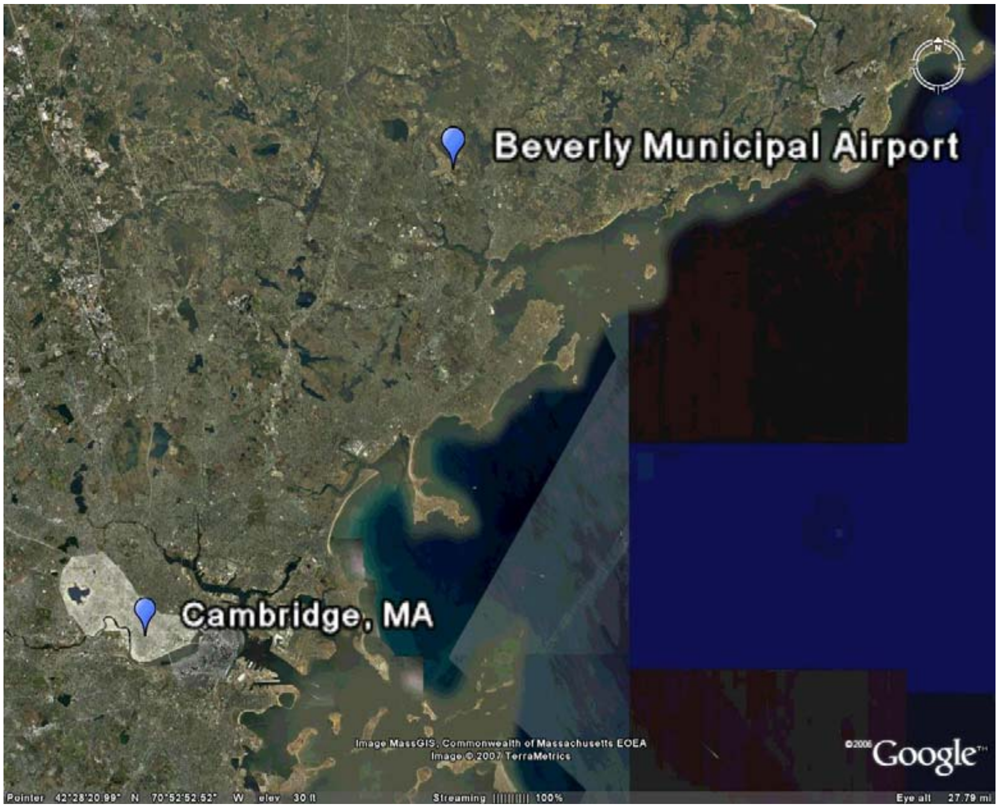

Figure 23. Location of Beverly Municipal Airport in relation to Cambridge.

Appendix B

Methodology Specifics

Power and Wind Direction

Team Wind's first attempt to take into account wind direction involved using excel to disregard data points unless they were in specified wind direction ranges (i.e 120-180 degrees). By looking at the geographical orientation (North/South/East/West) of specific edges of campus buildings, this method had the potential to very accurately predict the power produced by AV turbine systems on different faces of a building. Unfortunately, the Beverly wind direction data produced dominant wind direction results (N-NE) that contradicted MIT's actual predominant wind direction (S-SW), making the results useless. Consequently, one area of future analysis would be to use Green Building wind data instead of Beverly. One could produce much more accurate results with the said method coupled with accurate on-campus wind direction data. As a result of the predominant wind direction contradiction, we decided to use the wind rose method. The following table shows the percentage of total power produced from certain 60 degree bins. (It is a wind rose in tabular form). Note how AVX1000's mounted on the western edge of the building (Eastgate) would be able to capture as much as 50% of the total wind resource.

Table 4. Wind direction frequency and power from AWS True wind.

Historical Wind Orientation Data (almost identical for all of campus)

Orientation	Wind by Direction	Frequency (Percent)	Power (Percent)	50m Avg. Wind Speed (m/s)	Weibull Parameters c	Weibull Parameters k	Quadrant Power	Quadrant Heading
-11.25	N	4.6	2.9	5	0.9	2.28		
11.25	NNE	3.8	3.1	5	0.9	2.15		
33.75	NE	4.1	3.2	4.6	0.9	1.74	10.3%	30-90
56.25	ENE	5.6	3.4	4.5	0.8	1.97		
78.75	E	5.7	2.1	3.8	0.7	2.19		
101.25	ESE	3.1	1.6	3.9	0.7	1.69		
123.75	SE	2	1.2	4.4	0.8	1.96		
146.25	SSE	1.7	1.6	4.3	0.8	1.32	6.5%	120-180
168.75	S	3.4	5.4	5.8	1.1	1.63		
191.25	SSW	9.1	14.4	6.7	1.2	2.34		
213.75	SW	13.1	17	6.4	1.2	2.75		
236.25	WSW	10.7	13.5	6.3	1.1	2.45	50.8%	210-270
258.75	W	8.6	9.6	6	1.1	2.21		
281.25	WNW	9.9	10.7	5.8	1	2.11		
303.75	NW	7.6	6.1	5.5	1	2.68	16%.4	300-360
326.25	NNW	7.2	4.3	5.1	0.9	2.39		

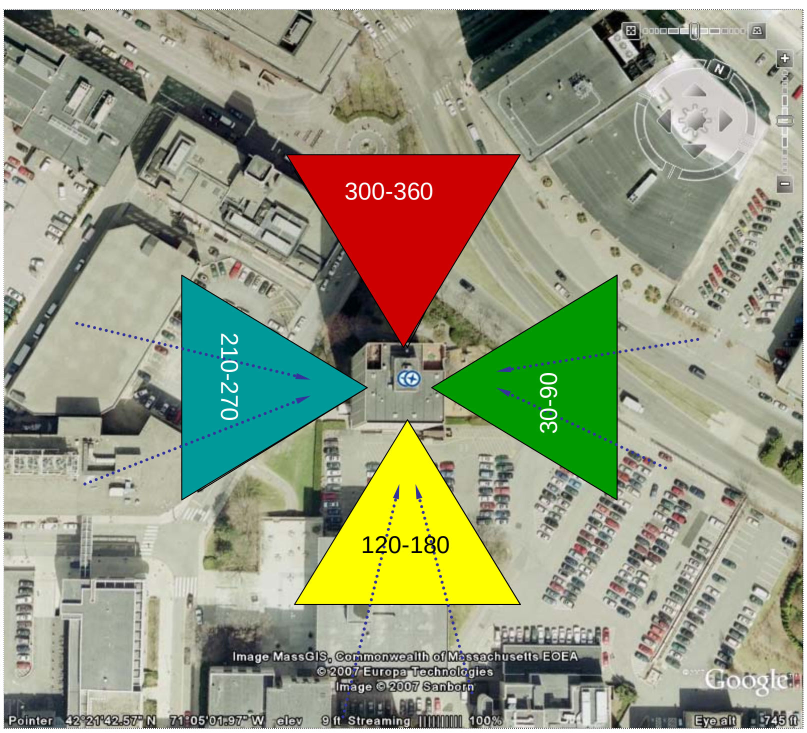

Figure 24. Color Coded quadrants for potential AVX1000 parapet placement on Eastgate. Numbers denote compass bearing ranges.

Appendix C

Error Analysis

Predicted Wind Speed Distribution Error

To measure the accuracy of the correlation and prediction with the Beverly Data, we followed the methods set out by Dr. Rogers and performed a Chi Square goodness of fit test.[49] Equation 3 shows the method of determined the normalized Chi square statistic. After wind speed were binned in the following way: "less than 3 m/s, 3 to less then 4, 4 to less then 5, …, 11 to less then 12, and 12 m/s or greater". We binned the Beverly Wind data during the testing period (3/21/2007 through 4/30/2007) and our own wind site data in the same way.

Equation 3. Chi Squared Goodness of Fit Test.

$$m_4 = \sum_{i=1}^{M} \frac{\left(n_{y,i} - n_{\hat{y},i}\right)^2}{n_{y,i} N}$$ [50]

n_{yi}- denotes (Observed frequency)
$n(_{yhat)i}$- denots (Predicted frequency)
N denotes the number of observations

We produced the following X^2 values for our wind speed predictions in **Table 5**. Note how Dr. Rogers X^2 values are as much as an order of magnitude smaller than some ours. This occurred because of the short logging time compared to the recommended nine months of logging.

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[49] Rogers et. al 7
[50] Rogers et.al 7

Table 5. X^2 values.

14	0.148
36	0.111
E51	0.106
Eastgate	0.644
Mac	0.194
w8	0.176
W20	0.159
Rogers, et al.	0.064

Additionally with the binned frequencies, we determined a percent error from these bins. Table 6 below shows the calculated percent error for each site. Unfortunately, Eastgate had the largest error because of the intermittency of our data collection.

Table 6. Percent error for predicted wind speeds.

Building	Error Bar (Confidence)
14	2.99%
36	2.02%
E51	2.02%
Eastgate	6.18%
Mac	3.38%
w8	2.92%
W20	2.90%

Predicted Power Error-

Because of the velocity cubed aspect of wind power, we can't extrapolate a 6% error in wind speed to be a 6% error in wind power or energy production. Rather, we must interpolate backwards from the average annual power, an "average wind speed". This "average wind speed" is defined as the constant wind speed that would be required to produce the average annual power. From this point on, we will refer to "average wind speed" as AWS'. Just to emphasize, AWS' is not that average annual wind speed.

With the AWS' calculated, we could calculate an upper and lower bound for AWS' by multiplying them by the respective error bars. Next, we take the upper and lower AWS's and re-input them back into the power curve to determine the upper and lower bound for average power. From there it is relatively easy to determine the upper and lower bound for: average annual kWh's produced, and average annual dollars of electricity produced. Table 7 shows example upper and lower average annual electricity

Table 7- Upper and Lower Bounds for Average Annual Skystream Electricity Production.

Skystream cost of Electricity offset annually				
	Building	Lower Bound (kWh's/yr)	Average (kWh's/yr)	Upper Bound (kWh's/yr)
	Eastgate	771	956	1172
	W8	355.125	393.75	431.625

Appendix D

Power, Generation, and Payback Tables

Skystream Summary Data

Table 8. Skystream energy production over 15.3 years.

Skystream Summary				Lifetime (Years)
				20
Building	Height (m)	Total KWh's	Annual KWh's	Total Offset Electricity ($/year)
14	21.8	2800	457.0	68.5
36	33.7	3610	588.2	88.2
E51	20.1	993	162.0	24.3
Eastgate	78.6	39000	6377.0	956.6
Mac	51.9	2461.7	401.4	60.2
w8	7.8	16105.4	2625.9	393.9
W20	18.8	2257.8	368.1	55.2

Table 9. Skystream Environmental and Economic Payback.

		lbs CO2 / kWh	lbs NOX / kWh	lbs SOX /kWh	
		1.38	0.00739	0.00429	
		$/lb CO2	$/lb NOX (EPA 2007)	$/lb SOX (EPA 2007)	Addl $/kWh Credits
		0	0.4825	0	0
		Original Installed Cost	Credits on Installation		Cost (Installed)
		19775	9000		10775
Building	Annual Offset CO2 (lbs)	Annual Offset NOX (lbs)	Annual Offset SOX (lbs)	Credits ($/yr)	Payback (Years)
14	630.2	1.3	0.8	0.651358785	155.8
36	811.8	1.7	1.0	0.838968527	121.0
E51	223.5	0.5	0.3	0.230986916	439.4
Eastgate	8800.3	18.9	10.9	9.095371218	11.2
Mac	553.9	1.2	0.7	0.572462402	177.3
w8	3623.7	7.8	4.5	3.745213041	27.1
W20	508.0	1.1	0.6	0.525033585	193.3

Table 10. Cost of Electricity Produced (Skystream).

Building	Lifetime $/kWh
14	1.2
36	0.9
E51	3.3
Eastgate	0.08
Mac	1.3
w8	0.2
W20	1.4

AeroVironment Summary Data

Table 11. AeroVironment Energy Production over 15.3 years.

AV Summary				Lifetime (Years)
				20
Building	Height (m)	Total KWh's	Annual KWh's	Total Offset Electricity ($/year)
14	21.8	734	287.5	43.1
36	33.7	868	340.0	51.0
E51	20.1	541	211.9	31.8
Eastgate	78.6	4270	1670.6	251
Mac	51.9	710	277.0	41.5
w8	7.8	2100	802.5	120
W20	18.8	606	237.3	35.6

Table 12. AeroVironment Environmental Impact and Payback.

		Original Installed Cost	Credits on Installation		Cost (Installed)
		34500	12000		22500
Building	Annual Offset CO2 (lbs)	Annual Offset NOX (lbs)	Annual Offset SOX (lbs)	Credits ($/yr)	Payback time
14	396.7	0.4	0.2	0.2	519.8
36	469.2	0.4	0.2	0.2	439.5
E51	292.5	0.3	0.2	0.1	705.0
Eastgate	2305.4	2.1	1.2	1.0	89.4
Mac	382.2	0.3	0.2	0.2	539.5
w8	1107.4	1.0	0.6	0.5	186.2
W20	327.4	0.3	0.2	0.1	629.7

Table 13. Cost of electricity produced (AVX1000).

Building	Lifetime $/kWh
14	3.898
36	3.296
E51	5.288
Eastgate	0.671
Mac	4.046
w8	1.396
W20	4.723

Appendix E

Rebates

Table 14. MTC Small Scale Renewable Incentives Matrix.[51]

Installation Matrix for Block 1 of Small Renewables Initiative			
	Technology		
	PV	Wind	Hydro
Distributed Generation	($/watt dc)	($/watt ac)	($/watt ac)
Base Incentive ($/watt)	$ 3.00	$ 2.00	$ 4.00
PLUS: Additions to Base			
MA-manufactured components	$ 0.50	$ 0.35	$ 0.75
Public Buildings	$ 1.50	$ 1.00	$ 2.00
Economic Target Area	$ 0.50	$ 0.35	$ 0.75
Low-income / Affordable Housing (40-B)	$ 0.50	$ 0.35	$ 0.75
Back-up for Critical Loads	$ 0.50	$ 0.10	N/A
Building-Integrated PV	$ 1.00	N/A	N/A
New High Performance Buildings			
LEED or CHPS certified	$ 1.50	$ 1.00	$ 2.00
Energy Star or equivalent	$ 0.50	$ 0.35	$ 0.75

Table 15. Incentives Matrix for Large/Medium Scale Projects.[52]

Technology Incentive per Watt Matrix – **Medium** Scale Projects

Distributed Generation	Wind	Fuel Cell	Hydro	PV	Biomass
System Scale	25-250kWdc	10-60kWac	10-60kWac	10-75kWdc	10-60kWac
Base Incentive	**$1.50**	**$4.00**	**$4.00**	**$3.00**	**$3.50**
Plus Additions to Base					
MA-Manufactured components				$0.50	
Economic Target Area				$0.50	
Low-Income/Affordable Housing				$0.50	
Back-up for Critical Loads	$0.10			$0.50	$0.50
Building-Integrated PV				$1.00	
Green Buildings (LEED) And/or Fuel-less electricity generator	$0.75	$2.00	$2.00	$1.50	$1.75
Or High Performance Homes				$0.50	

Technology Incentive per Watt Matrix – **Large** Scale Projects

Distributed Generation	Wind	Fuel Cell	Hydro	PV	Biomass
System Scale	>250kWdc	>60kWac	>60kWac	>75kWdc	>60kWac
Base Incentive	**$0.75**	**$3.00**	**$3.00**	**$3.00**	**$3.00**
Plus Additions to Base					
MA-Manufactured components				$0.50	
Economic Target Area				$0.50	
Low-Income/Affordable Housing				$0.50	
Back-up for Critical Loads	$0.10			$0.50	$0.50
Building-Integrated PV				$1.00	
Green Buildings (LEED) And/or Fuel-less electricity generator	$0.38	$1.50	$1.50	$1.50	$1.50
Or High Performance Homes				$0.50	

** For biofuels (such as biodiesel) calculate the design & construction incentive using the biomass incentives and the applicable limits. Any funds remaining from the biomass incentive–per-watt calculation may be applied to cover 100% of the incremental cost of the biofuel for up to two years.*
*** Funding for the green building components of projects targeting LEED standards cannot exceed 33% of the total funding sought*

[51] MTC, Small Renewables Initiative, 1.
[52] MTC Commercial, Industrial, & Institutional Initiative, 9.

Turbine Costs

Table 16. Cost per 2.4kW Skystream 3.7.[53]

SkyStream 3.7	
Suggested Retail ($5500)	**35' Tower**
Transporation (10%)	$ 6,100
Foundation and hardware (14%)	$ 610
Permit Fee* ($200 est)	$ 1,000
Dealer Installation	$ 200
TOTAL Installed Cost:	$ **7,910**

Table 17. Installed AVX1000 Costs. [54]

AVX1000 6kW (w/ Canopies)	AVX 1000 6kW (w/out Canopies)
$34,500 (installed by AV)	$46,100 (Installed by AV)

[53] This information was provided on request from the manufacturer, Southwest Windpower
[54] Jeff Wright, Director, Strategic and Global Sales Energy Initiatives