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Wind Energy Resources in Massachusetts
A GIS Assisted Analysis

An Interactive Qualifying Project Report

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By

Jason R. Potts

Jeff R. Hammel

Vlad C. Babau

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Approved:

Professor Steve W. Pierson

Professor Paul Mathisen

Executive Summary

Attention to wind energy has been increased dramatically in recent years. Fossil fuel sources continue to be depleted and produce power at the cost of poisonous emissions and greenhouse gases, whereas wind energy is a renewable source and is environmentally clean. Wind energy is currently the most cost-competitive of renewable energy sources and also the fastest growing. Governmental support of clean and renewable energy continues to increase with harsher standards imposed on traditional power sources and tax incentives to developers of clean renewable sources. The State of Massachusetts New Renewables Portfolio Standard states that a growing percentage of power in the region must come from new renewable sources. These factors, taken together, mandate the development and implementation of wind turbine technology.

Wind turbine siting is a critical part of furthering the development of wind power. Winds in the area of interest must be assessed to ensure that adequate wind power density exists to warrant the construction of a turbine. Wind power density is highly sensitive to speed and the difference of a few meters per second can correspond to a great change in wind power density. This makes it necessary to obtain as accurate an assessment of the wind speed as possible in order to appropriately site a turbine. Regions of adequate power density must then be assessed for social, economic and environmental concerns.

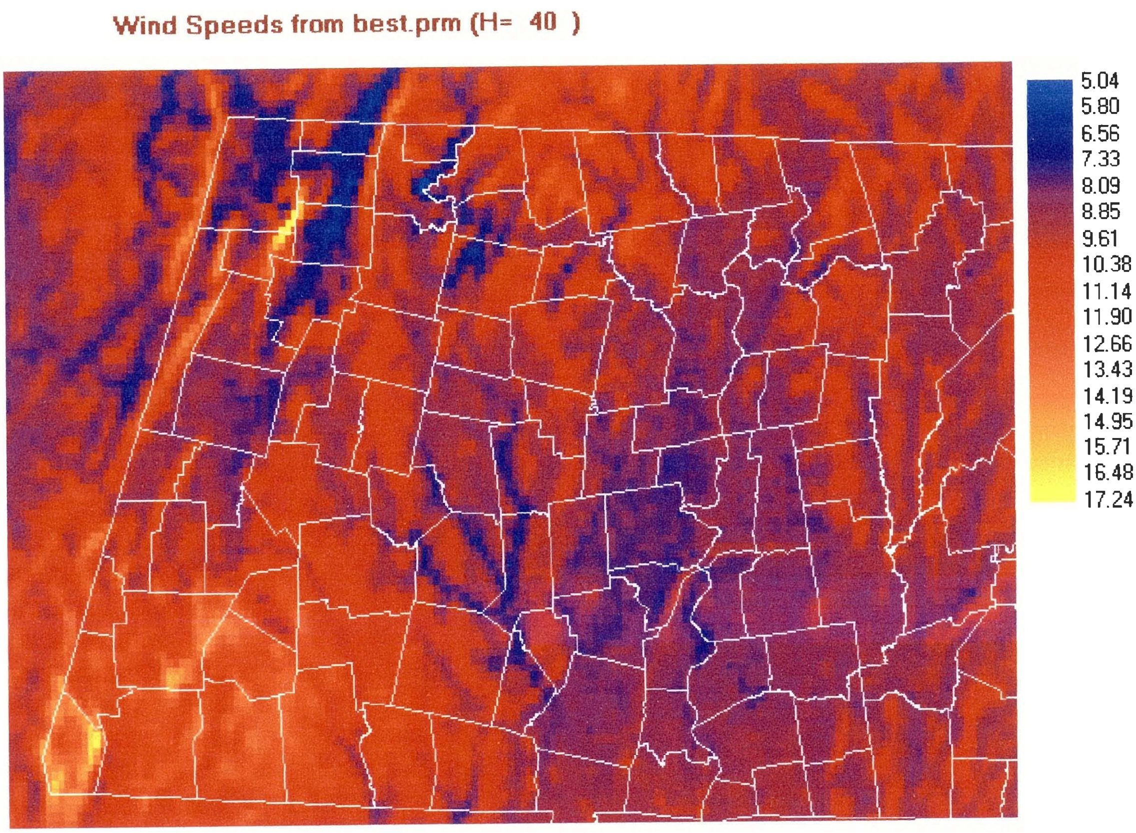
Traditionally, winds in an area were interpolated according to surrounding weather data and ad hoc methods. As the techniques used only gave a vague indication of promising regions, it was usually necessary to measure winds at a specific site over a period of time. Significant advances in wind turbine siting did not come until recently with

the Union of Concerned Scientists study Powering the Midwest, which used a GIS-based linear regression. This study served as a catalyst leading to several further studies in recent years using progressively sophisticated GIS techniques.

High fidelity siting techniques have been made possible by the rapid growth of the computer industry and the corresponding drop in the price of processing power. Geographic Information System (GIS) data exists as computerized maps of physical and social phenomenon, such as digital elevation models, areas of environmental concern, and roughness length. The WindMap software package was capable of calculating the entire wind flow field over the region by advanced numerical methods (finite elements). WindMap generates maps of wind speed, wind power density, and wind turbine output based on user-input GIS data, wind data, and run parameters. The Idrisi GIS software package can be used to manipulate these wind resource maps to form a credible and quantitative analysis of social, economic and environmental factors. Advanced computer software facilitates cutting-edge wind turbine siting.

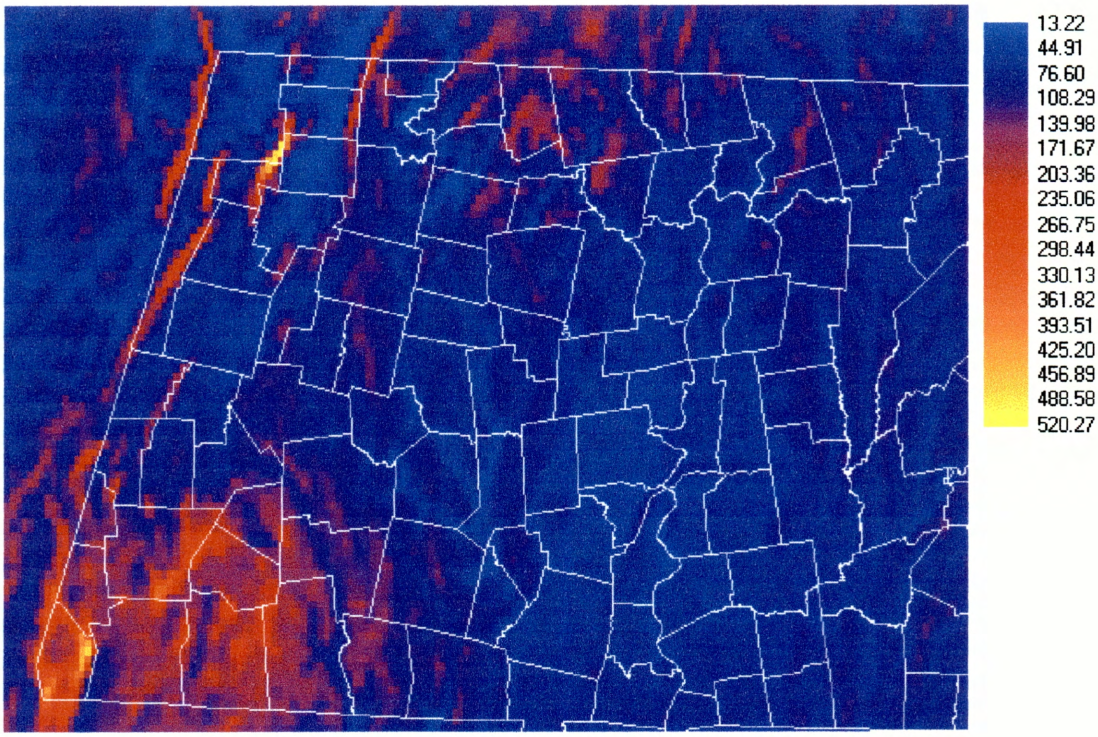
With advanced computer resources available and the clear need for high-quality wind resource assessment in Western Massachusetts, the goal of this project was to complete such an assessment over this region. Western Massachusetts was chosen as the area of study for this project because of the availability of high-quality wind data from the University of Massachusetts at Amherst Renewable Energy Research Lab (RERL) as well as the traditionally held belief that the region had high wind power density. After the wind-mapping technique was refined, WindMap produced wind resource maps on a 906 m grid size giving results comparable to the assessment by the RERL of winds at specific sites.

The maps produced by this project represent the first high-resolution wind resource maps of Western Massachusetts. Optimized wind speed and power density are shown in the two figures following. As illustrated in these figures, three areas exhibit high wind power density: the Mt. Greylock / Mt. Brodie region, the southwest corner of the state, and the Burnt Hill region. The first figure shows wind speeds in which you can see the three promising regions. The map of wind power density that follows further reinforces this. Knowledge of the wind resources in an area provides a foundation for wind turbine siting decisions.



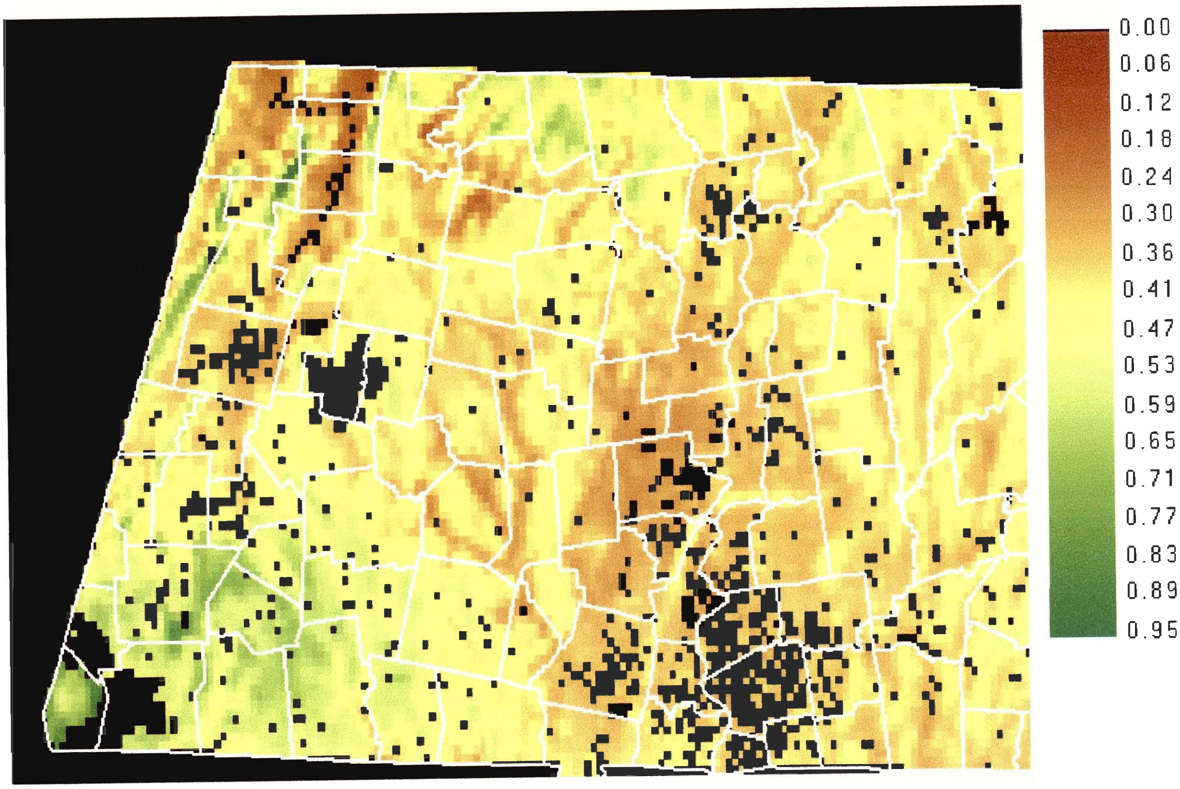
Map of Wind Speed over the State of Massachusetts (in Mph)

The wind resource maps produced by WindMap were used as the basis of a GIS-based siting analysis for wind turbine suitability. Idrisi32 was used to perform calculations to develop a suitability index based on considerations of social, economic and environmental impact in conjunction with the wind resources of a region. A wealth of relevant information was available from MassGIS. Population centers, wetlands, and areas of environmental concern were deemed inappropriate to wind turbine development and were dropped from the assessment. Wind speed, proximity to the power grid, and distance from population centers were weighted appropriately and combined. This resulted in a non-dimensional index over Western Massachusetts of the suitability of the region of wind power development that is shown in the final figure in this section. This figure corresponds closely to the wind speed map but additionally accounts for population centers such as Springfield and areas of critical environmental concern, both considered unfit for wind turbine development.



Map of Power Density over Western Massachusetts (in W/m²)

This project illustrates the reconciliation of science and society through the advancement of cleaner energy alternatives aimed to benefit Massachusetts in the long term. Understanding of the siting process allows wind turbines to be placed to best utilize existing wind resources and to match social, environmental, and economic considerations important in the area. The development of the siting procedure as evident in this project is an evolving process that strives to match areas of the most cost-effective wind energy to human concerns in the region. This project is part of an evolving siting technique and yields results significant to advancement of wind energy siting in Massachusetts, as well as provides a reference for future work on the subject matter.



GIS Assisted decision map of Western Massachusetts

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Abstract

Wind power resources in Western Massachusetts are assessed to aid in the siting of wind turbines for that region. We use WindMap, a GIS (Geographic Information Systems)-based software package that solves the continuity equations for a particular region, to produce maps of interpolated wind speed. Then, using Idrisi, a GIS software package, the resulting maps are analyzed for societal and environmental factors to address the suitability of particular locations in Western Massachusetts for wind farms.

1. Introduction

Renewable energy has been gaining attention in recent years. With the harmful emissions of fossil fuels, as well as their finite supply, people are beginning to realize that renewable energy is a viable long-term alternative. Government and state tax incentives have reinforced the interest in renewable energy sources. Further more, new technologies continually improve the efficiency of renewable power plants thereby decreasing their cost. This trend will likely continue with the increasing investment in renewable energy sources.

Among renewable energy sources wind, power has been thriving both in the United States and around the world. This is reflected not only by the declining costs of resources and the improvement in performance of wind power plants, but also by a growing awareness among utilities that renewable energy technology is beneficial to the economy and the environment. Wind energy is currently the most cost-competitive of the renewable sources. The cost per kilowatt-hr is 4.0-6.0 cents, comparable to coal at 4.8-5.5 cents and natural gas at 3.9-4.4 cents (California Energy Commission, 1997). The federal government also offers a production tax credit, lowering the cost of wind energy to 3.3-5.3 cents/kWh (California Energy Commission, 1997). Wind energy also has low upkeep, negligible emissions, and the cost per kWh will continue to decrease as turbine and siting technology improves.

The siting of a wind energy farm is a complicated issue but is also extremely important for the economic viability of wind energy. Some of the factors affecting wind turbine siting are the average wind speed of an area, visual and noise impacts in a scenic area or near residential communities, and also the potential impact it might have on birds and other wild life. All the factors must be considered to ensure a good understanding of wind energy resources and proper wind turbine placement.

Here in New England, the University of Massachusetts conducted a study for assessing wind energy resources in Western Massachusetts from 1996 to 1999. They installed wind-monitoring equipment at five locations around Berkshire County. Wind data from each of the five stations were analyzed individually and, based on that one site was selected (atop of Brodie Mountain) as being the most promising for wind power development.

The goal of this project is to assess wind energy resources in the rest of Western Massachusetts by interpolating between the five wind monitoring stations. Maps of wind power per unit area (wind power density) will be produced and assessed through Geographic Information Systems (GIS) based programs. The results will be weighed for social factors applicable to the region. This project illustrates the reconciliation of science and society through the advancement of cleaner energy alternatives aimed to benefit Massachusetts in the long term. It is hoped that this project will yield results significant to advancement of wind energy siting in Massachusetts and provide a reference for future work on the subject matter.

Section 2 of this report is the literature review, which provides the necessary background for a good understanding of wind energy. Section 3 describes the principles and procedures of the report, while Section 4 describes the results and its analysis. Finally, Section 5 presents our final conclusions, as well as recommendations for future work.

2. Literature Review

An understanding of wind power is important to place this project in proper context. The history of wind power is presented to give a perspective of the harnessing of the wind over the ages to modern times. The physical principals governing wind power in a geographic region are briefly summarized. This leads into the idea of wind turbine siting, which is then discussed. Wind power is then specifically applied to Massachusetts, and existing wind facilities in the state research concerning the state are illustrated. Finally, the economics and environmental effects of wind power are considered. These topics are important to the considerations necessary for wind power siting in Massachusetts. The following comprises a summary of the background material necessary for comprehension of the goals and methodology of the project.

2.1. Development of Wind Power

Wind energy has played a changing role in man's society since the very beginning of mankind's technological evolution. The application of wind power has evolved in accordance to society's means and needs and in competition with other energy sources. Since the dawn of the Industrial Revolution, fossil fuels replaced wind power repeatedly due to their inexpensive nature. While rarely a primary power source, the development of wind power continued through the twentieth century. An understanding of wind power's development is paramount to a proper understanding and identification of current trends affecting wind power as an energy source.

In its oldest and simplest form, sails on ships harness the energy of the wind to move a boat across the water. Yet other more innovative uses share a long history in man's society. Depictions of simple windmills with horizontal wind wheels on a vertical axis appear on Chinese vases dating back as early as 3000 B.C. Babylonians referred to the same type of windmill in 1800 B.C. In the twelfth century, modern windmills with a horizontal axis first appeared in Western Europe (Inglis, 1978). These windmills stayed in use for pumping water and powering simple machines until the nineteenth century, when most of their work was taken over by steam engines. Using a steam engine fueled by coal proved to be more efficient and productive than the windmills of the time. However, wind energy would return with the introduction of a new form of power.

In the early twentieth century electricity began to enjoy widespread use for the first time. Electric appliances began to show up in homes across the United States, yet public utilities did not reach the most rural of areas. This was especially so in the plains of the Midwest. These rural homes satisfied their need for electricity by using small windmills that ran electric generators. These small one-family windmills continued to be used into the forties, when public power lines reached these rural communities, and brought them the cheap and abundant electricity from power plants, many of them using fossil fuel such as coal. Once again, coal replaced windmills in man's society. (Hackleman, 1975)

Wind power continued to provide an economically feasible, clean, and abundant source of energy through the 1930s, and for these reasons, people have continued the pursuit of wind power, and strides have been made toward making it more feasible as a commercial power source. Denmark led this movement, having appreciable numbers of windmills (some producing as much as 100 kilowatts each) that fed into their commercial power grid. This cheap source of power was very useful during the Second World War when the German forces made transport of fuels like coal and oil more difficult (Inglis, 1978). The European application of wind power paved the way for advances in industrial wind turbine technology.

The Putnam Project of the late 1930's and early 1940's produced great advances in commercial wind power in the United States prior to World War II. S. Morgan Smith Company developed the first large-scale wind turbine for the commercial generation of electricity. From its conception in 1939 by Palmer C. Putnam, it was designed and built only two years later in 1941 (Putnam, 1948). It was constructed quickly in order to beat limits on supplies that would come with the brewing war. The engineers realized during construction that a part supporting the blades was not strong enough, yet they could not afford to replace it. The wind turbine was constructed anyway, and operated well until 1945 when the weak part finally broke, and the turbine threw a blade. After this accident, at the end of the testing period, the project was abandoned. Despite its termination, the Smith-Putnam prototype produced 1250 kilowatts, by far the largest of any wind turbine previously constructed (Putnam, 1948). The experience gained from its design, construction, and testing led to the development of a smaller model. Cost estimates suggest that installation of these smaller turbines would have resulted in a total cost of $191 per installed kilowatt in 1945. However, the Central Vermont Power Company required a cost under $125 per installed kilowatt, and proceeded to invest once again in coal-powered generators.

In the post World War II United States, development of wind power has continued until present day. Although rarely used as a primary source of power, and usually in the shadow of more popular sources such as fossil fuels and nuclear, wind power has continued to enjoy a slow growth. Innovations in turbine design and manufacturing methods have increased the output of modern wind turbines, while decreasing cost per kilowatt-hour. Throughout the late twentieth century wind power has emerged once again as a possible large-scale energy alternative as society finally comes to terms with the limited nature of fossil fuels.

2.2. Physical Principles of Wind Power

An understanding of the physical principals that govern wind flow is vital for a educated perspective of wind turbine technology as well as determination of potential wind turbine sites. The behavior of wind is governed by factors including boundary layer behavior and surface roughness, flow regime (turbulent or laminar), temperature and pressure gradients and other less important factors. Comprehension of the science of aerodynamics is vital to proper placement of wind turbines. What follows is a brief overview of the applicable aerodynamic theories.

Wind is generated by atmospheric temperature gradients caused by uneven heating by the sun. As the air is heated, it expands, causing it to move to areas of lower pressure. The atmospheric heat transfer in conjunction with existing convection currents and pressure differentials form the wind patterns. On a global scale, the rotation of the Earth also has an effect on the wind patterns as well. While only 2% of the solar power reaching the earth is transformed into wind, local conditions may raise the wind power density about the solar power density in some areas due to convective currents and thermal gradients. Also, wind turbine technology is currently more efficient and cost effective at transforming wind power to electricity than solar cells are at transforming sunlight.

The boundary layer is a description of the wind speed and direction as a function of height from a surface. The velocity vector goes to zero at a surface due to the no-slip condition. As the height (the distance from the surface) increases the velocity parallel to the surface increases until it approaches a free-stream velocity value. An empirical relation gives wind speed over a flat plate as a function of height to the $1/7^{th}$ power, though other exponential relations are used depending on the flow modeled. The boundary layer velocity distribution is governed by pressure gradients and the boundary layer profile develops as air flows across a surface. The curvature of the surface may be utilized to take advantage of high local velocities relative to the average velocity at a given height in a region. Examples of good topographic sites include the top of a gently sloping hill, and a mountain gap that accelerates the wind as a nozzle. Flat areas, including the open sea, are also good choices. The wind shear exponent, which determines how the velocity develops as a function of height, is a function of atmospheric characteristics and surface roughness.

The roughness of a surface affects how the boundary layer velocity profile develops over it. The friction coefficient of a surface, α, characterizes the roughness of the surface. This coefficient is an average protrusion length over the area considered. As the value increases, the rate of change of boundary layer thickness increases with increasing losses of kinetic energy due to friction with a surface – in this case, the ground and surrounding protrusions. Typical values of α might be 0.4 for an urban area and 0.16 for level country. The coefficient of friction can be used to generate a boundary layer velocity profile when integrated, either analytically or numerically, over a region of interest. The coefficient of friction can also be used with the average wind speed to determine probabilistically the number of gusts of wind up to a specific speed. Rougher regions have gustier winds. This, in essence, is turbulence – airflow fluctuates in both direction and strength in three dimensions. Turbulence is unsteadiness of wind speed and direction over a short time period of time as the boundary layer develops over a surface. Turbulence can threaten structural integrity, cause unwanted vibrations and noise, and lower the life span of a wind turbine. It is clearly advisable to avoid choosing an area with high turbulence for a wind power generation site, even if the area has strong winds.

Another factor to consider in siting is the variability of the wind. The wind speed and direction may change over the course of a year, as well as over a day. If the wind does not blow steadily then an energy storage system or the existing utility system must be used for this period. Usually, the wind power available is greater in winter, which is also when the most power is consumed. The power available over time must be compared to the power required over time to develop a complete picture of one's energy budget. For modern-day wind systems connected to the power grid, this is not an issue, for so little of the total power supply is generated by wind its variability over time is unnoticeable.

The number blades and turbine frontal area are, together with height, the primary gross physical considerations for wind turbine design. The exposure of frontal area of the turbine in conjunction with the wind speed determines the total power produced and the speed of the tips of the blades. For applications that require a high start-up torque, such as the pumping of water, many blades are used with a high overall coverage of the projected circular area. At high wind speeds, however, these blades act as a windbreak and have a lower maximum rotational speed. For electrical applications, only two or three blades are used in order to achieve a high maximum rotational speed (Hackleman, 1975).

The size of turbines varies from under 1000 watts for private-use wind machines (although these are becoming rarer) to the order of 10^7 watts. The size of the turbine determines the economic frame of its operation. Relatively small turbines, often maintained and engineered by a single person, cannot be economically compared with turbines designed with the aid of computer modeling and maintained by dozens of people. Indeed, the rate at which the turbines need maintenance makes the manpower they can economically support comparative to traditional power sources.

Momentum theory shows that the maximum amount of energy that may be extracted by a turbine is 8/9 of the kinetic energy passing through it. At this ideal condition, the wind speed will lose 2/3 of its original free-stream value. The amount of power extracted per unit frontal area by a turbine of 100% efficiency becomes:

$$\frac{P_{\max}}{A} = \frac{2V_o}{3} \cdot \left(\frac{8}{9} \cdot \frac{(\rho V_o^2)}{2}\right) = 0.593 \cdot \frac{\rho V_o^3}{2}$$

Where ρ is the density of the air, V_0 is the free-stream velocity of the air, P_{max} is the maximum wind power available for extraction, and A is the frontal area of the wind turbine. The factor 0.593 is known as the Betz coefficient after the first person to derive it. To obtain the power in a less than ideal case, multiply the maximum wind power available by the efficiency of the turbine. (Park, 1981)

In order to determine ideal locations for wind turbines, it becomes necessary to develop an accurate model of the geographic and atmospheric factors that influence the wind speed. Ideally, to analyze the wind power potential at a specific site, data showing the wind speed versus time at the location is needed. If only the mean wind speed is available, the Rayleigh distribution is a curve fit that gives the percent of time the wind blows at a certain speed given the mean speed. This curve gives hours per year, H, at a wind speed in the form of:

$$H = 8760 \times \frac{\pi}{2} \times \frac{V}{V_{mean}^2} \times e^{-\frac{\pi}{4}\left(\frac{V}{V_{mean}}\right)^2}$$

Where v_{mean} is the mean wind speed, V is the wind speed, and e is 2.718. The accuracy of the Rayleigh distribution is site dependent and is usually within ten percent (Park, 1981).

2.3. Wind Turbine Siting

The site of turbines is a primary consideration for the harnessing of wind power. As wind power density scales cubically with air speed, relatively small differences in local wind speeds can result in a significant difference in extractable power available in a region. Traditionally, wind siting was done with the aid of anemometers and available wind data. A new understanding of the physics of wind, coupled with the tremendous computational power of today's computers allow much more accurate mapping of predicted wind speeds. This will hopefully allow more educated placement of wind turbines, making them produce more energy and thus providing a more efficient and cost-effective energy source.

2.3.1. Factors Affecting Siting

The most important factor affecting wind turbine siting is the local average wind speed of an area. This factor will have a large effect on the overall output of a wind farm, ensuring that a location is chosen that will provide fairly constant winds, and therefore fairly constant power output. Before the computer age, wind speed was determined with the aid of anemometers. To investigate a specific site for wind power use, wind speed measurements were recorded at various heights over a period of time (ideally, at least a year). The National Weather Service maintains a Wind Speed Atlas of the United States from the wind speed data collected at several hundred stations across the country largely from data taken from the 1950s to 70s (Park, 1981). Wind speed data for a particular site was interpolated from this work and it remains a reference to date. With the advent of computers, numerical modeling using the continuity or conservation of momentum equations provided an alternative method for predicting wind speeds. As computing power has increased, wind speed predictions have become more accurate and more easily obtained. Information about modern siting techniques is scarce. Though there are several companies who do wind siting, their techniques and results are largely proprietary and not readily available to the public.

Aside from wind velocity, it is also necessary to take into account human factors. The location of population centers will affect the siting process as well. The aesthetic appeal of wind turbines has been controversial, as many people do not like the idea of having huge wind turbines running near their homes. Besides the physical appearance of the turbines, the sound that they have generated in previous installations has proven to be a nuisance to local populations. Population centers also affect siting by requiring that power generated by turbines be supplied to them. This requires proximity to power transmission lines, or the construction of new ones. These factors combine to make siting for wind farms a fairly difficult undertaking, consisting of compiling and combining large amounts of information.

2.3.2. Methods of Siting

Traditionally, investigation of wind speeds at a specific site involved setting up anemometers at various locations. The results of those anemometer readings taken from several hundred airports and meteorological stations across the United States were compiled and their data crudely interpolated to estimate wind speed classes (ranges of wind speeds) across the country. This work was known as the National Wind Atlas and remained the de facto standard for large-scale long-term wind speed behavior until its usurping by GIS based methods in the early 1990s.

With the constant and almost exponential development in computer technology, the number of applications for the computers has grown. One particular field of development is the Geographic Information Systems (GIS), a tool that is capable of accomplishing the information analysis necessary for deciding a promising site for wind turbine placement. Computers are capable of compiling information about the geography of an area through the use of a digital elevation model, or DEM, which provides all the necessary information about elevation, exposure, slope, and orientation to prevailing winds. The human factors described previously can also be entered into a GIS. This gives turbine siting a powerful tool for use in wind power siting.

In the early 1990s, the Union of Concerned Scientists conducted the first public GIS assisted study of renewable energy entitled Powering the Midwest. As part of this study, wind speed classes were determined over twelve states using the IDRISI GIS software package. DEMs and vegitative land cover GIS data was used in conjunction with a logarithmic relation between wind speed and exposure to calculate local wind speeds. The technique used gave a higher geographic resolution than maps from the National Wind Atlas. Powering the Midwest was done to provide data to the states enabling alternative energy siting. Michael Brower was among the four scientists conducting the study. He went on to use the experience gained in this study to develop GIS-based wind power siting in the private sector. The following section will discuss the evolution of GIS-based siting subsequent to Powering the Midwest study.

2.3.3. Evolution of Siting

After the introduction of GIS to wind resource assessment, Brower and Company began performing siting analysis for several states across the US. They used a GIS that took into account the topography of an area, wind resource data, land use, as well as land cover. In 1995, Brower and Company performed siting analysis for the state of Colorado. Brower continued in 1996 and 1997 to perform siting analyses for Iowa and New Mexico, respectively. Also in 1997, they performed an analysis for Norway, taking into account factors similar to those used in the Colorado project. The Norwegian project resulted in wind maps of Norway on a 1 km grid scale - a very detailed analysis indeed. The Colorado and Norwegian reports are very similar to the analysis that need to be done for the state of Massachusetts, since the topography of these regions is similar.

Colorado Project

In 1996, Brower & Co. performed a wide-area wind resource assessment for the State of Colorado Office of Energy Conservation and several collaborating utilities.

The importance of this project to this IQP is that it proves the effectiveness and ability of GIS systems to select promising sites for wind farms.

The Colorado project expanded the utilization of GIS technology from that of previous projects in many ways. Not only was the pure cost of energy taken into account, but several human factors such as distance from residential areas, distance from roads and transmission lines were also included. Table 2.3.3.a displays the factors considered when creating a final siting map for Colorado. Weighting is used to allow for the economic impact of these factors, based on the change in cost of energy over the full range of each factor. Heavier weights indicate higher importance, as well as an increased effect on the outcome of the site ranking. By merging these weights with the previously discussed DEM data relating to exposure, the Colorado project created detailed maps of the wind speed over different areas, as well as maps of site suitability for wind turbine placement.

Table 2.3.3.a
FACTORS AFFECTING SUITABILITY RANKING (FROM THE BROWER COLORADO REPORT OF 1996)

Parameter	Range		Weight	
	Worst	Best	Absolute	Normalized
Wind speed (m/s)	6	11	1.59	0.600
Air density	0.75	1.10	0.35	0.132
Terrain slope	55%	0%	0.02	0.007
Cost-distance to transmission	188 km	0 km	0.23	0.087
Distance outside large towns	0	>16 km	0.05	0.019
Distance outside small towns	0	>8 km	0.05	0.019
Distance from any town	212 km	0 km	0.01	0.004
Distance from national park, forest, large lake or stream	0	>8 km	0.05	0.019
Land cover	Forest	Grass/shrub	0.10	0.038
Relative exposure	0.5	1.0	0.20	0.076
Total Weight			2.65	1.000

(Brower, 1996)

Iowa Project

Brower & Company's wind resource assessment of Iowa took place from September, 1996, to February, 1997, under contract to the Iowa Wind Energy Institute (IWEI). Unlike the Colorado project for which wind data from the national wind atlas was used for the wind resource assessment, the Iowa project used higher quality wind data from the wind resource map recently published by the UCS in which a GIS was used to refine wind speed estimates to reflect local terrain and vegetation characteristics. Maps with an estimated maximum uncertainty of nine percent were made for each of the twelve months and an additional overall map.

The Iowa study used 13 sites set up by the IWEI, the best publically available wind data for the state. Twelve of these sites recorded data for the two previous years (June 1994 to May 1996), while the thirteenth had data for a full year (June 1995 to May 1996). In addition, 8 National Climatic Data Center (NCDC) sites were used in the analysis. These sites were selected for proximity to Iowa, constant monitoring and anemometer height since 1965, and a more reliable ground mast anemometer mounting rather than rooftop mounting. The data was adjusted for factors including height and shadowing effects.

The IWEI site data was adjusted to better correlate to long term weather patterns using linear regression to correlate the data for each IWEI site with data from nearby sites to obtain long term information. While this extrapolation introduces a measure of error to the data, it allows the data taken over a short period of time to be used to evaluate long term trends. The NCDC sites were used as the source of long term climatological patterns.

Investigation of several parameters for relevence resulted in choosing three primary factors governing wind flow over Iowa: elevation, terrain exposure (the diffrence between the elevation at a particular spot and the average elevation of the surrounding area), and terrain roughness associated with land form. The wind field as represented by the data of the 21 total sites was fit to these parameters. Elevation and terrain exposure were found to be the most significant factors in the regression. Surface roughness due to land cover was found to be less important.

New Mexico Project

The main goal of this project, which took place from June 1996 to June 1997, was to produce the first wind energy resource map with a high level of geographic detail that can be applied to the selection of candidate wind sites. In contrast with the previous projects, those of Colorado and Iowa that used wind resource maps as wind data inputs, the New Mexico project used wind data obtained from real-time wind measurements from 124 sites across the state. The wind data was compiled by Richard Simon, a consulting meteorologist, who assigned a reliability rating from 0 (least reliable) to 5 (most reliable) to each of sites where wind data was recorded. Reliability considerations included questionable data summaries, short period of recording and poor documentation. All sites with a reliability rating of less than 3 were discarded before processing (41 sites). Sites close together were merged and a final outlier was discarded for a total of 67 sites used in the study.

The method chosen to extrapolate a wind field over the state of New Mexico was a multi-variate linear regression of the known wind data against a variety of GIS-derived parameters, including an interpolation function that served to blend the results for the plains and mountain regions in a smooth and consistent fashion. The dependent variables for the regression was the measured and extrapolated wind speeds at each site and the independent variables were parameters affecting these speeds, such as elevation, exposure, surface roughness and ridge suitability. The goal of a multi-variate linear regression is the development of an algebraic expression, which describes the behavior of the dependent variable (in this case, wind) as a function of the dependent variables over the domain.

TABLE 2.3.3.b
PARAMETERS CONSIDERED WHEN MAPPING (FROM BROWER NEW MEXICO REPORT OF 1997)

Four parameters were initially considered important for mapping across the state:

- Elevation
- Absolute and relative exposure
- Surface roughness
- Distance from Rocky Mountain front range

Two parameters were important only to the rocky mountain region:

- Ridge suitability (defined below)
- Upper air speed

Two regions within the state, the Rocky Mountain region and the flatter eastern plains, were considered to be different enough to require different analytical treatments (see Table 2.3.3.b). Distance from the front range (locus where elevation exceeds 1000 m) was introduced as an analytical treatment of the mountains' effect on weather patterns. Other areas clearly associated with the Rocky Mountain weather regime were included along with the mountains with a distance of zero.

Two parameters were introduced for the Rocky Mountain region. The first of these is ridge suitability, which is a single measure of the combined effect of ridge slope and orientation on wind acceleration, ranging arbitrarily from 0 (least suitable) to 1(most suitable). The second of the parameters exclusively important to the Rocky Mountain region is upper air speed, which is closely correlated to peak and ridge top speed.

In the end, the only independent variables kept in the regression were absolute terrain exposure and distance from the Rocky Mountain front range. Elevation and relative exposure were too closely coupled with absolute exposure to treat as separate independent variables. It was found that surface roughness length had no consistent relationship, probably due to the coarse resolution used. Roughness changes typically affect wind speed near the ground over a distance of 1-2 km and therefore wasn't of primary importance in characterizing a wind field over a much larger domain. Ridge suitability as used in the study was a relatively crude approximation and too closely correlated with exposure to treat as an independent variable upon final analysis.

The final results of Brower's report largely agree with the National Wind Atlas, but provide a more realistic model due to the refined technique. The multi-variate regression also provides more geographic detail leading to better turbine siting.

In the assessment of wind energy in New Mexico, consideration is also given to economic and social factors on turbine siting. The most important of these factors were which zones should be excluded based on land use, distance to transmission lines and connection cost, large enough contiguous area for a wind farm, and road access. Based on the wind resource map of the state and social and economic considerations, Brower listed a number of recommended wind turbine sites for the state and commented on the nature of several of them.

One recommendation for further work mentioned in the New Mexico report was the use of wind flow models (conservation of mass and conservation of momentum) to get a better overall picture of wind energy over a region including more accurate terrain effects. Michael Brower went on develop WindMap, a finite-element representation of the differential flow field equations.

<u>WindMap</u>

WindMap v2.20, Michael Brower & Company's newest release, is capable of taking GIS information and applying the continuity (mass conservation) equation to it. A digital elevation model, or DEM, taken with wind speed data and terrain type, can provide all the information needed for WindMap to calculate the flow of wind over a geographic area. The DEM displays the elevation, exposure, slope, and orientation to prevailing winds of an area. By applying the flow equations to a DEM, WindMap can approximate wind speed over mountainous terrain (making it good for analysis of wind patterns in New

England, and more specifically, western Massachusetts). WindMap is also able to take into account information from other GIS analyses, such as the location of population centers and power transmission lines. This makes WindMap even more useful for determining the possible locations for placement of a wind farm in Massachusetts just as Brower & Co. determined in Colorado.

2.4. Wind Energy in Massachusetts

Modern history of wind energy in Massachusetts begins in 1970 with the beginning of the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts in Amherst. The lab studies a variety of renewable energy systems and concentrates on wind. Two chief research programs are design of a New England offshore wind energy system (not yet implemented) and the design and construction, as well as continuing operation, of a wind turbine. The latter is located atop Mount Tom in Holyoke, MA and is rated at 250 kW (the largest ever installed in Massachusetts). The turbine has supplied power to the Mt. Tom Ski Area, though its primary purpose is research into the nature of wind energy systems and educational projects. The RERL is interested in all areas of wind energy research (http://www.ecs.umass.edu/mie/labs/rerl).

Other projects of the RERL include a resource assessment and feasibility study of wind energy on Thompson Island in Boston Harbor. Wind velocity data are collected at two levels on a 40-meter tower and will be analyzed by the simulation program Hybrid2. Hybrid2 was developed by the RERL and the NREL (National Renewable Energy Laboratory) to analyze a wide range of hybrid power systems. The data will also help to characterize the renewable resource base of coastal regions in Massachusetts. The RERL also seeks to analyze wind turbine selection for the town of Hull, MA, which seeks to replace an older turbine at their high school. The final wind turbine is expected to have a capacity between 50 and 250 kW.

Since 1996, the RERL has established a program of wind resource assessment in western Massachusetts with the sponsorship of the Northeast Utility Company. Five mountaintop sites, approximately 40 km apart, were investigated. Wind velocity time series data were taken at several elevations and analyzed in an effort to accurately model the wind characteristics of the region (http://www.ecs.umass.edu/mie/labs/rerl).

AllEnergy has begun work on a 7.5 MW wind power facility on Brodie Mountain. This will be the largest wind energy project east of Chicago. It was supposed to have begun operation in summer, 1999. The site was selected since Brodie Mountain was already developed for skiing, so the addition of a wind energy facility only affects the aesthetics slightly. A series of public meetings were and are being held with AllEnergy representatives and the local population and officials. This facility is part of the AllEnergy ReGen program, a program designed to sell and develop clean energy. AllEnergy is a subsidiary of NEES. (http://www.allenergy.com)

The Richard Wheeler Wind Farm was constructed in Princeton, MA, in 1984 and is owned, operated and maintained by the Princeton Municipal Light Department (PMLD). The wind farm consists of eight 40 kW wind machines and produced approximately 180,000 kWh in 1998. (PMLD, "1998 Report to the Princeton Municipal Light Department", 1998)

The largest operating wind turbine in Massachusetts is located on the summit of Mount Tom in Holyoke. The University of Massachusetts acquired this 250 kW turbine from a California wind farm and it is primarily used for research and education. In 1984 the School Department in the Town of Hull, MA received a grand from the Division of Energy Resources for installation of a 40 kW wind turbine at the local High School. Due to weather damage, the Hull facility is currently out of service and the town is looking to replace the old turbine with a new one.

Renewable energy, including wind power, has been mandated by legislation for all electricity suppliers that serve Massachusetts. In addition to tax breaks offered to help cover wind turbine installation costs, the DOER will implement a Renewables Portfolio Standard (RPS) requiring a certain percentage of sales of power from new renewable energy sources, beginning in 2003. This bill has been signed into legislature as part of the Electric Utility Restructuring Act in 1997. The percentage required will increase annually, which may increase the demand for wind energy siting and research in Massachusetts. (http://www.state.ma.us/doer/programs/renew/renew.htm, 1999)

2.5. Economic Analysis of Wind Power

While its ecological cleanliness makes wind power attractive, its perceived economic shortcomings have prevented its adoption as a large-scale energy source in the United States. New advances in wind power continue to improve its economic standing as a possible commercial power source. These advances include the continual increase in performance, reliability, and cost effectiveness of modern wind turbines. A better understanding of the full impact of the implementation of wind power makes it more appealing by exposing new advantages while shattering previously held misconceptions that supported the continual use of conventional energy sources such as fossil fuels. A proper economic analysis is vital to understanding the true advantages and disadvantages of wind power, as well as its feasibility as a power source for the U.S.

This section begins by analyzing the factors involved in determining the cost of electricity generated by wind turbines, such as capital costs, operation and maintenance costs, and tax credits. The second part of this section examines the economic feasibility of wind energy by showing a comparison of estimated future costs between electricity generated by fossil fuel burning (mainly that of a coal-fired plant, being the cheapest of all other fossil fuels), and electricity produced by the use of renewable energy sources.

2.5.1. The Cost of Wind Energy

The economics of wind energy are dependent on several factors. The total cost of wind energy depends on the going rate of electricity in the region (in terms of dollar per kilowatt hour), the upkeep on the facility (including personnel costs), the cost per kW, and the capital investment necessary. The future value of money must also be considered, as well as the plant life, for a complete economic picture over time.

A comprehensive measure of the costs of wind energy is the life-cycle cost of energy (CoE), which is derived from the installation cost, annual generation, operation and maintenance cost, and the fixed charge rates (a factor accounting for the cost of taxes, insurance, and the interest of debt). The following equation describes CoE (from NWCC, 1997):

$$CoE = \frac{(ICC * FCR) + (O\&M) + (LRC)}{kWh / year} (cents / kWh)$$

where ICC is the installed capital cost (cents), FCR is the annual fixed charge rate (percent), O&M is the annual operations and maintenance costs (cents), and LRC is the levelized replacement costs (cents). The levelized replacement costs deal with overhauls and major repairs over the lifetime of the installation divided over the number of years of operation. This measure, in conjunction with the life of the system, gives a good picture of energy cost over time. The life span of a typical wind turbine system is 20-30 years.

The capital cost of wind energy systems, which includes the cost for land, access roads, distribution lines, and construction, has decreased by a factor of 2.5-3 between 1980 and 1995. Overall wind energy cost has decreased by 80%. The decline has been fairly steady and will most likely continue to fall in the future. As Capital cost is much larger for wind-turbines than most conventional power systems, the diminishing of this prohibiting factor increases wind power applicability. (NWCC, 1997)

Modern turbine maintenance costs are under 1 cent per kWh. A typical division of maintenance cost would be unscheduled maintenance visits (75%), preventive maintenance visits (20%), and major overhauls (5%). Most other operating costs are negotiated financial agreements, such as property use, insurance, administrative costs, and transmission access fees. (NWCC, 1997)

Another important factor in wind energy economics are tax credits offered to help compensate wind energy facilities. The Federal production tax credit amounts to 1.5 cents/kWh (adjusted for inflation), lowering the cost of wind energy to 3.3-3.5 cents/kWh in 1996 (AWEA on-line documents). In addition, the state of Massachusetts offers tax compensation for end users, helping to cover installation and negating property taxes for private users and providing tax deductions for corporations (DOER on-line documents). The financing of wind turbines through government compensation helps to reduce the relatively large capital investment and make wind power generation more practical.

The economic analysis of wind energy is also dependent on whether the wind generators are connected to the utility grid, or not. Wind power can be produced by distinct categories of users: individuals and corporations electrically isolated from the main power-grid, individuals and corporations connected to the power-grid, and the power utilities. The first class of users must generate all of their power from wind and other power sources. In the second case, when shortages of self-generated power occur, the main power grid supplies the electricity. In most cases, when excesses of energy occur, the utility company allows its customers to sell energy back to the company at cost. The class of user gives a general overview of the economics likely involved, whether micro or macro.

2.5.2. Economic Comparison of Renewable Energy Sources and Fossil Fuels

Within the last fifteen years, wind power has emerged as one of the most commercially competitive renewable energy sources (Gipe, 1995). Wind power's use has been retarded due to its slight economic shortcomings when compared to cheap fossil fuels. Opponents of wind power quickly point out the current cost of wind power as being higher than that of conventional power sources, yet they ignore current trends that will continue to affect the total cost of wind power into the future. These trends, when fully appreciated, show great promise for wind power in the long-term economic analysis.

According to the Center for Energy and Economic Development (CEED), which is an organization with pre-coal interests, a small increase in the contribution of non-hydro renewable energy sources, from 2% of total electricity supplied today to 4% in 2010, will cost the US an extra $52 billion above the projected electricity market costs. The figures were published in a report released in April of 1995 entitled "Energy Choices in a Competitive Era: The Role of Renewable and Traditional Energy Resources in America's Electric Generation Mix".

In response to these claims the National Renewable Energy Laboratory (NREL) was commissioned by the US Department of Energy (DOE) to review the assumptions contained in the report. They concluded that the study made by CEED was based on faulty data and assumptions that we will discuss below.

The NREL estimated that the extra cost for the renewable development would only be $1.9 billion over the next 15 years, or an average of a little bit more than $100 million per year. This figure is "less than one tenth of 1% of the total annual revenue of the US electric utility industry" according to NREL. The National Renewable Energy Laboratory also predicts that the wind energy technology will become more economic than coal during this period.

The difference in the estimated future costs for renewable energy technologies that appears in the two independent studies exists because the CEED analysis relied on data that overstated the cost and performance advantages of coal-fired plants. They have also used high cost estimates (unjustifiably) for renewable energy technologies and have assumed no improvement in technology and performance costs throughout the 15-year analysis period.

The NREL used renewable energy cost data obtained from the DOE, data that takes into account expected future technology improvements, which reduces the CEED estimate by about $31.6 billion. Also, since renewable energy technologies will become more cost competitive, non-hydro renewables could be expected to supply a much larger fraction of the future power market than the 4% assumed by the CEED.

To arrive at the $52 billion cost estimate, the CEED calculated the difference between levelized cost for a pulverized coal-fired plat (considered to be the cheapest generation potion), and the weighted average cost of a mix of non-hydro renewable technologies. These renewable technologies were divided into two groups (?), ones that involved combustion processes (biomass and waste to energy [WTE]), and those that are "naturally occurring" (geothermal, photovoltaic, solar thermal, and wind).

CEED assumed that renewable energy generation would grow from $75 billion kWh to $180 billion kWh in the 15-year period, or 2.3 to 4.5% of the total US electricity generation by 2010. The annual increase was multiplied by the cost differential (calculated by CEED) to obtain an annual cost difference. The sum of these annual costs difference yields the $52 billion estimate.

As you can see in Table 2.5.2.a, the CEED has ignored taking into account future technology and cost improvements over the 15-year period. NREL used in their study renewable technology costs prepared by DOE (see Table 2.5.2.b), which incorporated expected technology and costs improvements through year 2010.

TABLE 2.5.2.a

CEED BASE CASE SCENARIO (NREL "True Cost of Renewables")

	Levelized Cost of Energy					Annual Growth	Cost Diff.
		(Cent/kWh)				(Bill kWh)	(Bill.$)
Year	Coal	Biomass	Wind	Geothermal	Solar		
1995	4.2	11.6	6.8	8.8	21.0	n/a	n/a
2000	4.2	11.6	6.8	8.8	21.0	5	1.5
2005	4.2	11.6	6.8	8.8	21.0	8	4.4
2010	4.2	11.6	6.8	8.8	21.0	8	7.5
TOTAL							52.0

TABLE 2.5.2.b

NREL RECALCULATIONS (FROM NREL "True Cost of Renewables")

		Levelized Cost of Energy				Annual Growth (Billion kWh)	Cost Differ. (Bill $)
Year	Coal	Biomass	Wind	Geothermal	Solar		
1995	5.4	8.5	5.3	5.2	10.5	n/a	n/a
2000	5.4	8.1	4.1	4.0	8.6	8	0.5
2005	5.4	7.5	3.9	3.8	8.1	8	1.1
2010	5.4	7.2	3.5	3.7	8.1	8	1.1
Total:							11.8

2.6. Societal and Environmental Considerations

Wind energy is currently considered the most viable source of renewable energy to replace fossil fuel in the generation of electricity for the future, as the economic analysis section of this report discussed. The belief that wind power is "pollution free" is not far from reality, even when drawback such as land disturbance, visual and noise nuisances and the killing of bird populations are considered. To assess its advantages over conventional power sources, this section will investigate the impact that wind power has on society and the environment.

2.6.1. Wind Farms' Impact on People

Wind power development has led to environmental controversies. A proposal to build a wind farm on Redington Pond Range near the Appalachian Trail (AT) in western Maine has forced some local environmental and recreation groups, including the Appalachian Mountain Club (AMC), to choose between scenic vistas and renewable energy. The plans were to mount 30, 180 foot-high windmills along a mile and a half of the Redington ridge with an output power of 60 million kilowatt hours a year, enough to provide 9,000 homes with renewable energy (AMC Outdoors, March 1999). In the fall of 1998 the local environmental and recreation groups decided to oppose the project because the wind farm would be visible from the AT and could cause erosion and disrupt wildlife habitat.

Experience has shown that people attitudes quickly change once a wind farm has been installed. When plans for building the first British commercial wind plant were made, it had encountered strong opposition and it took several years before local planning board approval was granted. A survey conducted before the farm was built showed that the majority of the nearby area residents believed that the wind turbines would spoil the scenery and create noise pollution. However, with technologies available today, such as computer-generated rotor designs and appropriate sites determined by advanced computer software, these noise emissions and other aesthetic concerns have been mainly dealt with. A follow-up survey conducted after the installation of the farm, showed that the number of residents who believed that the wind farm spoiled the landscape had dropped by 28%, and 80% of those surveyed found that noise was not a problem (12% were unsure) (Gipes, 1995).

2.6.2. Public Opinion of Wind Power

A growing awareness of the impacts that fossil fuel and nuclear power generation has on our environment has made renewable energy alternatives attractive to the general public. A national public opinion survey conducted after the 1996 U.S. elections found broad support, from both political parties, for federal funding and tax incentives to promote renewable energy. Sixty-six percent of the respondents gave the Department of Energy's renewable energy and energy efficiency research and development programs, their highest funding priority. Also 31% indicted that nuclear power research and development should be the first program subjected to budget cuts, followed by 21% that said funding for fossil fuels research and development should be reduced (AWEA Wind: Public Acceptance, 1996).

2.6.3. Wind Farms' Impact on Birds

It has been estimated that hundreds of birds are killed annually in the US by turbine collisions. One site in particular is the Altamont Pass, CA where the wind plant was inappropriately sited in the middle of the golden eagles migratory flight paths (National Audubon Society, 1993). A study conducted by BioSystems, a contractor hired by the California Energy Commission (CEC), tried to determine the exact number of killed birds, the reasons for the deaths, and the measures that need to be taken to prevent further deaths. The study estimated that wind turbines at Altamont Pass alone were killing 160-400 birds per year, most of which were birds of prey. At a site in Tarifa, Spain, numerous bird deaths led to the closure of an entire wind farm. This problem was solved by removing an illegal garbage dump from the base of one of the turbine towers (Amit Romen-web based document "Will the US Harness the Wind?"). Besides the placement of windmills on more appropriate sites, a solution found to reduce the number of birds stroked by the blades of turbines is to set up perches on nearby anemometers. At a height of approximately 10 meters, these devices give birds an alternative to the turbine towers.

Unfortunately, all energy sources kill birds to some extent. The Exxon Valdez oil spill alone killed from 375,000 to more than 500,000 birds, far more than any other oil related accidents. If BioSystems' estimates are correct, it will take wind turbines in the Altamont Pass 500 to 1000 years to kill as many birds as the Exxon Valdez (National Audubon Society, 1993).

2.6.4. Ecological Advantages of Wind Power

Wind energy represents a clean alternative for generating electricity. Every 10,000 MW of wind capacity installed will reduce approximately 37 million tons of carbon dioxide emissions annually if it replaces coal power, or about 23 million tons if it replaces generation from the U.S. fuel mix (Amit Romen-web based document "Will the US Harness the Wind?"). We pay a heavy environmental cost for our current reliance on the fossil fuel generated electricity. Despite the considerable progress made in pollution control technologies for the past 20 years, the power plants are still the largest polluters in the Unites States. They are responsible for 66% of sulfur dioxide emissions, 35% of all carbon dioxide emissions, and 21% of all the mercury released into our environment. As a result, there is a lot to be gained from widespread adoption of wind power. Financially, the government spending on the environmental and health costs associated with conventional electricity sources would decline, since it pays the majority of the costs for environmental clean up efforts. The government spends millions of dollars on acid rain moderation programs and it assumes great risks in the case of nuclear power plant accidents. Also, since wind energy is a clean source of renewable energy, it can help reduce the greenhouse gases emitted into the atmosphere. By installing 30,000 MW of capacity by the year 2010, would ensure a reduction of the greenhouse gas emissions by 18%, or approximately 100 million tons.

2.7. Conclusions of Literature Review

When all the facts about wind power are taken into account, and benefits and costs are weighted against each other, there is a great tendency to believe that we have only to benefit by encouraging an increase into the energy mix for electricity production. This project's preliminary research has shown that wind power has consistently served mankind throughout the ages, while trends seem to indicate that it will continue to do so in an increasingly efficient manner in years to come. Current understanding of aerodynamic theory seems to indicate that the northeast United States holds potential for wind power development. GIS systems seem to be the most effective manner of information processing when dealing with the vast amounts of data necessary to calculate wind power density over rocky terrain. Economic analysis shows wind power to be highly competitive with fossil fuel resources such as coal and oil, as well as other alternative energy sources such as biomass and geothermal, with promise of increasing economic efficiency in the future. While some small groups still oppose the development of wind power for environmental and aesthetic reasons, wind power continues to make up for these shortcomings by proving itself to be a clean power source with zero fuel costs. For all of these reasons, this research has shown wind power to be a viable clean energy source for Massachusetts, with easily accessible siting technology ready to be exploited.

3. Methodology

Efficient and accurate wind turbine siting is vital to the development of wind power. As mankind enters the next millennium, fossil fuel resources will continue to dwindle; alternative energy sources such as wind power will enjoy interest from both corporate America and the public. It is the goal of this project to determine and analyze the wind power resources of Massachusetts, and generate maps of wind power density. The generation and subsequent analysis of these wind maps will directly impact this socially relevant issue.

Massachusetts was selected for several reasons. Preliminary assessments from several sources state that Massachusetts has good wind energy potential. As part of the Massachusetts Electric Utility Restructuring Act, companies providing electricity to Massachusetts are required to have a growing percentage of their electricity generated by new renewable energy sources starting in 2003. The Division of Energy Resources (DOER) is interested in mapping wind resources in Massachusetts and has agreed to provide data necessary to the project.

Once the wind resource maps are generated, analysis will be performed in order to assess the best sites considering wind power density as well as social and economic factors. These will include location of utility lines, land ownership, aesthetics, and other relevant factors. Based on the wind maps and analysis, a report will be written on the feasibility of wind power in Massachusetts. The report will be made available to the DOER, Brower and Company, and other interested parties.

There are three distinct phases in this project: the preliminary investigation, the generation of wind maps, and the subsequent analysis of the maps. The preliminary investigation will focus on researching the appropriate programs and gathering the relevant data. The project will then proceed to generate wind maps, utilizing said programs. Finally, through analysis, this project hopes to gain valuable insight into wind power siting in Massachusetts. Estimated expenses for the project have been tabulated and explained at the end of this report. The three phases of this project will be implemented in B term of 1999 and C term of 2000 at Worcester Polytechnic Institute.

3.1. Preliminary Investigation

In the preliminary stage, this project will determine what data and maps will be necessary for the completion of its objectives. These data will be those required to form an accurate continuity equation as it applies to wind. Factors such as wind speed, land cover, and elevation have already been outlined in this proposal. These will be assessed and any additional factors aiding in the physical modeling will also be accounted for in this stage. This stage will also include the identification of social factors influencing the applicability of wind power in Massachusetts. These are expected to closely parallel the social factors taken into account by Brower & Co.'s Colorado project previously mentioned. Throughout the entire preliminary process, this project will provide insight into the GIS approach to wind turbine siting, as well as identify flaws in the current method.

The capabilities and requirements of both WindMap and IDRISI will subsequently be investigated, although there is overlap here since determining the data necessary may come in part from program parameters. The interface and capabilities of each program will be learned through manuals and on-line support. WindMap and IDRISI both have in-depth tutorials provided with the software. The technical support of Michael Brower will also be enlisted.

The next step of the preliminary phase is to obtain the data. The DOER has offered some relevant data, including DEMs of Massachusetts. Other GIS data is available from the United States Geographic Survey (USGS) at their web site. The cost of these maps is estimated to consume lion's share of this project's budget and has been outlined in the budget (section 3.4).

3.2. Wind Map Generation and Input

Once the data are available, it will be possible to generate the wind maps. WindMap is a software package created by Michael Brower that uses GIS data to predict wind resources in a region by solving the continuity equation. WindMap was chosen because it takes into account all of the relevant factors necessary to describe wind resources in Massachusetts. Michael Brower has demonstrated the effectiveness of the theory behind WindMap by working on a similar project in Norway. It was also chosen because it seems to be one of the only two computer programs (a similar wind-flow model called WASP was developed in Denmark) in the current generation that has wind mapping capabilities. The program is easy to use and allows a large amount of user control. Numerical modeling programs are currently rated accurate to within 10%. In order to better match measured wind data, WindMap has a user-defined weight on the output.

It may be necessary to use IDRISI to manipulate the data before entering it into WindMap, as WindMap has limited GIS capabilities (it can generally only read existing maps). IDRISI is a fully functional GIS program, which might fill any gaps where WindMap is less than sufficient. With the data in the proper format, WindMap will be used to generate wind power density maps. Initially, maps of small regions such as individual mountains will be made. The construction of these maps will provide an opportunity to perfect our utilization of the software and optimize the efficiency and accuracy of the map generation process. Once the wind map generation process is perfected, maps of the entire state will be concatenated and the final wind maps generated. The process up until this point will take one term.

The input that WindMap requires to generate maps of wind speed can be broken into two major categories: data and run parameters. The primary data are digital elevation models (DEM) and experimental observations of wind speed. Maps of roughness can also be applied for more accurate results. Run parameters consist of geometry constraints governing the area covered, atmospheric controls, power controls, initialization settings, and iteration control. WindMap provides help files and tutorials defining each of these inputs in relative detail, explaining to the user how to manipulate them, and what their effects on the final product will be. In this section each of these inputs will be explained, and their importance to the project examined.

3.2.1. Data

All of the inputs required by WindMap are vital to generating accurate results. Most of the data inputs of WindMap do not have defaults and must be provided by the user before any maps can be generated at all. The inputs requiring user manipulation include a digital elevation model (DEM), wind observations, and the optional roughness maps. If roughness maps are not supplied, WindMap will assume a constant roughness to approximate its effect. Due to their importance to the final results obtained by this IQP, we will explain these inputs and the methods used to obtain them in detail.

Digital Elevation Model

The first, and possibly most important input for GIS-based Wind Resource assessment is a Digital Elevation Model. The DEM provides a map of elevation thereby giving it all of the data that it needs to account for both the total and relative exposure of the terrain being mapped over. Because wind speed is highly affected by these two factors, an accurate DEM is essential to producing high quality maps of the wind speed over a specific area.

The USGS offers 250,000:1 scale DEM's for free download, organized in approximately rectangular sections called quadrangles. They are only approximately rectangular as a result of the distortion caused by the earth's ellipsoidal shape. The USGS divides each quadrangle into two files, each containing the eastern and western half of the quadrangle, respectively. These maps, with a small amount of manipulation, satisfy WindMap's requirements for DEM input.

In order to construct a full DEM of Massachusetts, it was necessary to append multiple rectangular sections to each other. Since our focus is mainly on the western half of Massachusetts, more specifically Berkshire County, we constructed our rectangular map by appending maps of the following quadrangles: Albany-West, Albany-East, Boston-West, and Boston-East. In order to accomplish this merging, we used Idrisi32's CONCAT utility. Placement type was selected as "Automatic Placement Using Reference Coordinates." This would account for and correct the overlap, if any, in the separate maps of each half quadrangle. Concatenation type was selected as "Main Reference Image Transparently Covers the paste images." It was then a simple matter to have the CONCAT utility concatenate the smaller maps into one single map.

After concatenation of the maps was complete, the next task was to convert it from the degree based system (a holdover system from Idrisi Version 2.x referred to as "Plane" in the image's document file) into a meters-based coordinate systems. Because Idrisi32 was unable to recognize the system used by the USGS we used Idrisi Version 2 to convert the map from the older reference system into Latitude and Longitude using the PROJECT utility. PROJECT takes both an input filename and an output filename (as well as reference systems for each as input), and outputs the map to the output file, with the desired reference system. After the map was converted to Latitude and Longitude, we were able to then further convert it to a state plane coordinate (SPC) system using Idrisi32. The exact reference system used was Idrisi32's spc83MA1. We once again used the PROJECT utility, which changed little between versions of Idrisi. After this conversion, we finally had a DEM in a meter-based system that WindMap could deal with, which also covered the entire region that this IQP dealt with.

In order for this map to function as a DEM in WindMap, we had to determine the map resolution that would be within the mathematical computation power of our PC and WindMap. Higher resolutions result in more data for WindMap, thereby increasing the amount of computational time required by each run, sometimes resulting in complete failure to return useful data. In the DEM obtained after concatenation, each row and column was only 90 meters wide. While this provided great detail, it made the number of rows and columns needed to cover an area very large.

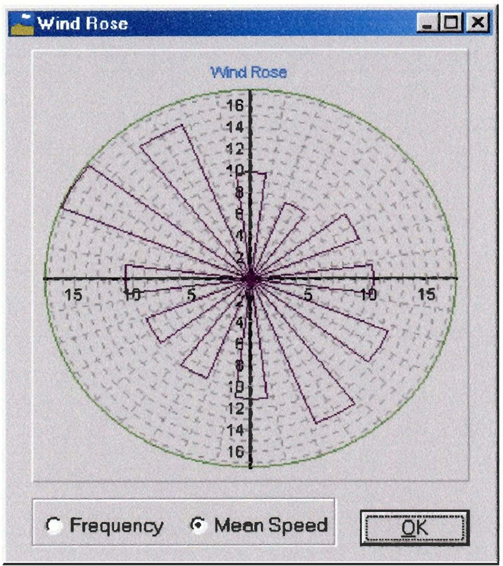
To change the resolution we used Idrisi32's CONTRACT utility, which generalizes an image by reducing the number of rows and columns while simultaneously decreasing the cell resolution. We used a contraction factor of 10 for both X and Y. This resulted in an output DEM with a grid size of approximately 900 meters. It also reduced the number of rows and columns by the same factor of 10, allowing us to cover a much larger area in the maximum number of rows and columns allowed by WindMap (maximum of 400). Since our main focus is on only the western half of Massachusetts, we then used Idrisi32's WINDOW utility to isolate the western half of the DEM produced by the CONTRACT utility. This resulted in a map of fairly high resolution (900m grid scale) that covered the entire western half of Massachusetts in a number of rows and columns.

Wind Data

The next crucial inputs are the wind speed and direction data taken from several different stations throughout the area. WindMap requires that at least two observation stations be entered into it in order to formulate the most likely model of initial winds over a section of terrain. For purposes of discussion, the wind data can be subdivided into surface data and upper air data. Surface data comes from wind observation stations located near the surface of the terrain, while upper air data comes from weather balloons that rise to a given pressure level, and observe the wind at that altitude. Both upper air and surface wind data provide valuable input for WindMap, and a combination of both results in the most accurate results.

WindMap can take wind data in several forms: a single average wind speed and direction, or a wind rose of 8, 12, or 16 directions. We chose to break down our data into 12 direction wind-roses (Figure 3.2.1.a). By this we mean that the data, which includes direction originally in a range between 0 and 360 degrees, was simplified into wind speed and frequencies from only 12 directions (0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, and 330 degrees). 12 directions offered more detail and a better approximation of real data than only 8 directions, while offering quicker and easier computations than those required by attempting to use 16 direction wind-roses.

Figure 3.2.1.a A 12-Direction Wind-Rose



Surface Data

The University Of Massachusetts Amherst provided data consisting of wind-speed and direction from 5 surface stations in Berkshire County: Century Cable Tower in Great Barrington, Borden Mountain in Savoy, Brodie Mountain in New Ashford, Burnt Hill in Heath, and Petricca Tower in Washington (MA). In order to gain a proper sampling of data through all four seasons, we concatenated all of the wind data for each site over the entire year from May of 1998 through June of 1999. These specific dates were selected so that the wind measurements from all five surface stations shared the same time period. Each site's data came in the tab-limited format that generally included date, time, wind speed and wind direction at both 25 m and 40 m. We chose to use wind data from 40 meters above the ground, as it was less prone to interference due to the air's friction with the surface, and therefore better approximate free-stream wind. Lower heights risked interference from local features too small to be accounted for within the resolution of the

DEM.

Following the collection of the data, they were processed as a spreadsheet to produce the wind-roses. First, all records with a speed of 0 (periods of calm and/or freezing of the anemometers) were separated and the number of these records was recorded. These records represented the period where the wind was calm. The remaining data were then sorted by averaging the wind-speeds occurring in each of the twelve directions of the wind-rose, with each direction encompassing all of the speeds occurring in any direction between 14 degrees below the direction's heading, to 15 degrees above the heading. For example, all records with a direction greater than 345 degrees or less than 16 degrees were averaged together to obtain a wind speed for a Northerly wind direction (i.e. 0 degrees). The number of records going into each direction was also recorded in order to know the relative frequency of wind in each direction. The number of records in each direction, when divided by the number of total records in the original data, produces this frequency. The resulting speeds and frequencies for each direction were finally entered into WindMap for each site.

Each site's coordinates were provided by the University of Massachusetts at Amherst in Latitude and Longitude; however, in order to properly place the stations within WindMap, it was necessary to convert those coordinates into the same coordinate system as we used in the DEM. Text files were created for each station, with each file containing the X coordinate (i.e. longitude), Y coordinate (i.e. latitude), and a zero for the Z coordinate (since elevations were included in the DEM). We next used Idrisi32 to import the files as a software specific format called XYZ_Idrisi. It converted each file into a simple vector file of only one point, the coordinate. Viewing the files in Idrisi32's Metadata viewer presented each point as having X values and Y values equivalent to both the maximum and minimum values given in the metadata for each vector file. These coordinates were then entered into WindMap for each respective site.

The elevation and location of each surface station is summarized in Table 3.2.1.a, and the wind roses (mean speeds) of each station are shown in Figure 3.2.1.b.

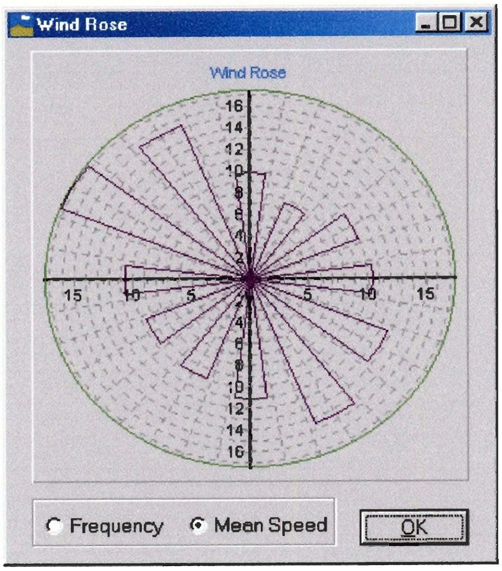
TABLE 3.2.1.a

ELEVATION AND LOCATION OF THE STATIONS OF BERKSHIRE COUNTY

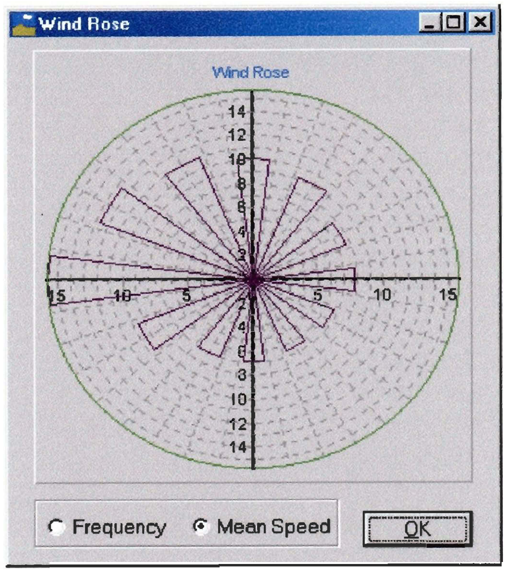
Station Name	Elevation(ft)	X Location (in spc83MA1)	Y Location
Century Cable Tower	1790	51179	881834
Petrica Tower	2000	63391	905291
Burnt Hill	1710	93018	934456
Brodie Mountain	2590	54668	928951
Borden Mountain	2490	74318	929656

Figure 3.2.1.b Mean Wind Speeds from 5 wind stations

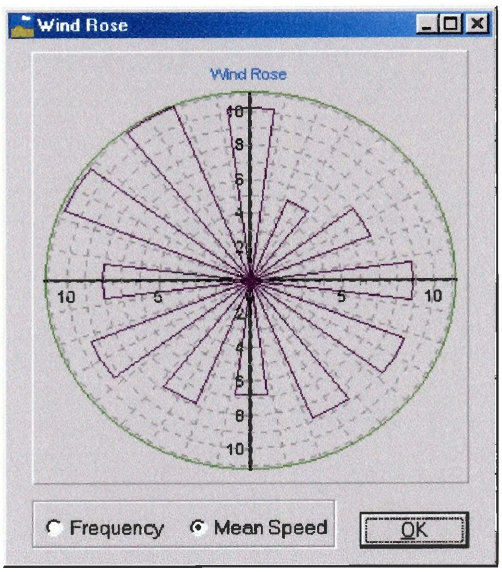
a. Century Cable Tower –



b. Burnt Hill –



c. Petricca Tower –



d. Brodie Mountain –

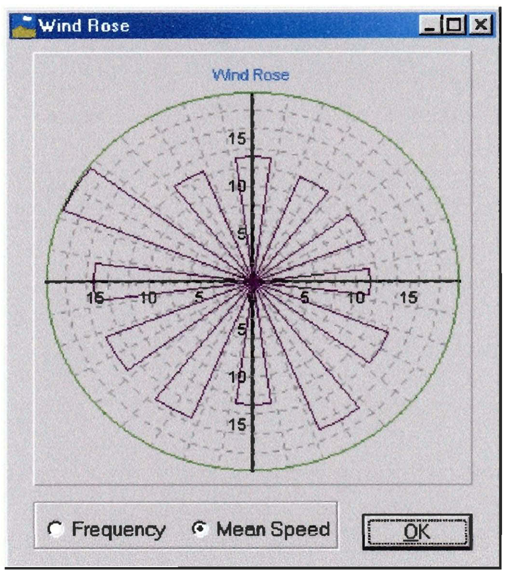
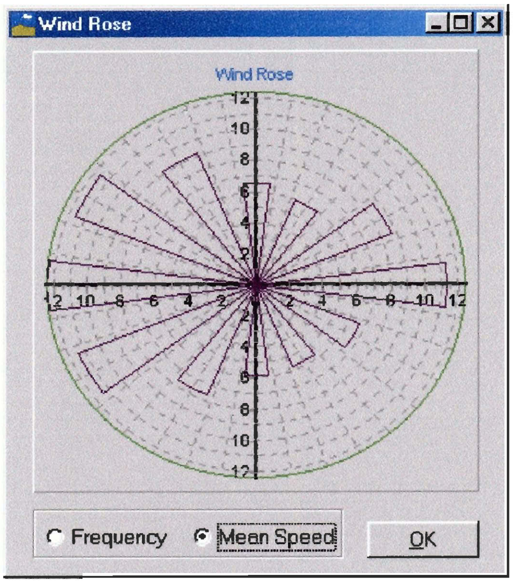


Figure 3.2.1.b (cont.): Mean Wind Speeds from 5 wind stations

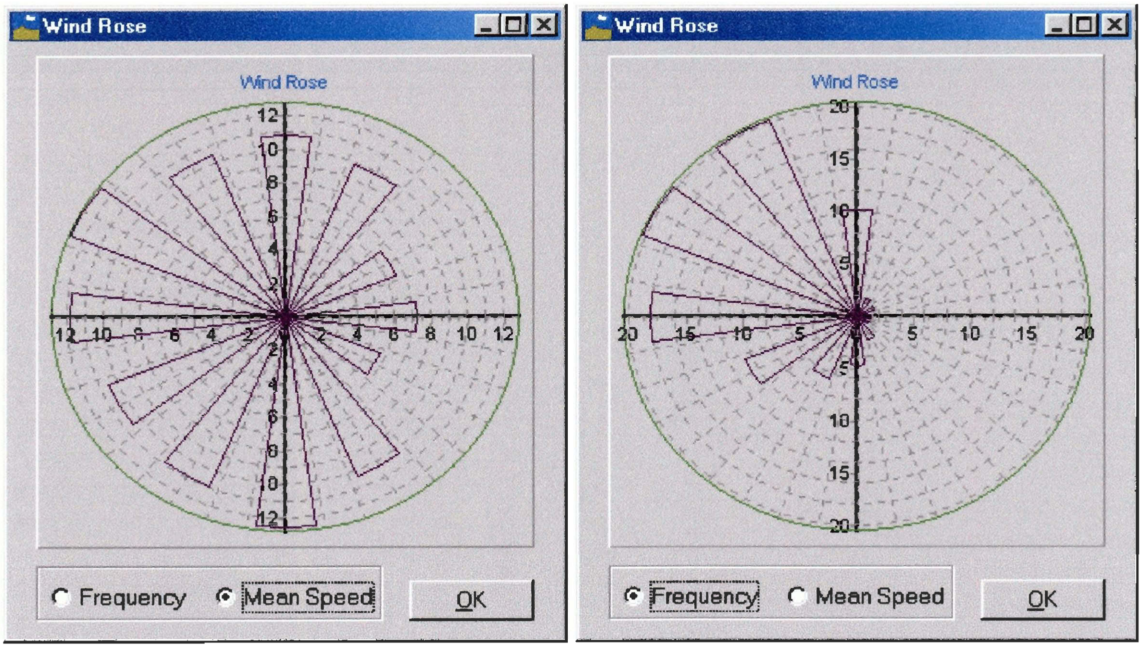
e. Borden Mountain



Upper Air Data

Upper Air data were collected from the Albany Radio Sounding Post, and its processing was completed in nearly exactly the same manner as that of the Surface data. The one difference was that instead of needing to deal with a singular location that the data was supposedly coming from, we needed to locate the data from a particular height. Here an actual location within an X Y reference frame is not needed, as the upper air wind data is expected to be relatively uniform over the entire section of terrain. Since weather balloons are designed to go up to a certain pressure, the actual height above the ground varies considerably. We therefore had to ignore the extreme upper and lower ends of the dataset located approximately past the inflection points, and average the majority into one speed in each direction, at an average height of 1467 meters. As it can be seen in Figure 3.2.1.c, the largest measured wind speed of Albany's upper air data is of approximately 12 m/s predominantly coming from a Northwesterly direction.

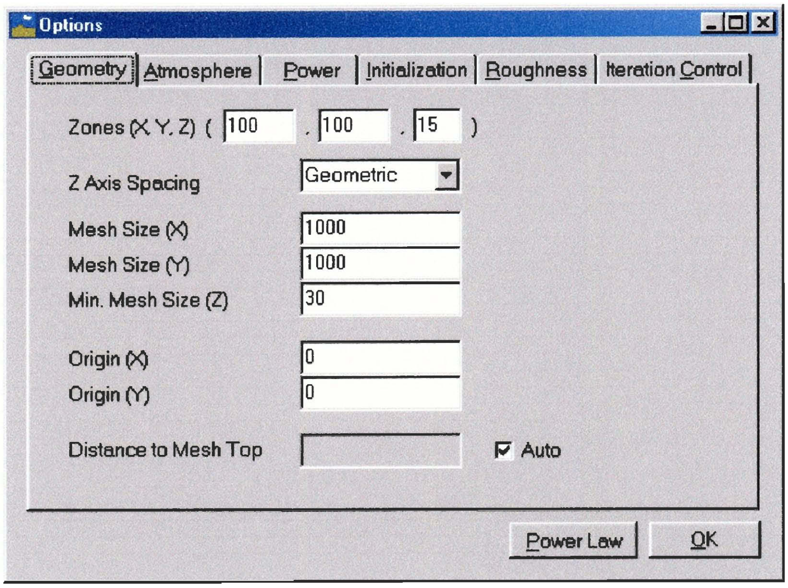
Figure 3.2.1.c Mean Speed and Frequency of Upper Air Data



3.2.2. Run Parameters

WindMap offers a variety of controls that the user can set in order to optimize the accuracy of the maps produced. The run parameters all have default values that should result in fairly accurate wind maps, although their results will not be optimum. By changing the parameters, it is possible to generate maps that fit more closely to actual data recorded in the real world. These parameters include geometry constraints governing the size and shape of the area covered by the DEM, controls governing the atmospheric properties, controls involving power density and output, initialization settings, roughness controls, and iteration controls. In order to fully utilize the power of WindMap, the user must have an understanding of these parameters, and their corresponding effects on the resultant maps produced.

Figure 3.2.2.a: Geometry Constraints



The dimensions of the grid used by WindMap's calculation model are set in the Geometry menu of WindMap's options (see Figure 3.2.2.a). They vary depending on the dimensions of the DEM used. However, when using DEM files in Idrisi, ERDAS, or SURFER format, the size of the grid cells are entered automatically. Only when using a DEM represented as an ASCII text file does WindMap require these values to be changed. The total number of grid cells in the X and Y directions is limited to 300 in the standard version of WindMap, and increases to approximately 400 in the big memory version. The maximum number of cells in the Z direction can take on values between 15 and 25, with higher numbers of cells resulting in greater accuracy, but longer computational time requirements. To encompass a map covering the quadrangles over the western half of Massachusetts, we utilized 201 columns, 120 rows, and 25 levels in the Z direction. This map was then further cropped to a final size of 166 columns, and 95 rows. This was necessary due to the limited land-use data available for construction of a roughness map. We wished to have accurate roughness values for as much of the terrain mapped as possible. A map of this size has a resolution of approximately 909 meters, and has enough vertical levels to properly deal with the mountainous terrain of western Massachusetts.

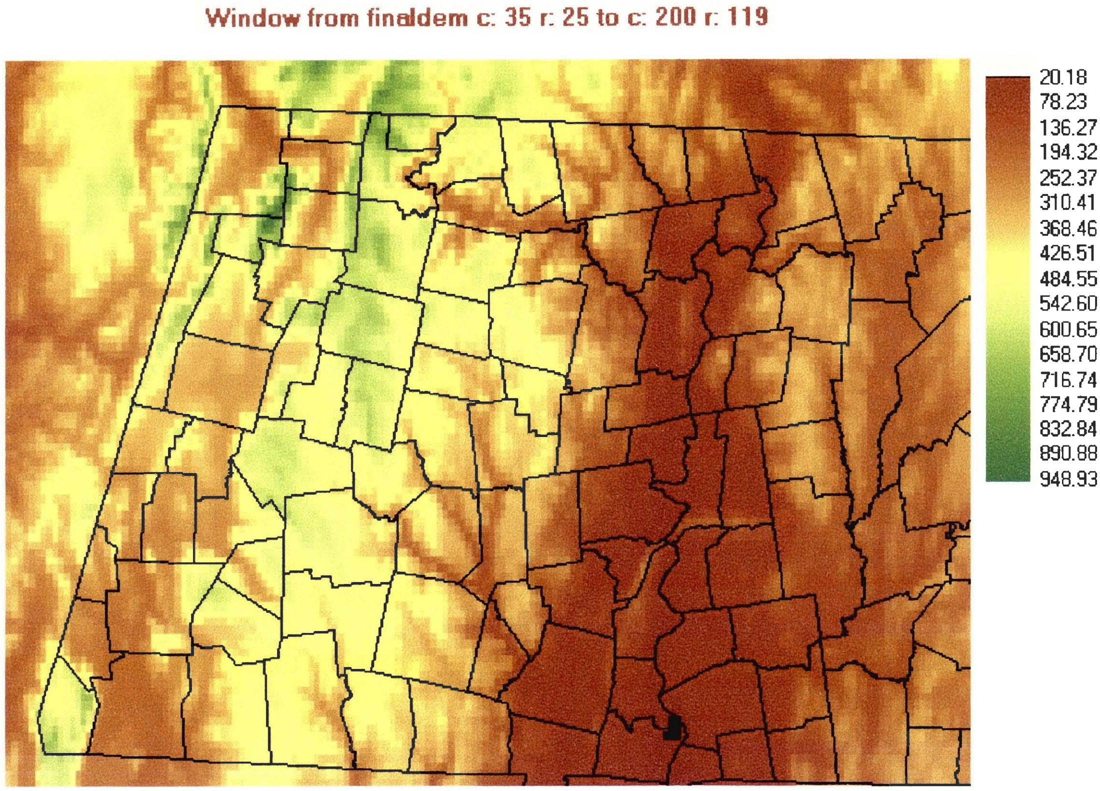
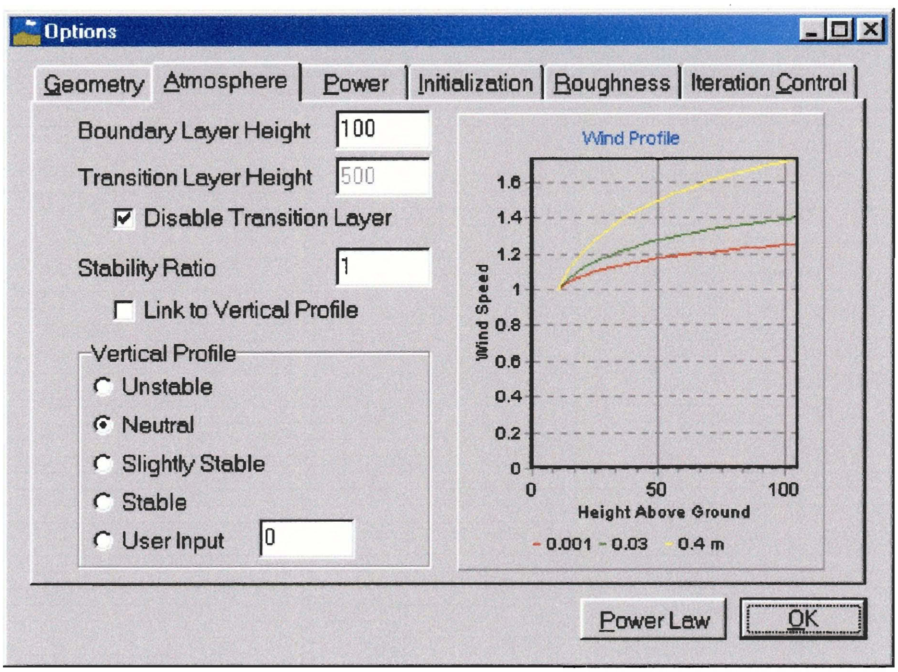


Figure 3.2.2.b: Final DEM of western Massachusetts (height in meters)

The Geometry menu also offers a control for the depth of each level along the Z-axis. It offers the following options for Z-level spacing: constant spacing, geometric spacing, and log-linear spacing. We chose to use geometric spacing to best approximate the model over mountainous terrain. Geometric spacing increases the level of each level by a constant amount compared to the one below it. This results in the thinnest levels being near the surface, with the thickest at the top of the mesh.

The user can also control the total distance to the top of the calculation mesh. Lowering the top of the mesh forces air flowing over obstacles into a smaller space, causing greater acceleration, which will most likely not correctly approximate observed wind patterns. However, raising the mesh once again requires more levels, resulting in greater computation times. Setting this option to "Auto" will set the top of the mesh at twice the relief, or 2000 meters, whichever is greater. This option appropriately designates a mesh top suitable for the terrain our IQP is concerned with.

Figure 3.2.2.c Atmospheric Controls



While WindMap functions mainly on Mass-Conservation, and does not solve the fundamental equations that determine the effects of surface and thermal stability on wind flow, it is able to reproduce these effects in the Atmosphere sheet in the Options dialog menu (see Figure 3.2.2.c). It offers settings to control the height of both a boundary and transition layer.

The boundary layer height is the height at which a logarithmic dependence of wind speed with surface roughness and thermal stability is assumed to hold. We chose to set this height at a typical level of 100 meters.

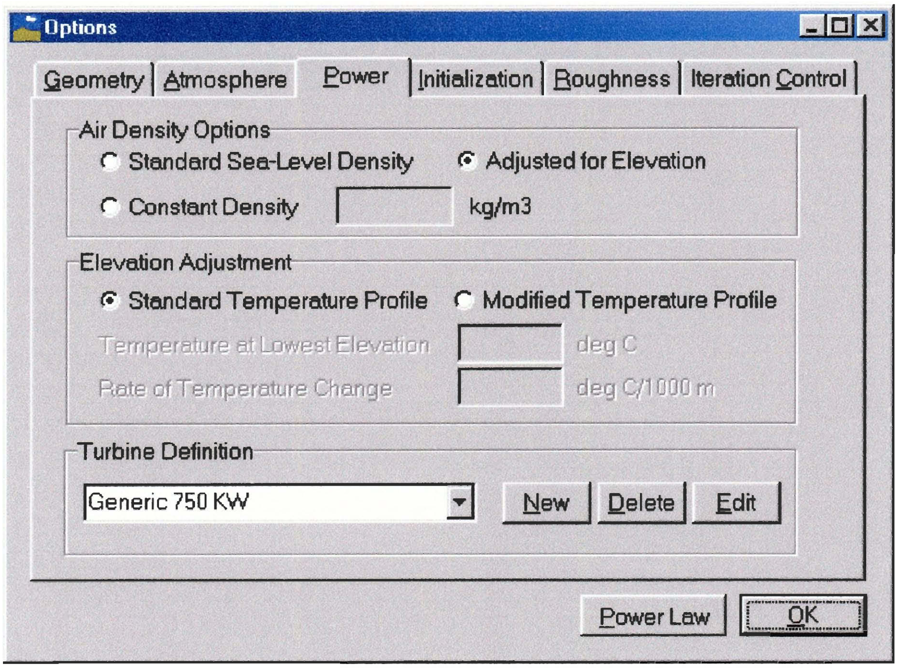
The transition layer height is the zone in which WindMap blends the wind speed and direction at the boundary layer with that of the upper air data. We chose to disable the transition layer entirely, allowing the program to instead blend the wind speeds linearly from the top of the boundary layer to the top of the mesh.

The final options displayed in the Atmosphere dialog menu involve the stability ratio that determines how WindMap adjusts wind flow in the vertical direction in order to satisfy mass conservation. Stability ratios less than one depict an atmosphere where vertical motion is suppressed, a stability ratio of one depicts a neutrally buoyant atmosphere where air can move up and down as easily as side to side, and a stability ratio greater than one implies movement of air vertically is easier than horizontally. Finally, stability characteristics determine the initial wind speed within the boundary layer. "The choice of stability characteristics determines, for a given value of surface roughness length, the initial vertical wind speed profile (wind shear) within the near-surface boundary layer.

"The vertical profile is based on Monin-Obukhov similarity theory, in which thermal stability is characterized by a parameter known as the stability length, L. As L approaches infinity, the atmosphere becomes neutrally stratified. When L is negative, the atmosphere is unstable; when L is positive, it is stable. Since most users will not be familiar with typical values of L, the program provides four standard options: unstable (L=-50 m), neutral (infinite, but here shown as zero), slightly stable (L=200 m), and very stable (L=50 m). You can also enter a value of L directly. In theory there is a connection between the stability ratio and the Monin-Obukhov stability length L, but it is a tenuous one, and in practice the two are used in quite different ways. Nevertheless, based on experience with the model in real situations, WindMap will assume a stability ratio for any given value of stability length if the "Link to Vertical Profile" box is checked."(WindMap

Helpfile) More stable atmospheres result in greater increases of wind speed as you leave the surface. WindMap provides plots of wind speed to height, traveling over 3 types of surface: .001m(smooth surface), .03m(grassland), and .4m(woods or residential buildings).

Figure 3.2.2.d: Power Controls



WindMap's Power settings (Figure 3.2.2.d) control the output of maps of power density and turbine output. These settings include options for controlling the air density. The user can either set the density at a constant value, or they can choose to have it adjusted for elevation. If adjusted for elevation, the rate of change is based on a temperature profile. WindMap offers a standard temperature profile, but the use is also able to enter in a modified profile if they wish. The final option on the Power dialog is a choice of turbine type. The user simply selects a turbine from among the ones WindMap provides, or enters in specifications for their own. WindMap then takes these specifications in order to approximate the probable output from such a turbine. As our

IQP deals little with this aspect of wind mapping, we have chosen to mainly ignore this aspect of WindMap.

Figure 3.2.2.e: Initialization Settings

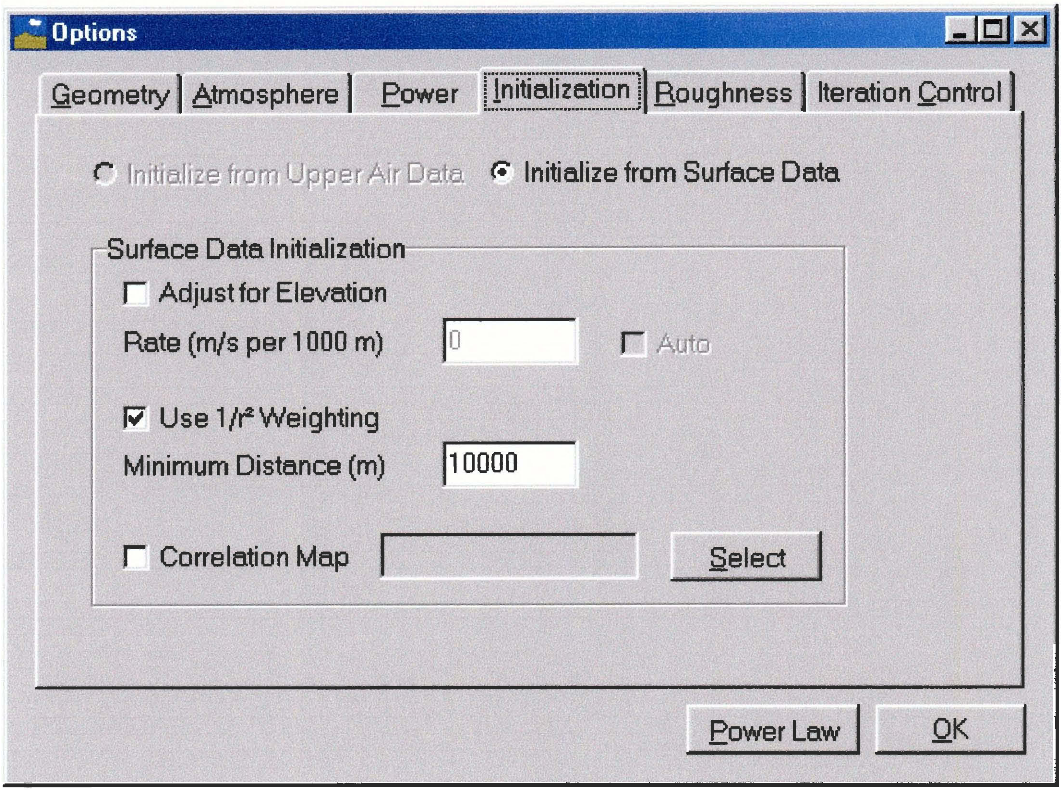
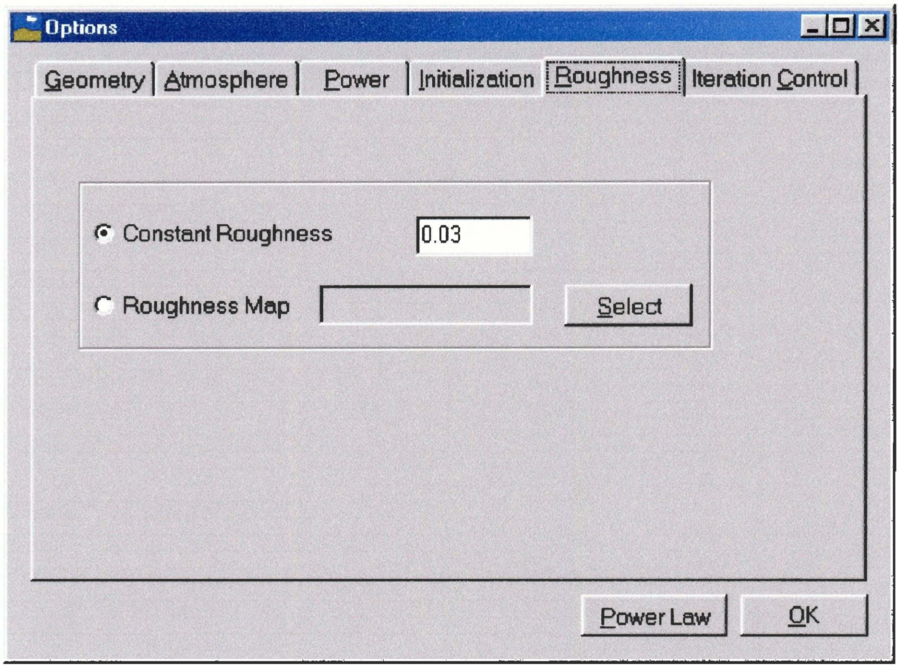


Figure 3.2.2.e displays the initialization settings for WindMap. WindMap offers the ability to initialize itself from either upper air data, or surface data. In order to initialize from upper air data, two air levels are required. In order to initialize from surface data, a minimum of one surface station is required. In this case, each point comprising the initial wind field consists of a weighted average of all of the surface stations. WindMap allows the user to customize the weighting by adjusting the effect of each station for Elevation. The user may also choose to use $1/r^2$ weighting, where each point in the initial wind field is a weighted average of all of the stations used for initialization, with those being closest to the point having the greatest weight. Different minimum distances can be used for this

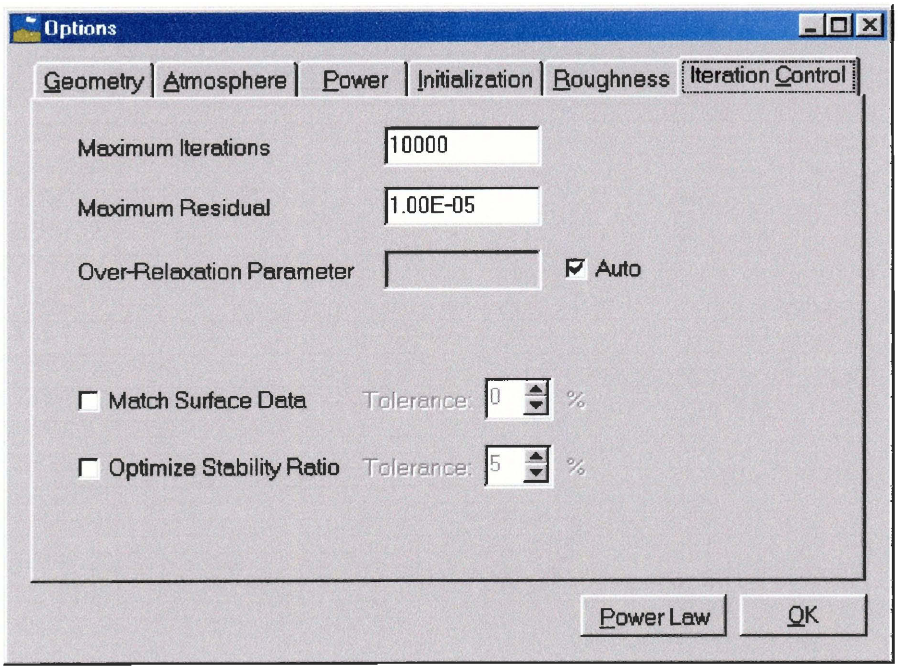
option, effectively changing the range of effect of each station. Larger minimum distances result in a "smearing" of the localization around each station, allowing the different observed speeds to mix more. This gives a more uniform wind field over the entire terrain. Finally, a correlation map can be used, dividing the terrain into different sections, each section having its own weighting and its own stations affecting it. None of these choices applies to all situations, and the user must decide which settings best fit their particular project.

Figure 3.2.2.f: Roughness Settings



WindMap's roughness settings are straightforward (see Figure 3.2.2.f). Either a constant roughness can be applied to the entire terrain, or a roughness map can be used. Michael Brower provides maps of roughness for $50. However, in order to gain a better understanding of the roughness values used, as well as the GIS software used, our project has chosen to create the maps ourselves through the process discussed later in section 3.3.2.1.

Figure 3.2.2.g: Iteration Controls



WindMap's final option dialog (Figure 3.2.2.g) contains controls for the iterations throughout the map generation process. The main objects of control within this dialog window are the match surface data and optimize stability ratio options. When the "Match Surface Data" option is selected, and a tolerance entered, the model will adjust the wind field at every iteration in order to ensure a reasonable match between initial and final wind speeds. With this option checked, WindMap attempts to match the initial wind field at every station which has the "use for initialization" box checked. While this option slows calculations, the small difference in time required per run seemed a fair price to pay for slightly increased accuracy. Tolerance was set at 0%. While increasing the tolerance to around 5% would reduce the calculation time slightly, the time gain was not enough to balance any loss of accuracy. The other method provided to improve the fit between predicted and measured speeds is optimization of the stability ratio. When this box is checked, WindMap repeatedly executes the main iterations when generating WindMaps, changing the stability ratio until an optimum fit is found. This can lead to more accurate data, and is especially useful when different stations are located at vastly different altitudes, such as on top of a mountain peak, and in the bottom of a valley. However, the optimization iterations result in far longer calculation times, as well as sometimes causing calculation errors and unrealistic stability ratios. For these reasons, we chose not to utilize this option.

3.3. Analysis

WindMap is capable of outputting maps of wind power density across a region, and these maps can be further analyzed to take into account various social and other factors to generate a complete picture of the applicability of wind power to Massachusetts. Analysis of the output data will take an additional term. Criteria for analysis will be defined based on the wind maps and relevant factors. The criteria are divided into two classifications: physical, which will be shown in the wind maps; and social, which includes environmental, economic and other factors. Important social factors include proximity to the power grid, land ownership, aesthetics, population density and other factors detailed above. Using these criteria, the state of Massachusetts will be assessed for wind power feasibility. The criteria will be weighted as deemed appropriate through study, much as Brower & Co. weighted social factors in their Colorado project. The social analysis of previous IQP studies of wind power will also be drawn upon when relevant.

Ultimately, potential turbine sites will be recommended and reported on as well as the overall wind power picture for the state. GIS information will be used for this phase if applicable. The analysis will be forwarded to the appropriate agencies. Through the generation of wind maps, as well as proper analysis, this project hopes to provide data that will aid in the effective placement of wind turbines in Massachusetts. This may lead to cleaner, cheaper power in the state, which may provide and example for renewable energy.

Finding areas of high wind power densities is only part of the siting effort. Social and economic factors are important in determining if areas with high potential wind power are conducive to construction of a wind farm on the site. In this section, we explain our methodology for determining these factors. We have evaluated the guidelines from Michael Brower's works ("Powering the Midwest" and his assessments of Colorado, Iowa and New Mexico) and have adapted these to Western Massachusetts and our project. We chose his reports as a basis as they are readily available to the public and present a thorough and evolved consideration of social and economic implications on wind siting. The primary factors considered in this assessment are land type and use and distances from power transmission lines, population centers, and major roads.

An analysis of this type requires a way of manipulating the various data necessary across the domain considered. GIS lends itself to this task and was used for this assessment. GIS information concerning the area was available from the Massachusetts Division of Energy Resources. The general use of GIS software is examined first, as the types of analysis performed were dependent on understanding its implementation.

3.3.1 GIS Implementation

A GIS-based system will be used for assessment of applicability of wind resources in Western Massachusetts. The use of GIS has the advantage of producing easily interpretable output taking into account potentially complicated user-defined relations in a mathematically rigorous way. Additionally, once the procedure for producing a set of qualitative maps is defined, it is easy to modify to fit different sets of criteria.

Output from WindMap may be opened in Idrisi (or other GIS system). Layers may be added on top of wind power density maps as vector files. The map may be then manipulated by applying user-defined relationships across the domain (such as the distance of a point from a utility line). Layers used include: power transmission lines, major roads, land-use and land cover. The maps used were MassGIS data (in ESRI shapefile format) provided by the Massachusetts DOER.

The ESRI shape files were imported as vectors in Idrisi32. However, Idrisi operations needed for this analysis, such as distance comparison and concatenation, were not available for vector maps. So the vector files were converted to raster format before the analysis was performed. For the power lines, conversion was done manually as the vector files covered the whole state. The land-use and land cover (LULC) files were done by township, so several Idrisi macro file were written to facilitate conversion.

3.3.2. Factors

An accurate and thorough analysis is dependent on proper identification of factors important to the assessment at hand as well as correct interpretation of their interdependency. In a complicated situation, identification and interpretation of all factors may be impossible. A meaningful analysis may still be obtained from consideration of only a few factors if appropriate simplification is possible. As such, the factors used in this study are land type and use, and distances from power transmission lines, population centers, and major roads. While these are only a handful of the myriad of factors affecting turbine siting, they may be used to generate simple and meaningful analysis. This section examines the factors used and their importance to wind turbine siting.

Assessment of the type of land may help determine appropriateness for turbine siting. Some areas may be excluded out-right. For example, urban areas are inappropriate to the traditional wind farm (though there are modern and experimental designs that incorporate buildings into wind turbine implementation). Vicinity to the population is also undesirable for preliminary consideration of turbine siting, for concerns of aesthetics and noise production.

Two primary economic factors are connection to the power grid and distance from roads and other means of transportation. Cost to connection to the power grid is based on a number of factors: existing utility company infrastructure, distance from the existing electric system, terrain type and slope, vicinity to roads, and others. Distance from roads and other transportation facilities is additionally an important cost consideration in wind farm siting as materials for construction and maintenance will have to be transported to the site.

3.3.2.1. Land-Use and Land-Cover Assessment

Land-use is a primary consideration for any sort of siting. Knowing the land-use over the whole area allows the elimination of inappropriate areas (such as urban areas in our study) as well as weighting allowable types of land use for appropriateness. A particular type of land-use may be considered individually and operations performed on each layer. Additionally, the land-cover type may be weighted appropriately to provide a roughness map of the region suitable for use by WindMap. The land-use and land-cover assessment consisted of importing the ESRI land use files into Idrisi and then manipulating the resulting maps in conjunction with the wind power density to produce a meaningful interpretation of the data. We describe this procedure here.

An initial macro converted from the ESRI format to Idrisi vectors. The initial naming convention for the ESRI land use files was 'Lus' followed by the town ID number and the letter a or p, indicating whether the file was a group of arcs or a group of polygons. As we were interested in the interior values delimited by the lines, the polygon format was more useful for our purposes.

Once imported into Idrisi, the vector files contained a number of sub-maps linked via a Microsoft Access database file created by Idrisi during the conversion. Each utilized the same polygon areas but displayed different values depending on the map. These sub-fields could not be used directly for concatenation, so a field linking ASCII file (called an attributes values file, or file type *.avl) was made for each of the files using the export utility in Idrisi's database workshop. The input field was the Idrisi ID, a number associated with the number of the polygon (arbitrary to each map) and the land use codes associated with the file. Once the .avl files were created, a second script was used to convert each of the polygon values associated with the 351 township LULC files to lu37 values.

The MassGIS data was compiled from aerial photography taken in years 1971, 1985, and 1990-1992; most of the data was from 1985 or later. The maps are at 1:25,000 scale interpreted from 1:40,000 scale photographs by the Resource Mapping Project at the University of Massachusetts, Amherst. There were 21 original land use categories that was expanded to 37 as a result of additional studies. Each of the extended categories (codes 23-37) was orginally part of the 21 land use category system. The land use categories are detailed in the Table 3.3.2.1.a.

Table 3.3.2.1.a: Land Use Category By Lu37 Code

Lu37 Code	Category	Definition
1	Cropland	Intensive agriculture
2	Pasture	Extensive agriculture
3	Forest	Forest
4	Wetland	Nonforested freshwater wetland
5	Mining	Sand, gravel & rock
6	Open Land	Abandoned agriculture, power lines, areas of no vegetation
7	Participation Recreation	Golf, tennis, playgrounds, skiing
8	Spectator Recreation	Stadiums, racetracks, fairgrounds, drive-ins
9	Water Based Recreation	Beaches, marinas, swimming pools
10	Residential	Multi-family
11	Residential	Smaller than ¼ acre lots
12	Residential	¼ to ½ acre lots
13	Residential	Larger than ½ acre lots
14	Salt Wetland	Salt marsh
15	Commercial	General urban, shopping center
16	Industrial	Light and heavy industry
17	Urban Open	Parks, cemeteries, public & institutional greenspace, also vacant undeveloped land
18	Transportation	Airports, docks, divided highway
19	Waste Disposal	Landfills, sewage lagoons
20	Water	Fresh water, coastal embayment
21	Woody Perennial	Orchard, nursery, cranberry bog
22	No Change	
23	Cranberry bog	Part of #21

24	Powerlines	Part of #6
25	Saltwater sandy beach	Part of #9
26	Golf	Part of #7
27	Tidal salt marshes	Part of #14
28	Irregularly flooded salt marshes	Part of #14
29	Marina	Part of #9
30	New Ocean	(areas of accretion)
31	Urban public	Part of #17
32	Transportation facilities	Part of #18
33	Heath	Part of #17
34	Cemetaries	Part of #17
35	Orchard	Part of #21
36	Nursery	Part of #21
37	Forested Wetland	Part of #3

(adapted from MassGIS on-line documents, 1995)

Once each vector file was converted to lu37 values, another macro was used to concatenate them by changing them to raster format and placing on top of an existing raster image. The background image used was made from the 1:250,000 scale DEMs (quadrangles Albany (east and west) and Boston (east and west) concatenated together). The final resulting raster had approximately 1:250,000 resolution, possibly slightly lowered during the conversion process.

Several of the land-use types could be eliminated due to inappropriateness for wind turbines. As the aesthetic qualities of wind power are considered undesirable near population centers, it was possible to eliminate commercial, industrial, transportation modes and facilities, as well as residential facilities up to ½ acre. Recreation areas (codes 7, 8, 9, 26, 29) could similarly be eliminated. The urban public and cemeteries were not considered, though the heath (code 33) and urban open (code 17) were left in the analysis, to be considered by developers on a case-by-case basis. Wetlands (codes 4, 14, 27, 28, and 37) were also eliminated for environmental concerns.

The knowledge of land use also allows the construction of roughness maps. The roughness maps were made by assigning values in meters to each of the lu37 codes in the LULC map. The values used were interpolated from a table given in the WindMap help file from Wind Turbine Technology, 1994, and validated by values used in Brower &

Co.'s Iowa Report (see Table 3.3.2.1.b and 3.3.2.1.c). As the terrain types given in the table did not exactly correspond to the lu37 categories, in some cases a "best guess" approach was used. LULC data was only available for Massachusetts. As part of the region investigated was not in Massachusetts, it was necessary to use a constant roughness value for this region. Since approximately 61% of Massachusetts is encoded as forest and no single other code approached this percentage, this was value was used for the surrounding area as well. Since forested areas are prevalent in New England, this is probably a good approximation, as roughness effects on the wind are largely localized and much less important than exposure and elevation. The final roughness values used are shown in Table 3.3.2.1.d. These values are not definitively accurate, though use of a roughness map is a qualitative improvement over a constant roughness value.

Table 3.3.2.1.b: Roughness Value Guidelines taken from WindMap

Land Cover Type	Typical Roughness Length (m)
Urban and suburban areas	0.4 to 3.0
Cities with tall buildings	3.0
Cities and large towns	1.2
Small towns	0.55
Outskirts of towns	0.40
Woodlands and forest	0.4 to 1.2
Farmland and grassy plains	0.002 to 0.30
Many trees and hedges, a few buildings	0.30
Scattered trees and hedges	0.15
Many hedges	0.085
Few trees (summer)	0.055
Crops and tall grass	0.050
Isolated trees	0.025
Few trees (winter)	0.010
Snow-covered cultivated farmland	0.002
Large expanses of water	0.0001 to 0.001
Flat desert	0.0001 to 0.001
Snow-covered flat ground	0.0001
Mud flats and ice	0.00001 to 0.00003

Source: David A. Spera (editor), Wind Turbine Technology (New York: ASME Press, 1994), p. 393.

Table 3.3.2.1.c: Roughness Values Used In Brower's Iowa Report

Land Cover Type	Roughness Length (m)
Forest	0.8
Woodland and Urban	0.4
Mixed Woodland-Cropland	0.1
Cropland	0.03
Water	0.0002

Adapted from Brower, "Iowa Wind Resource Maps", 1997.

Table 3.3.2.1.d: Final Roughness Values Used for lu37 Codes

lu37 code	roughness value (m)
0	0.8
1	0.05
2	0.025
3	0.8
4	0.05
5	0.15
6	0.05
7	0.01
8	0.01
9	0.002
10	0.8
11	0.55
12	0.4
13	0.4
14	0.05
15	1.2
16	3
17	0.4
18	1.2
19	0.1
20	0.0001
21	0.6
22	0.45
23	0.4
24	0.4
25	0.001
26	0.002
27	0.05
28	0.05
29	0.002
30	0.0001
31	0.4
32	1.2
33	0.4
34	0.4
35	0.8
36	0.45
37	0.5

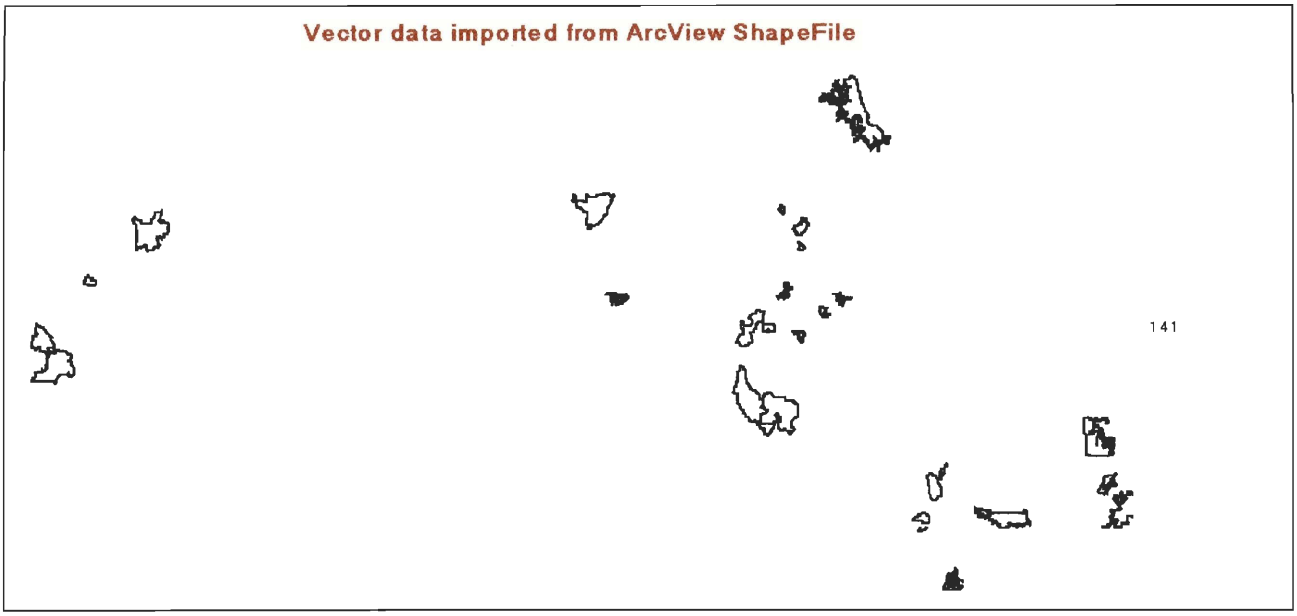


Figure 3.3.2.2.a: Massachusetts areas of environmental concern

3.3.2.2. Areas of Critical Environmental Concern

A MassGIS map was available of areas of critical environmental concern (ACEC) as designated by the Secretary of Environmental Affairs (Figure 3.3.2.2.a). The ACEC map is maintained by the Department of Environmental Management and the Massachusetts Coastal Zone Management, which continue to add areas (polygons) as investigation further reveals environmental hot-spots. Examples of protected areas are various wetlands (river basins, watershed areas, bogs, marshes, etc) and delicate coastal areas less relevant to our land-locked study. The original maps are at roughly 1:25,000 scale, but as with the other ESRI shape-files conversion to Idrisi raster format cut the resolution to approximately 1:250,000 (the resolution of the background image).

Areas of environmental concern were treated as forbidden grounds for turbine developers in the same way as excluded land-use/land-cover codes. From the two maps a single map was produced that contained a zero for a grid cell in an area excluded from LULC or ACEC considerations and a one for a grid cell not excluded as such. This was done to allow values from another image to be multiplied by values from this map in order to develop a suitability index across the region of interest. Areas outside of the Massachusetts boundary were not considered as they were beyond the scope of this project. Though there is overlap between excluded LULC codes (particularly the various wetland codes) and the ACEC, using a combined map excluding both areas ensures that inappropriate land would not be developed.

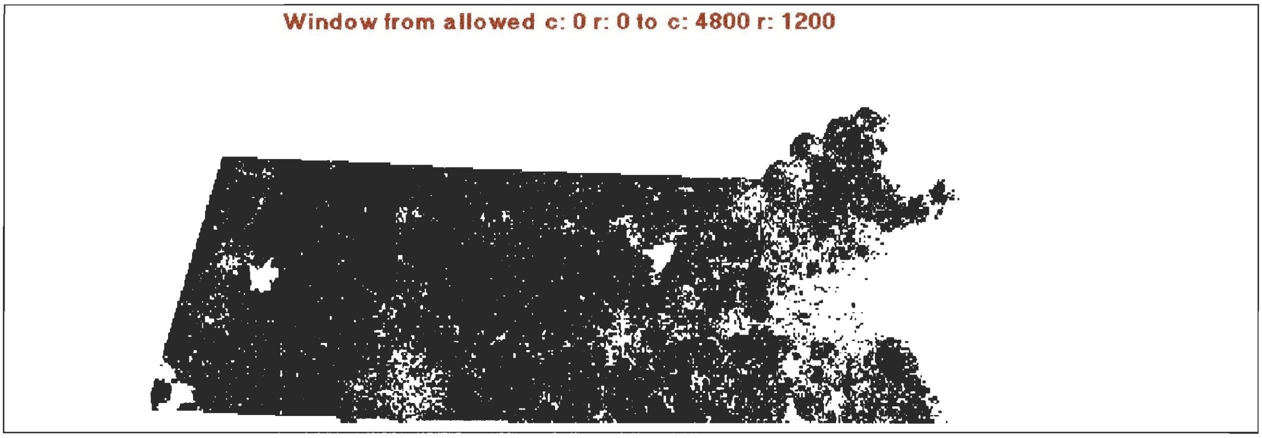
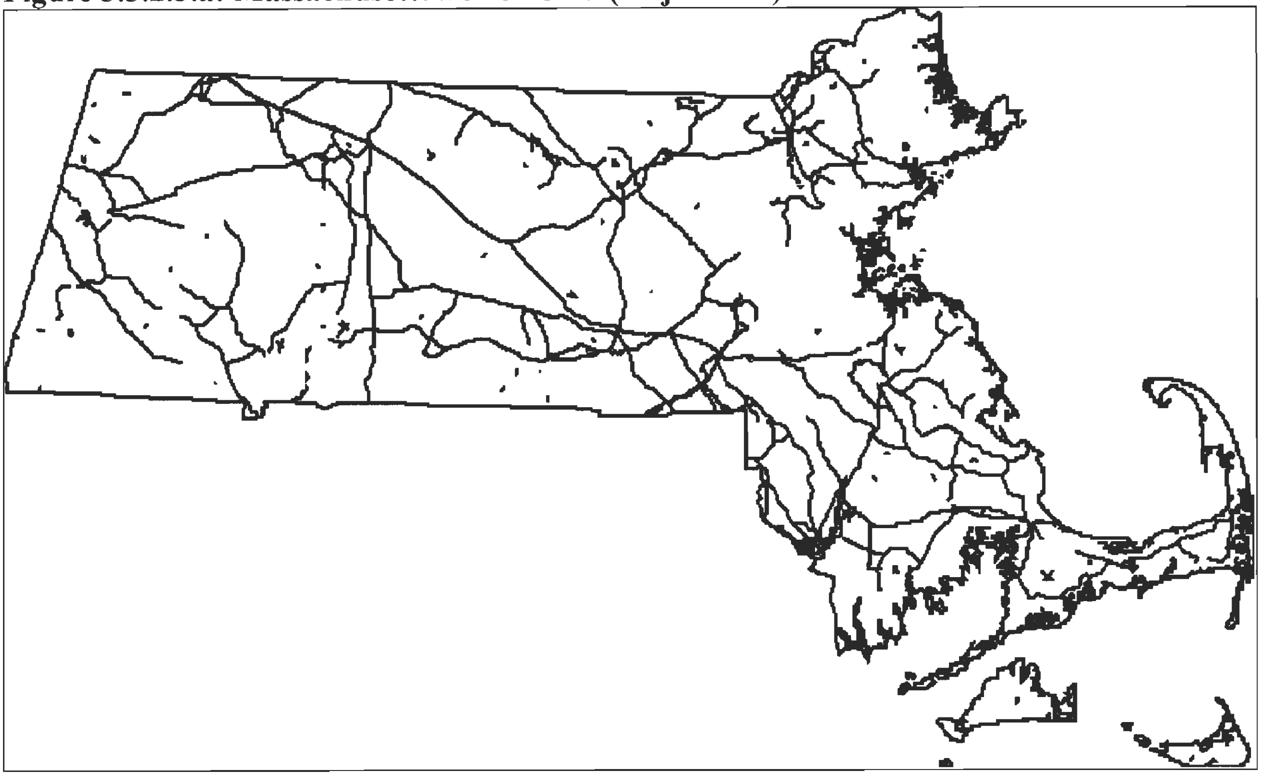


Figure 3.3.2.2.b: Area considered for Wind Turbine Development

Figure 3.3.2.3.a: Massachusetts Power Grid (major lines)



3.3.2.3. Power Grid Proximity Assessment

A primary economic concern of utility-scale turbine developers is cost associated with connection to the electric grid. While this cost is based on many factors, distance from the existing power lines is a major factor and the only factor available to us for consideration. As a generalization, two types of cost would be associated with connection to the grid: a fixed charge regardless of distance and a distance-based charge

Brower's treatment of the affect of distance from power lines on the suitability index is discussed in the most detail in his New Mexico report. A linear value ($150,000 per kilometer) is used for construction cost for flat-ground distance from the transmission lines. For a sloped area, this was multiplied by the value of the slope of the ground. This value was considered constant independent of wind farm size (the 25-200 MW regime was the focus of this estimate). To this value was added a fixed cost of $300,000 to cover installation of a sub-station. The linear nature of power-line cost (neglecting slope) lends itself to the linear-weighting method used for overall analysis.

The Idrisi distance operator was used following conversion of the power grid vector into raster format. Distance from power-lines is shown in Figure 3.3.2.3.b. From this image, algorithms could be applied to give an estimate of cost to install to the electric grid.

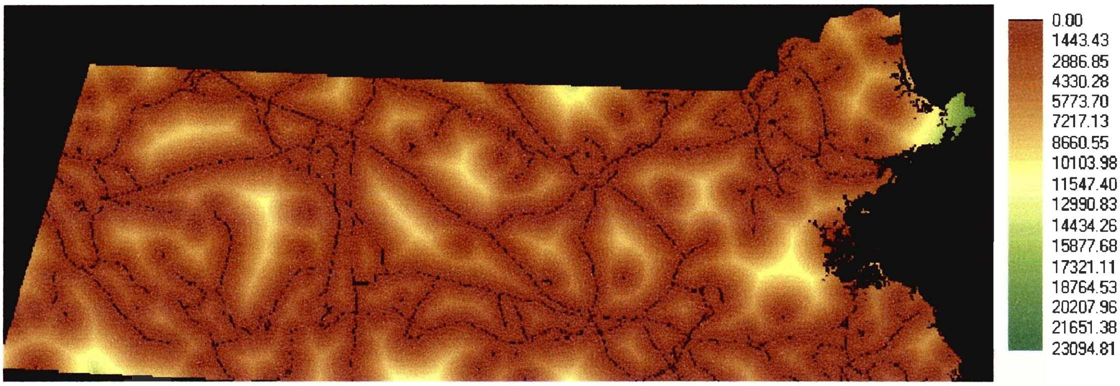
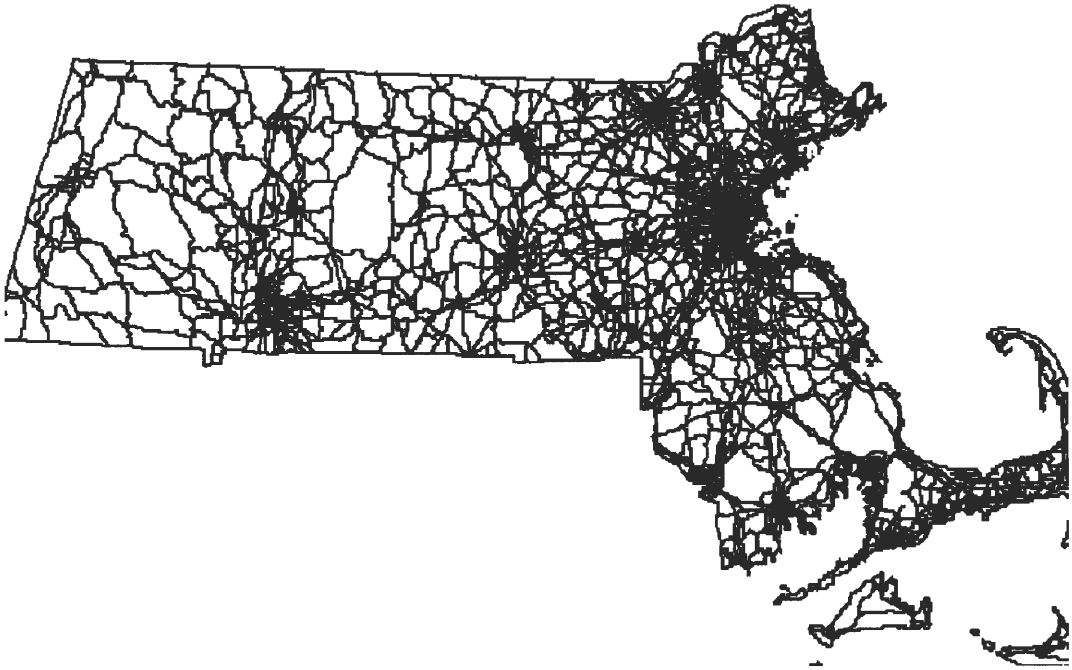


Figure 3.3.2.3.b: Distance from nearest major power-line (in meters)

Fig 3.3.2.4.a: Massachusetts Major Roads

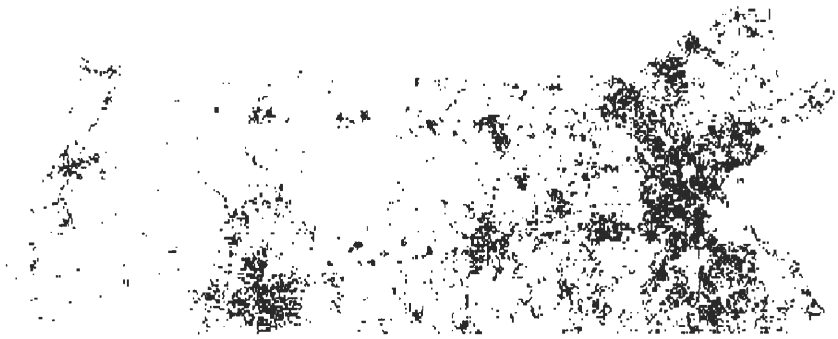


3.3.2.4. Major Road Proximity Assessment

Distance to major roads is an obvious economic factor in turbine development. With increasing distance comes increasing shipping cost to a region. The installation of turbines is materials intensive when one considers utility-scale turbines, though much less so for smaller devices. Turbines must also be serviced, involving similar transportation costs.

The assessment of proximity to roads and other transportation features was found to be outside of the scope of this analysis. The availability and condition of minor roads was not included in the data used and obviously important to this study. As Massachusetts is generally well-developed, transportation may be considered available to most sites. Transportation cost may be broken down into a myriad of factors, including the mode of transportation, range and fuel related factors, and consideration of the materials to be transported. Without a more in-depth assessment of what factors should be considered for a transportation assessment, a valid analysis of its impact on turbine site suitability cannot be made. Transportation to a potential site should be considered by developers independently of the suitability index presented here.

Fig 3.3.2.5.a: Population Centers in Upper Massachusetts (before mode filtering)



3.3.2.5. Population Center Vicinity Assessment

Siting of turbines near population centers has been an issue in several cases, as indicated in the preceding literature review. Complaints have been made concerning turbine aesthetics and noise production. Regardless of the validity of these complaints when considered objectively, historic precedence lends to consideration of distance from population centers with other quantitative factors. There is a range beyond which distance to population centers is no longer a factor – however, the relatively dense population of Massachusetts allows consideration of this range limitation to be neglected.

A map of the population center was made by assigning a value of one to the LULC map based on lu37 population type categories. The categories considered parts of population centers were residential (up to ½ acre), commercial, and industrial. As only the distance from the population center is of interest, negligence of individual features questionably part of population centers does not adversely affect the generalized map. The map produced is shown above (Figure 3.3.2.5.a).

Examination of the above map reveals several islands too small to be considered part of population centers. As the Idrisi distance operator calculates the distance from the nearest point, inclusion of these islands gives a distorted picture of population center proximity. To optimize the map to this end, the Idrisi filter module was used. Since the values were exclusively one or zero, mode filtering was used. In a small area of interest (N by N cells, where N is small compared to the resolution of the map) the values of all the cells in the area are set equal to the predominant value in the area. This provides elimination of noise while preserving the overall quality of the map. The following population map (Figure 3.3.2.5.b) shows the effect of a 7 by 7 cell mode filtering over the population map. From this map, a map of distance from population centers was made.

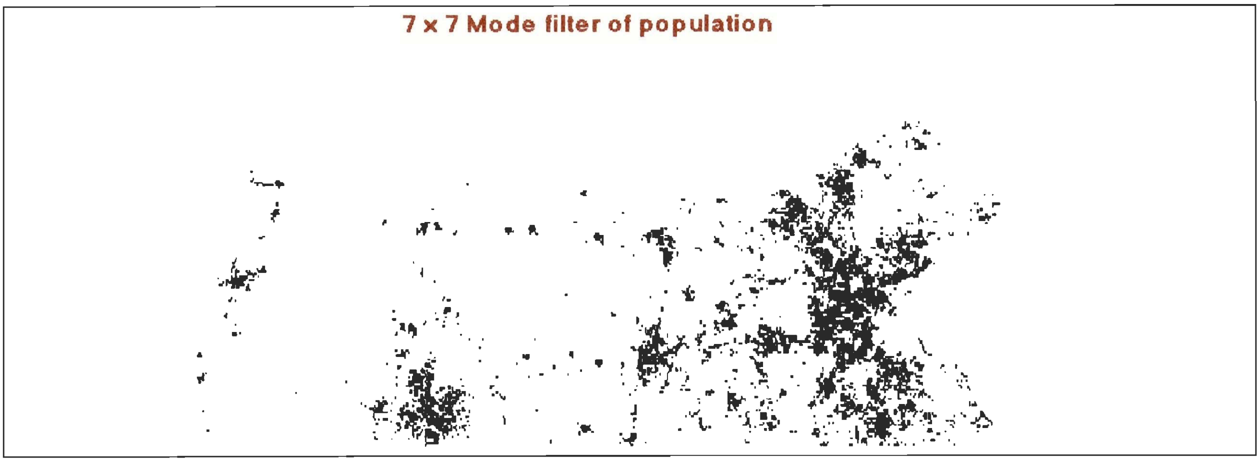


Figure 3.3.2.5.b 7x7 Mode Filter of Population Centers

The decision to filter out small population centers was made in order to give a higher weight to distance from more populated areas. As only the smallest areas are filtered out, this is probably the best treatment for the simplicity of the current model, although individual residents may protest as much as populations if a turbine is sited near their residence. A better model would incorporate a population density factor along with the raw distance.

3.3.3. Overall Assessment

Each factor in this analysis will be considered individually first and then in conjunction with other factors. This allows a qualitative understanding of the individual factors and how they are combined to form the overall site analysis. It is important to remember that this analysis is done on a largely qualitative and subjective basis in accordance to factors important to mid- to large-scale wind farms. Individual and corporate needs may vary from this model. In such cases, return to the raw wind map and apply the needed analysis to the application at hand, using the above procedure as applicable. A complete economic analysis of all relevant is not feasible because of time and resource issues. Further, an analysis of societal views toward wind farms in Berkshire county is beyond the scope of this project and would indeed be a project of its own right.

Once each of the factors is considered and understood separately, an overall analysis could be done considering each factor appropriately. Each factor is assigned a weight based upon its perceived importance. The values in each separate map are multiplied by its normalized weight and the values of all the maps are added with Idrisi's image calculator. The result is a wind power suitability index for Western Massachusetts. The weights used in this study are largely derived from the weights in Michael Brower's previous reports. It is important to remember that these weights are in reference to other regions and may or may not be appropriate to Massachusetts. In principal, the weights could be changed and the entire suitability map recalculated based on individual needs.

The maps of allowed areas, distance from power lines, and distance from population were converted to the resolution of the final output of WindMap. This was done via the project using a macro to reproduce the same parameters for the three maps. This allowed the values and extrema to be compared only over the domain of interest, as well as format the maps for the final manipulation necessary to complete the analysis.

The method by a suitability index over the domain was derived used linear dimensionless weighting. For quantitative factors, such as wind power density and distance from transmission lines, a non-dimensional index was created between zero and one, corresponding to least and most suitable for siting, respectively. The extrema of a quantitative GIS map are assigned to zero and one, the assignment corresponding to whether the attribute is beneficial or detrimental to turbine siting. For instance, the minimum value of the wind speed map would correspond to zero as it is the least desirable value, but the minimum value of distance to utility lines would correspond to one, as it is the most desirable value. The map values are converted linearly to the 0-1 range.

Once the separate desirability ratings are indexed non-dimensionally, they may be combined according to weights. The total weight (the sum of all individual weights) was arbitrarily set to one. The separate non-dimensional maps are overlaid after multiplying by their individual weights. This results in a suitability index over the region considered ranging from least desirable at 0 to most desirable at 1. A location with an index of one would have the theoretically perfect location for siting – right on the power grid, highest wind speed in the domain, etc. As coincidence of all favorable (or unfavorable) conditions is unlikely, in practical application the extrema are rarely reached.

As this method is dependent on linear behavior, wind speed was used instead of wind power (which exhibits cubic behavior). Proximity to the power grid is also treated as linearly important as is distance from population centers. While there are other factors adding different dimensions to both of these, they may be treated linearly for a simple analysis.

	Weight	Least Suitable	Most Suitable
Wind Speed/Wind Power	84.5%	5.04 mph	17.24 mph
Proximiy to Power Grid	12.25%	14768 m	0 m
Distance from Population Centers	3.25%	0 m	17310 m

Table 3.3.3.a Weights used (adapted from Brower's collected works)

This analysis, while producing viable results, is done in part to demonstrate the applicability of numerical manipulation using a GIS system. Developers could do a cost-study analysis to produce a more meaningful result for their particular needs. Scaling the siting variables non-dimensionally allows a very generalized treatment of the siting method. However, the suitability index generated is subject to the understanding of the method by which it was created. A more economic-intensive analysis could also be done leading to a GIS map with more economically definitive values. Given the type and number of turbines to be developed, as well as extrapolation of the wind field to the operable turbine height, the rate of energy production may be obtained. With cost analysis of each siting factor and going rate of electricity known, this allows the life-cycle cost of energy to be evaluated as described in the economics section. This would allow for a more accurate GIS siting implementation on a case-by-case basis.

3.4. Budget

What follows is a tentative approximation of the required costs for this project. Computers as well as our main software package, WindMap, are already available and will require no more funding. However, other software we use may require an upgrade whose cost we estimate at $100. Books and publications that we may require throughout this project have been factored in with a cost of $100. Maps and technical support make up the bulk of this project's budget. The cost of 7.5 minute by 7.5-minute GIS maps is $45 for the first map and $1 for each additional map (Tinkham et al., 1999). This price is for DEMs. The estimated cost of the land use and ground cover map is $100. Total map cost is estimated at $250. Technical support will cost 150 dollars. Finally, we've factored in a cost of 50 dollars to cover possible travel expenses to regional wind farms, as well as the DOER and the UCS (gas, tolls, etc.). This results in a total proposed budget of 550 dollars. After factoring in a contribution of $15 per term, per team member, this project's final budget comes to $515.

TABLE 3.4.a BUDGET

Materials Needed	Cost ($)	
Computers	Available (0)	
IDRISI Software Upgrades	200	
WindMap	Available (0)	
Maps	250	
Technical Support (Brower)	150	
Travel Expenses	50	
SubTotal		**550**
Minus 3x$45		135
Total		**515**

4. Results and Analysis

The methods outlined in Section 3 were used to create and evaluate wind resource maps over Western Massachusetts. An in-depth consideration of the specific results of these techniques is presented in this section. The results correspond well with existing data and represent a successful preliminary effort. Section 4.1 explains the findings of successive runs of WindMap. The maps produced are considered in this section along with techniques for further possible refinement. Section 4.2 describes the results obtained through use of basic GIS analysis techniques as applied to criteria important to potential developers. These findings can be used as a preliminary basis for wind turbine siting. However, more importantly, they demonstrate the power of a GIS-based system for the purposes of this type of assessment.

4.1. WindMap Results

In order to insure the most accurate maps of wind speed, our IQP required multiple runs within WindMap involving small changes to individual parameters. We adjusted roughness values, the vertical profile, stability ratios, and initialization points. After generation of maps adjusting for these three key controls, our project team proceeded to compare them in order to establish absolute and relative importance of each control factor. By such comparison, we have arrived at our final optimized maps, and have established the maximum parameter-related error possible in our final output.

4.1.1. Roughness

The roughness parameter has been found to have a minimal effect on the final output of WindMap, this effect increasing slightly as the vertical profile becomes more stable. Our project team foresaw this relative lack of importance and did not dedicate large resources to this parameter at first. However, as the project continued and resources were freed up, we explored this parameter in further depth. We explored the effect of different constant roughnesses, eventually abandoning them in order to use a roughness map which we constructed ourselves from MassGIS land-use files. This progression proved to be of value to our final understanding of WindMap, as well as our final understanding of the physics of wind in general.

Our IQP began our analysis with a constant roughness value of .4m, defined by WindMap as a good approximation of forested and urban terrains. To see the effect of changes to this roughness value on final wind speeds, we conducted identical runs, changing only this roughness value to a constant .8m, another approximation given by another table within WindMap. Using Idrisi32's image calculator, the resultant maps were compared. This comparison generated the following map (fig 4.1.1.a)showing differences in predicted windspeeds.

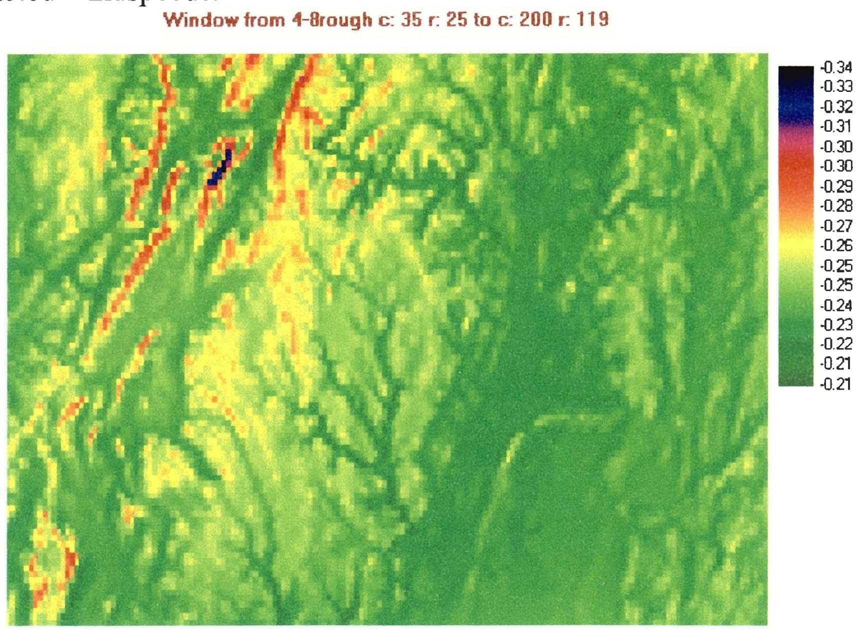


Figure 4.1.1.a: Change from .4m to .8m constant roughness (in Mph)

As shown in figure 4.1.1.a, changing the roughness value results in very small changes to the predicted wind-speed. By increasing the roughness value from 0.4m to 0.8m, wind-speed predictions increase by a maximum of 0.34 m/s (approximately 3%). While the areas most affected by the change in roughness are centered around areas of high altitude, the change over them differs from the change over the least affected areas (change of 0.21 m/s) by only 0.13 m/s. This shows that changes to a uniform roughness value, while affecting final predictions slightly, do so in a manner that is fairly uniform over the entire terrain. It is worth noting at this point that as the vertical profile moves toward that of a more stable atmosphere, the effect of roughness on final wind-speeds increases slightly. However, even in a totally stable atmosphere the effective difference between common roughness values remains minimal, especially when a uniform roughness value is used. These effects result in maps that, while possibly not showing absolutely accurate wind-speeds, succeed in showing relative wind speed differences over an area. These relative wind-speeds are most important when choosing the best location for a wind turbine site. If you choose the best location as shown by our maps of wind speed, even though they might not predict the exact speed, you can be fairly sure that the chosen location is the windiest compared to other sites in the area.

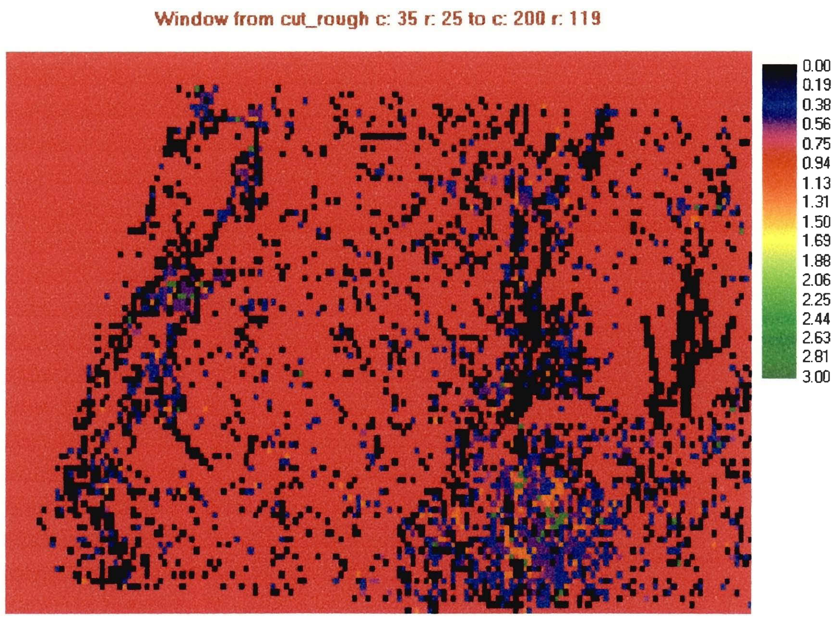


Figure 4.1.1.b: Roughness Map of Western Massachusetts

While changes to a constant roughness resulted in fairly uniform changes in wind-speed across the terrain, the addition of a true roughness map resulted in more important changes. By utilizing a map that consisted of different roughness values corresponding to different terrain types across Massachusetts, we produced dramatic changes in the initial and final wind fields predicted by WindMap. We used the roughness map shown in figure

4.1.1.b. Running WindMap with this roughness map created a noticeable change in the initial wind field from runs using a constant roughness value of 0.4. Figure 4.1.1.c shows the initial wind field produced with a constant roughness of 0.4, while Figure 4.1.1.d shows the initial wind field produced with a roughness map.

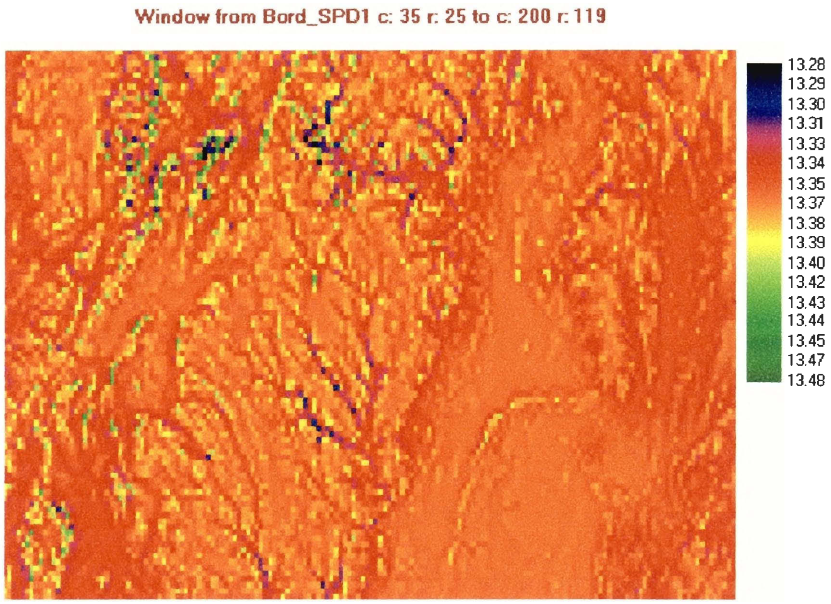


Figure 4.1.1.c: Initial Wind Speeds produced with constant .4m roughness (in Mph)

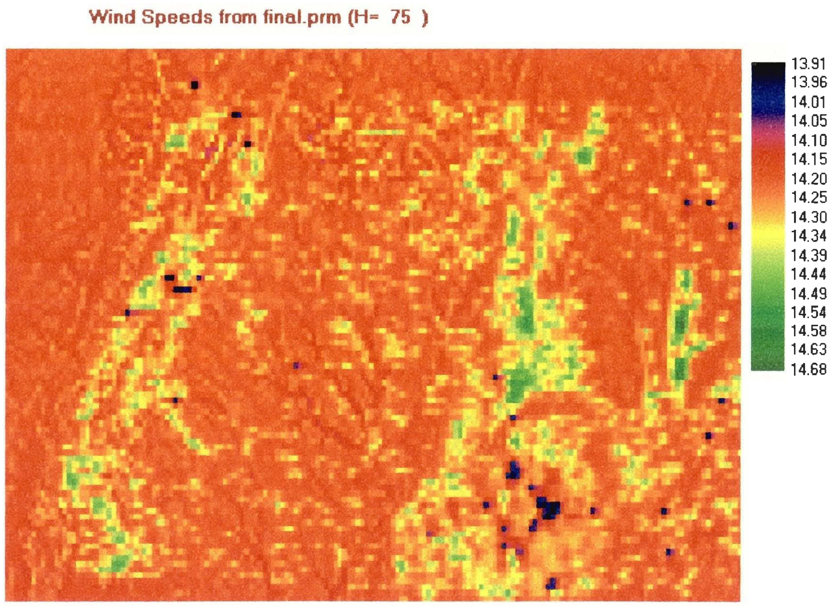


Figure 4.1.1.d: Initial Wind Speeds produced with Roughness map (in Mph)

Obviously, the addition of the roughness map resulted in definite changes to initial wind speed based on Terrain type. While the initial winds do not directly represent what will be seen in the final wind speed predictions, a definite correlation can be seen between them. The initial winds serve as a starting point for iterations run by WindMap. By starting with an initial wind field most similar to actual observed winds, we maximize the likelihood that the final predictions arrived at when WindMap's calculations converge are in fact correct. More significant differences in initial winds will be discussed later, when investigating the effects of different initialization methods.

As far as roughness is concerned, it is important to note that changes to this parameter create distinct, albeit small, changes to the initial wind field. This can be noted especially over the Quabbin, the large body of water in central Massachusetts. When no terrain based roughness was taken into account, the eastern section of our map seemed fairly barren. However, when we introduced the roughness values associated with water (approaching 0), the Quabbin displayed higher wind speeds, as we would expect to occur over a smooth surface such as water. We also notice expected changes occurring over urban population centers such as Springfield. The results obtained by using the roughness map seemed more in tune with actual observations, and we decided to use it rather than a constant roughness in hopes of achieving slightly more accurate predictions.

4.1.2. Vertical Profile

Changes to the stability of the vertical profile directly affect the wind shear. Recall that wind shear describes the variance in wind speed corresponding to changes in height. More stable atmospheres result in reduced turbulence at the surface, and higher wind shears. It also results in a slightly more pronounced effect from areas of higher roughness; the difference in speed over areas of different roughness is increased. As the stability of the vertical profile increases, the increase in speed over areas of low roughness compared to areas with of high roughness increases. Thus, increases in the stability of the vertical profile result in maps of initial wind-speed with a stronger correlation to the roughness map. Changes to the vertical profile resulting in a more stable atmosphere also result in an overall increase of wind speed across the entire map, also somewhat focused on peaks, although not as directly as changes to the stability ratio result in. By completing runs using each of the set vertical profiles that WindMap provides (Unstable, Neutral, Slightly Stable, and Stable), we concluded that a slightly stable vertical profile best fit our observations. A slightly stable vertical profile resulted in predicted wind-speeds across the terrain that best matched those observed. With the addition of the roughness maps, the slight increase in predicted wind-speeds was less uniformly distributed across the terrain. The effect instead centered where it should, on areas of specific roughness, thereby allowing our maps to correctly represent the effect of different terrain types, and not simply elevation.

4.1.3. Stability Ratio

The next critical factor analyzed by our project was the stability ratio of the atmosphere. A neutral atmosphere, by which we mean an atmosphere where packets of air are neutrally buoyant and move as easily vertically as they do horizontally, is represented by a stability ratio of 1. As the stability ratio decreases from 1, the atmosphere becomes more stable. This results in a funneling effect over peaks and ridges. Since the air cannot move as easily vertically after coming over a ridge, it stays more compressed at that height. This results in higher wind-speeds at peaks, and lower wind-speeds in valleys. This also results in high mountains blocking more of the wind passing over them, although it is not truly blocked. It is merely pushed up to a higher altitude, higher above the surface of areas downwind from the mountaintop. Compare the maps of final wind speed in figures 4.1.3.a and 4.1.3.b. Figure 4.1.3.a shows wind-speed taken in a neutral atmosphere with a stability ratio of 1. Figure 4.1.3.b shows wind-speed taken in a slightly stable atmosphere with a stability ratio of 0.2. Note that the wind-speeds of figure 4.1.3.a vary more than those of figure 4.1.3.b, resulting from the compression of wind at the peaks and its subsequent removal from the valleys. By comparison to recorded observations, and our understanding of the flow of wind, the stability ratio corresponding to a slightly stable atmosphere most closely approximated the real world. It resulted in a variance that we expect, without unrealistically boosting the speeds over peaks or suppressing speeds in valleys.

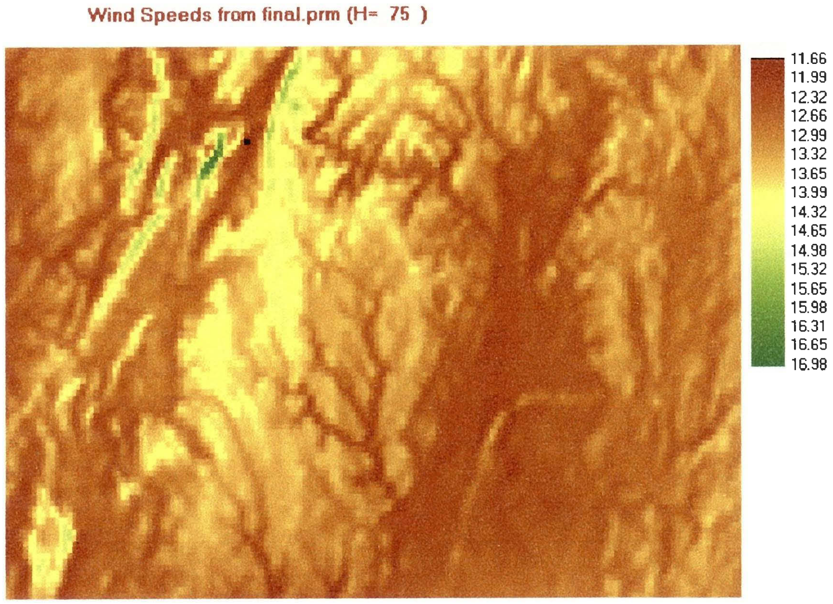


Figure 4.1.3.a: Wind Speeds in neutral Atmosphere (stability ratio = 1) in Mph

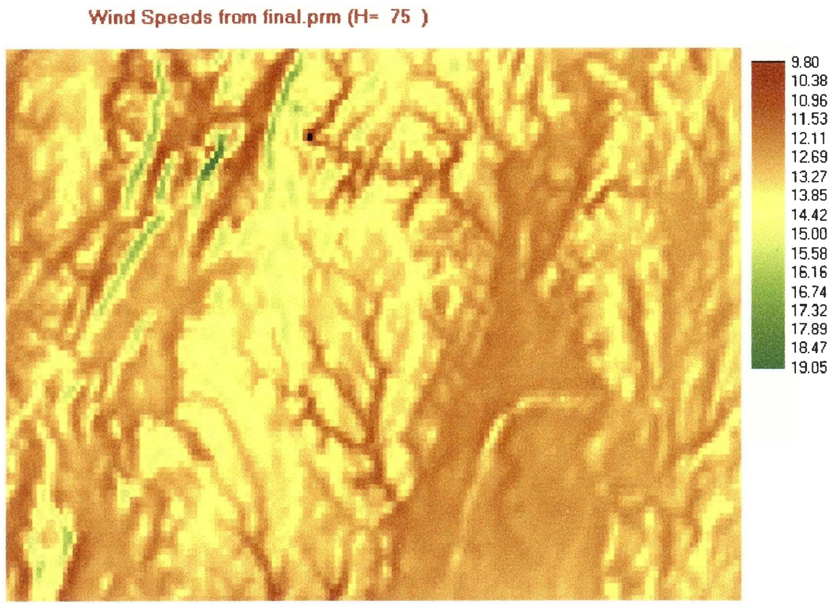


Figure 4.1.3.b: Wind Speeds in Slightly Stable Atmosphere (stability ratio = .2) in Mph

The difference between Figures 4.1.3.a and 4.1.3.b is shown in Figure 4.1.3.c, which displays the result of subtracting Figure 4.1.3.a from 4.1.3.b

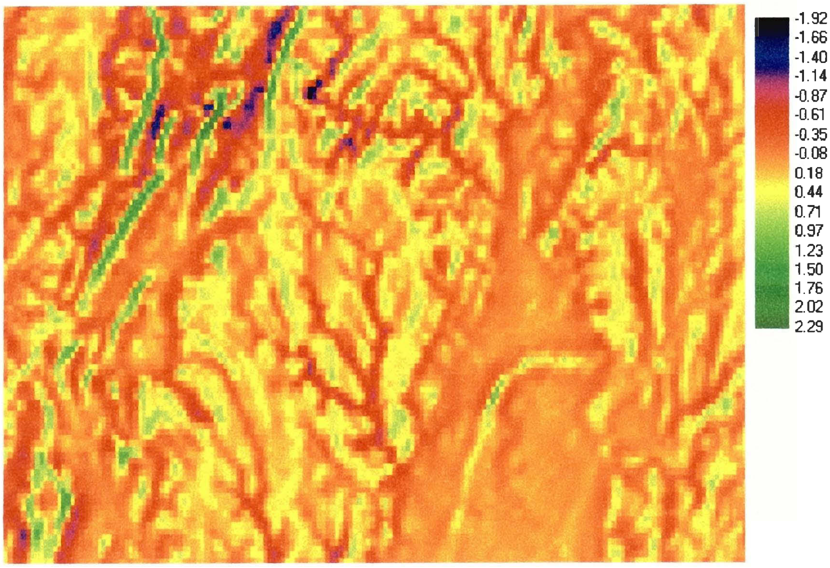


Figure 4.1.3.c: Difference between Neutral and Slightly Stable Atmosphere on Wind speed (in Mph)

4.1.4. Initialization

The final critical factor affecting wind speed predictions involves the initialization of the wind field. WindMap offers different weighting schemes, one involving changes in elevation, and one involving proximity to initialization stations. We chose to use the $1/r^2$ weighting, which initializes each point across the map based on the observed speeds at each station, with the closest stations affecting the wind-speed more. We used all of the 5 stations available to us to initialize the data. The reader should note, however, that this is not always the best choice of action. Stations which are located in strange terrain settings can give observed wind speeds that are not good depictions of the wind speed in that area. However, in our project, due to the low number of stations available to us, and the relatively large distance between them, chose to use them all for initialization. Removing one or more from the initialization resulted in very poor predictions over those stations. The terrain our IQP is creating maps over simply cannot be correctly represented with so few stations. However, while using all of the available stations increases the likelihood that the wind field predicted is similar to reality, it removes our ability to check whether the final maps are correct. Since the model is forcing the predictions to match the data at the ground stations, the model will always predict speeds close to observed speeds over the stations. Ideally, the user would have many more data points, in order to be able to correctly represent the wind fields over the terrain, while still having other stations to compare predictions with.

The $1/r^2$ weighting can be set to directly impact the initial predicted speeds over different minimum distances from the ground stations. Larger minimum distances result in a "smearing" of the wind speeds out from the stations, while smaller minimum distances result in more localization of observed wind speeds around the stations. This is best illustrated in figures 4.1.4.a and 4.1.4.b. Figure 4.1.4.a shows initial wind fields generated using all stations except Borden Mountain for initialization, with a minimum distance of 1000 meters used for weighting purposes. Figure 4.1.4.b shows the initial wind field generated when the minimum distance is increased to 15,000 meters. The reader should note how the localization of each station's effect is somewhat smeared out, resulting in overall speeds closer to an average of all stations.

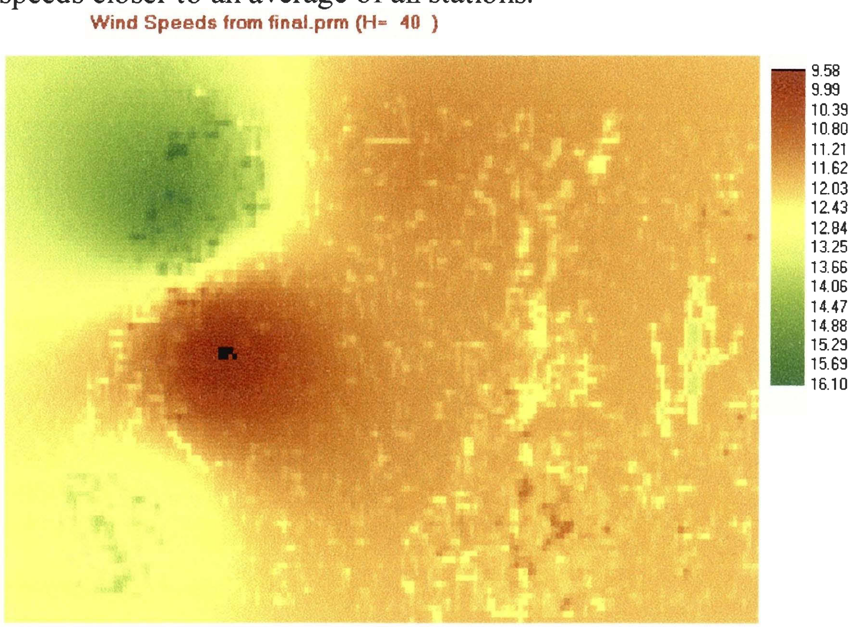


Figure 4.1.4.a: Initial wind field using minimum distance of 500m for weighting

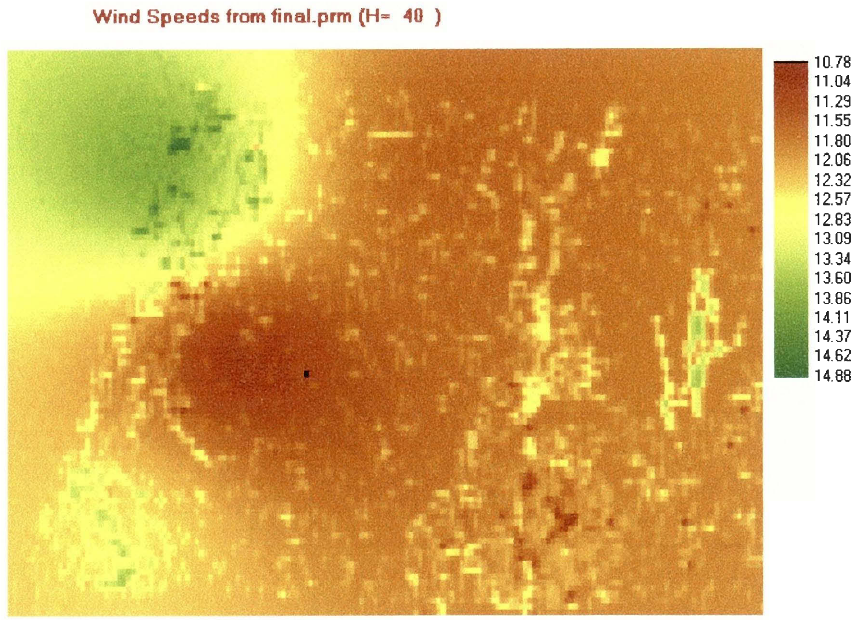


Figure 4.1.4.b: Initial wind field using minimum distance of 15,000m for weighting

We used a minimum distance of 10,000 meters from each station as the basis for the effect of the weighting. This resulted in a localization of the effect of each station, with a melding of the initial wind speeds between stations. However, the localization is lessened some by the fairly large distance. By attempting to balance localization with averaging of the windspeeds, we hope to achieve an initial wind field that most closely depicts the observations and our expectations. This gives us initial speeds that are much closer to our observations over the surface stations, while not being as forced as those generated using smaller minimum distances.

4.1.5. Optimized Maps

Through repeatedly running WindMap with varying parameter settings, our IQP manually optimized the model to best fit our observed wind data. Our final results include the following maps of wind-speed, and power density, shown in Figures 4.1.5.a and 4.1.5.b respectively. These maps were created using a stability ratio of 0.2, and a slightly stable vertical profile, over the roughness map of Figure 4.1.1.b.

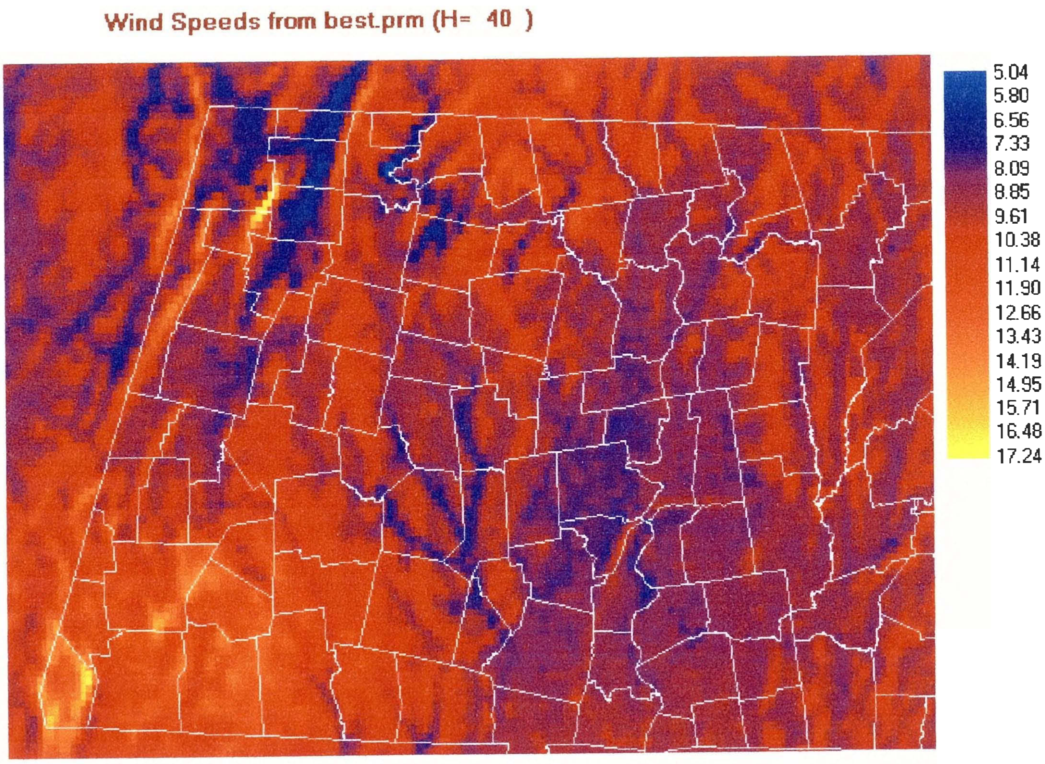


Figure 4.1.5.a: Predicted wind speeds at 40 meters (in Mph)

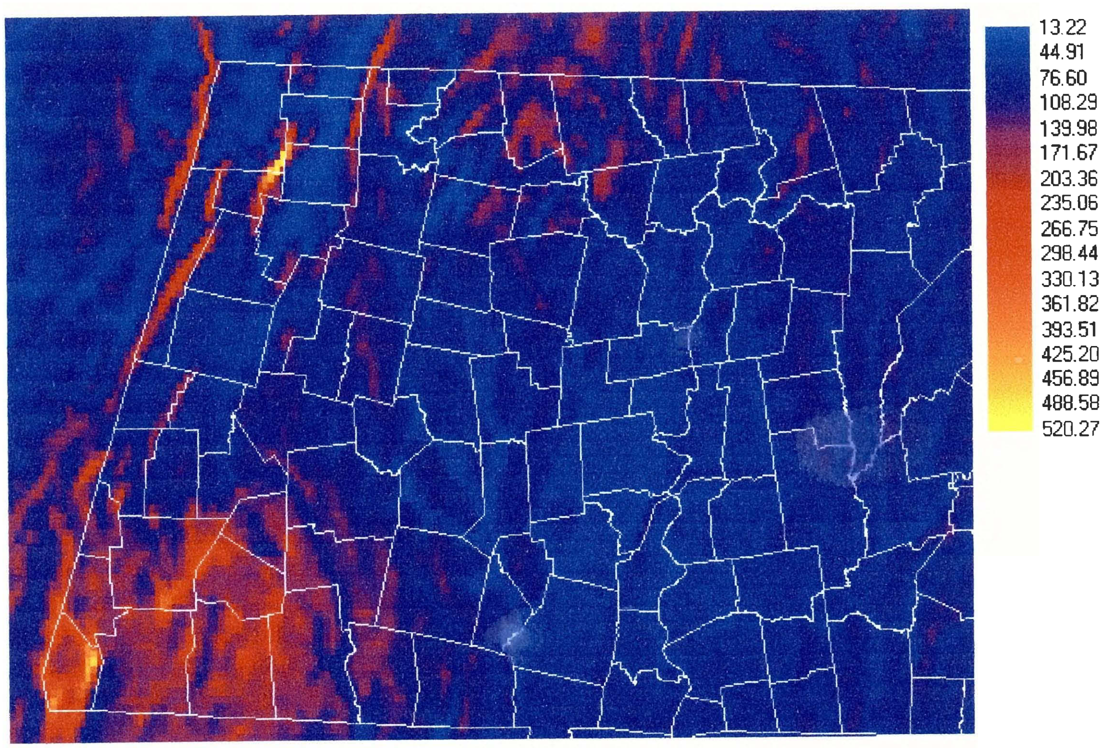


Figure 4.1.5.b: Predicted Power Density (in W/m^2)

The final run was done at 40 meters, in order to generate a map at the same level as our recorded observations, and thus more easily facilitate visual comparison of the map to our recorded data. It should be noted however that most commercial wind turbines are taller than this, and will benefit from higher wind speeds and power densities at these heights above the surface. Table 4.1.5.a displays the log summary of the wind fields observed over each ground station, and the corresponding predicted wind speeds.

#	Station Name	Elevation (ft)	Measured Speed	Predicted Speed
1	Century Cable	1790	12.876	12.687
2	Brodie Mtn.	2590	15.252	14.057
3	Petricca Tower	2000	9.559	10.554
4	Burnt Hill	1710	11.251	11.321
5	Borden Mtn.	2490	9.844	10.924

Summary

RMS Error (m/sec) 8.61E-01
Mean Bias (m/sec) 4.13E-01

Table 4.1.5.a: Log Summary of Final Run

Both the RMS error and Mean bias are within acceptable tolerances for wind speed predictions. Our project believes these maps to be reasonably accurate, and although the wind speeds predicted may not be exactly correct, we also believe that the maps generated can be of great use when comparing different possible wind farm sites. The correctness of relative wind speed across the terrain allows the viewer to easily find the best places to build wind farms, even if the predicted wind speed at that area may not be correct. Even if the predicted "best" site in Massachusetts turns out to be less windy than our maps predict, we are confident that it is still the best site when compared to other areas predicted as having lower wind speeds by our map.

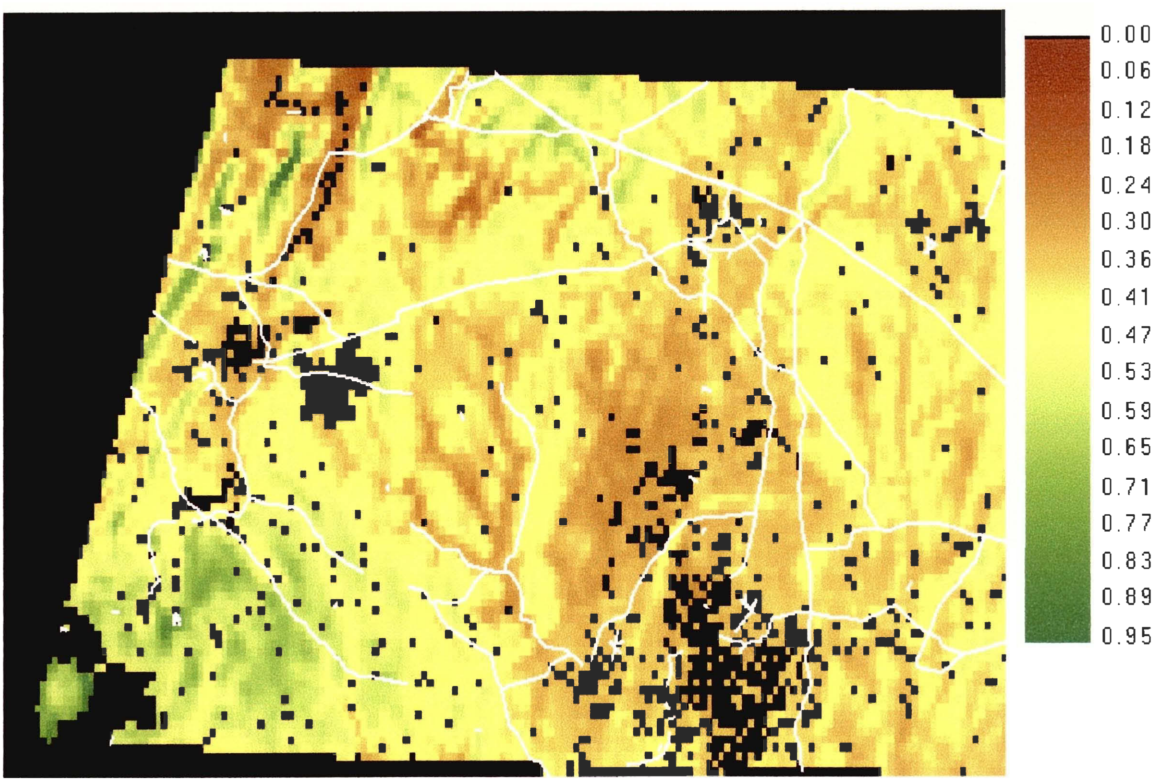


Figure 4.2.a Decision Map with Powergrid Superimposed

4.2. Analysis of Results

The wind resource maps being created, we now consider the procedure for environmental and social analysis outlined in the Section 3.3. This analysis considers along with wind speed land use and type, and distance from population centers and power lines. The results of its implementation are shown in Figure 4.2.a (with power grid superimposed) and Figure 4.2.c (with town boundaries superimposed). The scale shown with these figures is a non-dimensional index corresponding to zero at the theoretically worst sites (i.e. areas not considered applicable to the analysis) and one at the theoretically ideal location. As the coincidence of the perfect conditions at one site (highest wind speed, on the power grid, and furthest from population centers) is unlikely, this theoretical value is never reached. The index is a linear scale of suitability of a site for wind turbine construction.

The maps used for the final analysis were done on a wind speed maps generated at a height of 40m. The stability ratio was 0.2, a neutral vertical profile was assumed, and a 10000m minimum distance from the stations was used for the calculation of initial winds. Examination of this map in comparison to the map of wind speed reveals that they are very similar and areas of a high suitability index correspond to areas of high wind speeds. As speed was the highest weight factor, this is to be expected and lends to the credibility of the analysis.

Three primary areas of interest can be seen on the map: the ridges near Mt. Greylock and Mt. Brodie, the southwest corner of Massachusetts, and the Burnt Hill area. Each of these areas has an index of more than 0.65 in some locations. There are various other areas that also may have potential (as indicated by green on the map) especially the ridge east of Burnt Hill, but these are less likely candidates and would be considered only if the first three areas were not available for development or if outside factors increased the perceived suitability of such a location. The maps also show populated areas such as Springfield, Amherst, Greenfield and Pittsfield as largely black areas excluded from consideration.

The Mt. Greylock/Mt. Brodie area has the overall highest index of suitability (up to 0.947), just as it has the highest wind speeds. Developing the ridge-tops of this area would harness the most wind power. However, siting a wind turbine in such an exposed location may result in heavy opposition on the grounds of aesthetic concerns. The Appalachian Mountain Club operates within this region and such sites may be highly visible from the Appalachian Trail. It is unknown how these factors may influence siting in this region and so they must be further investigated. Further surveying of this region may also reveal sites that would not have such high visibility. Much or all of the area may be within State or National Parks or Forest, making its development unlikely and contingent upon finding which favorable sites might be open for development.

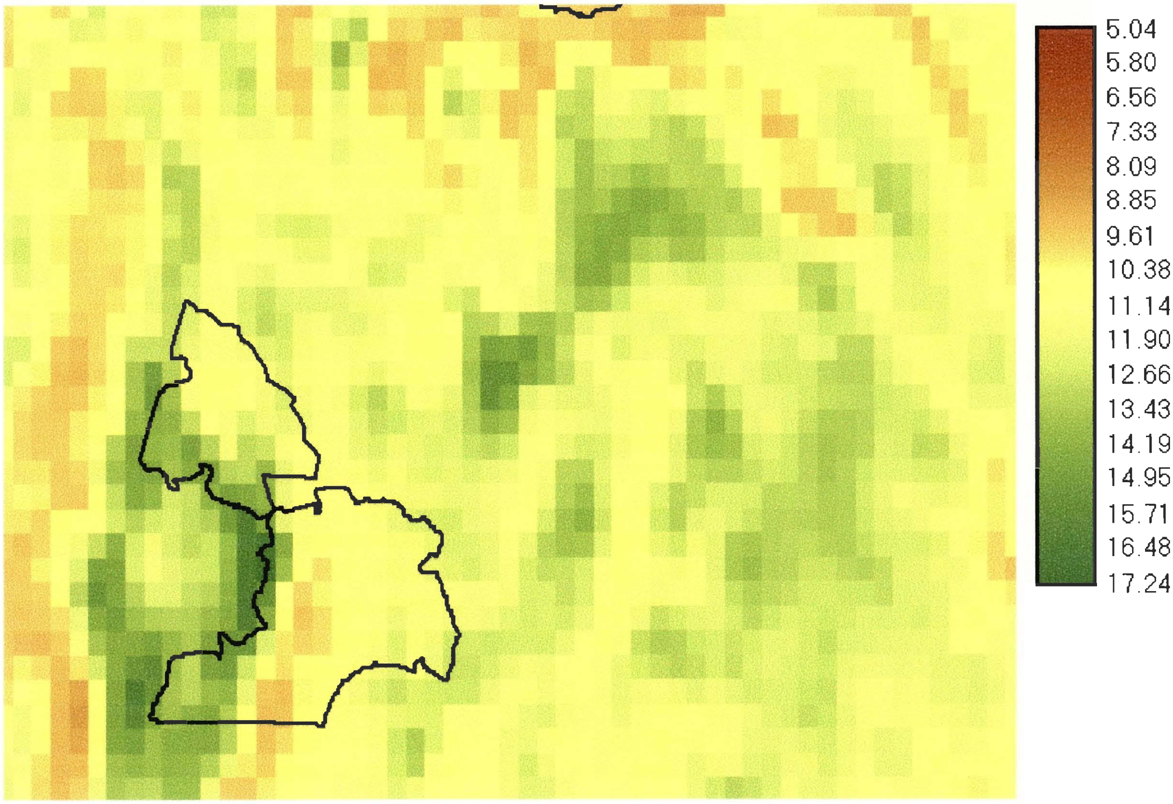


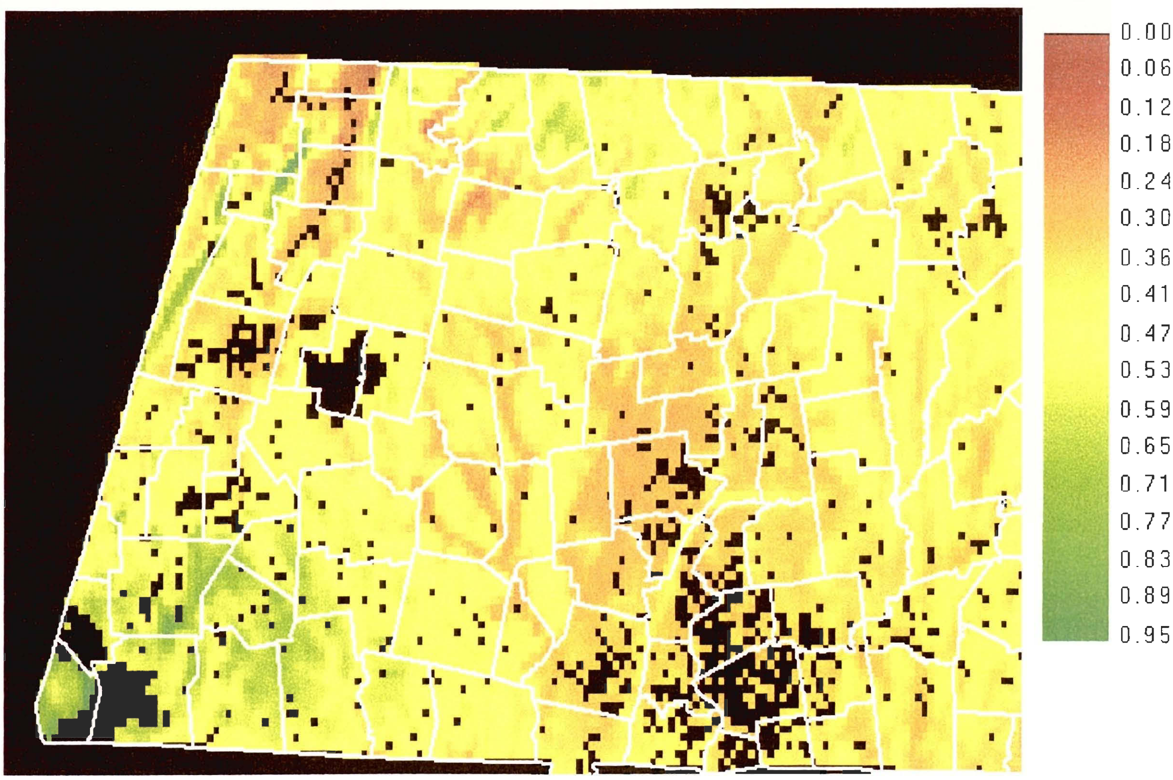
Figure 4.2.b Close-Up of Southwest Mass. With ACEC Superimposed

The southwest corner of the state has a large area with an index of suitability up to 0.921, making it another primary potential site. One may notice a large part of this area is blacked out as forbidden territory of sighting. While parts of these areas have high wind speeds (as shown Figure 4.2.b), they have been eliminated as areas of environmental concern. The more northern area is the Karner Brook Watershed and the southern area is Schenob Brook. They were named Areas of Critical Environmental Concern on 7/17/92 and 8/10/90, respectively, by the Department of Environmental Management. Determination of the possibility of turbine siting on these lands was beyond the scope of this project. Development may be possible on parts of these lands, but is dependent on further investigation.

The Burnt Hill area is the third primary candidate, but with a maximum index of suitability of only 0.663 it is of less importance than the first two regions mentioned. Development in this region may still be favorable if outside factors, such as local reaction, favor such an area and wind power density at the turbine height can be shown to be profitable. However, the region is wind power class 2, which is lower than traditionally considered acceptable for wind turbine development.

Further investigation of sites is mandatory for assessing potential applicability. Consultation of the wind power density map and extrapolation to the desired height may demonstrate whether the region is capable of generating the desired power rating. Wind statistics near the region must be interpreted to see if the potential power is matched by demand for it. The siting process is a complicated and open-ended affair involving technical assessment to see if the potential power of a region is economically viable to harvest as well as social and environmental considerations of the area. A complete assessment must determine which factors are important to siting in a region and then ensure that all of these factors, when taken together, lend to an applicable site. This analysis is done as a starting ground, hoping to highlight areas for further consideration.

Fig. 4.2.c: Speed-weighted Index of Suitability with Town Borders



Recommendations for Further Analysis Work

The potential exists to improve the analysis, making it more robust and overall effective at describing the suitability of sites for potential wind turbine development in a "real-world" context. The analysis as shown above is a simplistic approach and does not consider factors potentially crucial to promoting or condemning a site, such as presence of State and National Parks and Forests. Inclusion of these factors and refinement of the overall analysis technique could be used to produce maps that serve potential developers better.

- Use a more economic intensive approach. The existing siting technique presents the suitability index in a very generalized and abstract way. Each of the relevant factors could be analyzed for life cycle cost effects and a more direct index could be developed with a definitive and meaningful economic value.

- Consideration of State and National Parks and Forests as well as other protected areas. In the current analysis, no attention is given to such regions. Building turbines in these areas may not be applicable and as such they should be eliminated from consideration or assigned a weight appropriate to the likelihood of siting in such areas. Maps are available from the USGS in digital line graph form.
- Consideration of minimum contiguous area. Placing a wind turbine or farm on a small parcel of land may result in problems, including protest from neighboring landowners. The size requirements for a turbine should be assessed and small areas should be weighted appropriately or eliminated.
- Further investigation of aesthetic concerns with ridge-top siting in the Mt. Greylock/Mt. Brodie region. This would involve contacting the Applachian Mountain Club to determine which factors would be important to them as well as consideration of State and National Parks and Forests as described above.
- Further investigation of Areas of Critical Environmental Concern for turbine development applicability. Depending on the status of these areas and the reasons for their declaration as such, development within them may or may not be possible in the southwest corner of the state. The Department of Environmental Management should be contacted for more details.

5. Conclusions

The harnessing of wind power is a socially and environmentally relevant issue. As fossil fuel sources continue to be depleted, renewable power sources such as the wind become increasingly attractive. Use of wind turbines in place of fossil-fuel power plants displaces harmful emissions. Understanding of the siting process allows wind turbines to placed to best utilize existing wind resources and to match social, environmental, and economic considerations important in the area. The development of the siting procedure as evident in this project is an evolving process that strives to match areas of the most cost-effective wind energy to human concerns in the region. This project is an important part of the evolution of wind turbine siting in Massachusetts and New England.

This project has demonstrated the applicability of WindMap and GIS-based siting in Massachusetts. The wind resource maps generated are qualitatively comparable to results found in the National Wind Atlas with a higher resolution (grid size 906m) and improved prediction technique. A preliminary analysis was performed in Idrisi-32 based on social, environmental, and economic factors. Potential wind turbine sites in Massachusetts have been found in the southwest corner of the state, the Mt. Greylock/Mt. Brodie region, and the Burnt Hill region. Their applicability to development has been discussed along with the results. This project provides the groundwork for establishing a state-wide (or even region-wide) public wind power assessment.

The work done on this project could be extended in numerous fashions to better match criteria important to developers. With further experimentation and research, the wind-mapping technique could be refined. The use of more stations would lend additional accuracy as well as allow further comparison between measured data and calculated data. The accuracy of WindMap could also be improved through fine-tuning of various parameters and additional meteorological data.

The analysis of the wind resource maps could be refined to a higher standard of fidelity to better suit the criteria of developers. Additional types of analysis meaningful could be incorporated into the assessment such as consideration of State and National Parks. Further research into the factors important to turbine siting could be done to produce a more quantitatively definitive assessment. The portability of GIS data lends itself to a developmental and progressive analysis process, improving in accuracy as additional data are considered.

This project provides a starting point for siting considerations in Massachusetts. The application of WindMap and GIS-based siting analysis has been illustrated over the region of Western Massachusetts. Further work will need to be done by or with the DOER and other public agencies to expand upon the work of this report and continue to improve accuracy and fidelity of wind turbine siting over the state and the region. The State of Massachusetts Renewable Portfolio Standard requires that a growing percentage of all electricity in the region be generated by new renewable sources beginning in 2003. Much work needs to be done in order to ensure the best possible application of wind turbine generated power to keep up with the state mandate for new renewable sources.

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