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WIND ENERGY IN EASTERN MASSACHUSETTS

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Executive Summary

The growing needs for energy have left the world looking for sources that are reliable and permanent. The use of coal, nuclear, and other types of power plants that supply the vast majority of today's energy demands have serious repercussions on the environment. Each of these types of plants pollutes the air, emits greenhouse gasses, or creates waste that cannot be disposed of. The positive sides of these plants are that they keep up with the amount of power needed by consumers.

Looking into renewable resources is of great importance to anyone concerned with keeping a clean and livable environment. These are the most efficient use of the world's resources that have minimal effect on the environment. Without this technology, the world's coal, oil, and other precious natural resources will be depleted without the possibility of regeneration.

Within the category of renewable resources lies the use of wind energy as source of power. This, unlike coal and oil, is of infinite supply. The ability to harness the wind is a clean and permanent use of a natural resource that will help eliminate the use of power plants. This is a long-term solution that is an efficient use of a resource that remains untapped.

Although there are many positive aspects to wind energy, it is not flawless. Some concerns lies with the avian mortality rates near wind farms, the noise produced by the turbines themselves, and the sporadic nature of wind. Furthermore, fuel-burning plants are still considerably more cost-efficient per unit of energy in almost all cases. However, due to the increasing popularity of wind energy, the technology is becoming more readily available to correct or improve these specific problems.

Since other types of power are, on the short term, able to keep up with the demands of consumers, they are a necessary and vital part of society. However, investing time and money into the research for wind technology is essential to helping the environment, establishing a long term solution to energy demands, as well as keeping up with the progress of other countries pursuit of this technology.

The intent of this project is to produce information about potential locations for wind farms in Central and Eastern Massachusetts that is more accurate than data previously generated. Recent, similar work has been done for Western Massachusetts, laying a foundation for this research. We take advantage of prior research and new software to accomplish this goal.

Finding the most useful and productive locations for a wind farm is called siting, a process that involves several steps. The first step is acquiring data about wind speed and direction. Second, we establish where the wind will be most abundant. This requires interpolation of data for the area being researched (in this case, using the WindMap software package). Finally, we must compare that map to any societal factors that could prohibit the development of a wind farm in the area.

We use wind data from various sources, including data from airports, weather services, and data from the Typical Meteorological Year CDROM archive and the National Climate Data Center. These data files are parsed and processed to produce standardized “wind rose” data about each source for use in WindMap. The wind roses express frequency and mean speed of the raw data.

WindMap processes these wind roses, along with other data, to produce a map of interpolated wind values for a target area. Other data used includes upper-air speed and direction information, Digital Elevation Models (DEMs) constructed from freely available USGS satellite imagery, and a roughness map expressing terrain variations across the target area.

Societal factors considered include relations to the current power grid, distances to population centers and land use concerns. Connecting a potential wind farm to the power grid will be cost-dependent on the distance to cover between existing infrastructure and the new site. Residents and owners of populated land may object to the aesthetic aspects of a wind farm. Also areas of protected status, such as environmentally sensitive zones and national parks, may be implausible sites for wind development.

The use of WindMap yielded several maps, each with varying results, and each with its own unique good and bad features. We considered the balance between smooth interpolation and accurate data. Multiple maps were considered in our analysis, allowing for a holistic interpretation of the wind maps.

Our societal analysis was combined with the wind maps. The results suggested highly attractive wind farm sites in the northeastern region of the state, as well as the Nantucket area and portions of Central Massachusetts near Worcester.

We conclude that several of these identified areas bear further investigation as potential wind sites in Central and Eastern Massachusetts. While our project takes advantage of newer technology than previous work, future research would likely benefit from more detailed examination of wind and societal data as well as more powerful wind-interpolation techniques.

Some of the data used in our analysis may be inaccurate in its representation of area wind patterns or societal details. WindMap, while a considerable improvement over prior technology, is not perfect. Newer and different wind analysis technologies could be used to complement or supercede WindMap. Different societal factors and weighting decisions could create a different view of Massachusetts more aptly suited to the state's idiosyncrasies. Future projects could benefit from a more intense consideration of the societal impact of wind siting specific to Massachusetts, as well as a detailed analysis of each wind data source and the relationships and discrepancies between those sources.

I. Introduction

In today's society, the energy demand is constantly increasing and the problem of where the power will come from must be addressed. Energy sources in use today, such as coal and oil, are finite and cannot be depended on as a long-term solution. The average power consumer is neither required nor likely to be aware of how their energy is produced. There exists an implicit assumption that energy will always be cheap and readily available.

Today, electrical power is generated primarily by fossil fuel plants and nuclear facilities. Fossil fuels like coal and oil pollute the air and will inevitably run dry, leaving the world searching for alternative sources. Nuclear plants pose a real danger of meltdown and produce waste for which there is no long-term disposal solution. Other power plants emit greenhouse gases known to constantly raise global temperatures. This will inevitably lead to rising sea levels and altering climate conditions, which will threaten humans and wildlife alike.[1] All of this shows how very impractical and environmentally unsound current fossil fuels and nuclear technologies are as an energy source.

Some alternatives that have been found to be better for the environment than burning fossil fuels are renewable resources. These are defined as any source that uses the world's natural resources and will not be depleted, or can be replenished.[2] Much research has been put into the development of renewable energy in the United States as well as in other countries. However, a common resource that has yet to be fully exploited is that of wind energy. This is one specific resource among many that has been found to be an environmentally and economically sound use of the world's natural resources, as we will explain further in Chapter 2.

Due to its positive aspects, there has been a recent growth in the research and pursuit of wind energy. Finding the locations where wind turbines will be most productive in converting wind energy directly to power is one of the main aspects of wind development. By ascertaining these locations, the wind can be harnessed most effectively and economically. A single location can house an array of turbines, which is called a wind farm.

Research has aided in the development of more efficient wind farm placement. New software and maps are being developed that enable more accurate and informed identification of potential wind farms. This process, called "siting," can be divided into a set of distinct subtasks. These tasks are gathering and manipulating wind data, producing wind maps, and analyzing these maps in contrast with societal factors. A more detailed description of these tasks is outlined in the methodology.

A previous IQP (SWP-9903) has broken ground and applied newer wind processing techniques to Western Massachusetts. Like this project, the previous IQP made use of the WindMap and IDRISI software packages. However, their wind data was limited to only five stations, reducing the potential accuracy of their wind interpolations. *****

Eastern Massachusetts has not yet been evaluated using similar techniques. Our contributions, including our use of WindMap for wind data analysis, will offer a great deal of potential improvement over existing knowledge about wind farm siting in this area. Furthermore, our available wind data consists of 19 distinct sources, providing a great deal more potential for highly accurate wind interpolation maps.

Our goal is to use newly available technology to produce a state-of-the-art wind analysis of Eastern Massachusetts. We will use the knowledge gained by Western Massachusetts research, as well as a comparatively large number of wind data sources, to create detailed wind maps of the state. We will analyze social factors impacting the development of wind energy in sited areas, and identify promising locations for the placement of wind farms.

Upon the completion of this project, there will exist a more accurate assessment of the entire state of Massachusetts' wind patterns and potential resources than has previously been available. Our results will reflect a higher precision in interpolation and more informed analysis of localized geographic features than previous research, thanks in large part to the use of Brower's WindMap package. The information we will produce is of great potential value to energy developers in New England, and will further the capacity to responsibly apply wind energy technology in Eastern Massachusetts.

II. Literature Review

The validity of our research depends on fully understanding the state of wind energy in the context of current global energy production. We completed an extensive review of the necessary literature on different forms of energy, their applications and environmental impacts. Throughout our research, we focused primarily on wind as a source of power, and particularly its politics, advantages, and problems therein.

A. Present Situation

In 1990, the United States generated 3,023 billion kilowatt-hours (kWh) of electricity. Of that number, over 2,000 billion kWh came from burning fossil fuels, while nuclear power contributed slightly less than 600 billion kWh. These two sources represent approximately 85% of the total power produced in the United States that year. In that same year, wind, solar, and geothermal energy combined contributed less than 1% of the total power produced.[2]

The demand for energy is always increasing, and it is projected that in 2010, fossil fuels will be producing nearly 3,000 billion kWh of electricity, with nuclear plants slowly moving up to approximately 650 billion kWh.[2] This increase in the use of fossil fuels will deplete the supply even faster, leaving future generations with fewer resources.

Fossil fuels and nuclear power are not without their own advantages. The world's coal supply, while finite, is still quite abundant. Coal plants are also capable of keeping up with the demand for energy, which is why it is the most widely used form of power. Nuclear power, in addition to being economically sound, emits very few air pollutants and only half as many greenhouse gasses as coal power plants do.[3]

While these power plants may be necessary to accommodate the increasing energy demands, fossil fuels and nuclear power plants have serious repercussions toward the environment. Nuclear power has gotten a bad reputation since the Three Mile Island accident in 1979. This meltdown, one of the most well-known nuclear power plant accidents in the U.S., shows that this kind of disaster not only could potentially happen, but actually has, and thus could recur.[4]

Coal plants are not without their faults either. These power plants create pollutants such as sulfur dioxide and carbon dioxide, the latter being known to enhance the greenhouse effect. Although the exact implications of the greenhouse effect are still unclear, it may affect the world's crop production, with grain constituting 80-90% of the world's food supply. Recent studies have shown that overall crop losses to insects and weeds will increase with global warming.[5] Sulfur dioxide is known to be a cause of acid rain.[6] To put the amount of pollutants that non-renewable energy sources cause into perspective:

> In 1990, California's wind power plants offset the emission of more than 2.5 billion pounds of carbon dioxide, and 15 million pounds of other pollutants that would have otherwise been produced. It would take a forest of 90 million to 175 million trees to provide the same air quality.[7]

Increasing the use of renewable resources would allow for less dependency on those sources which pollute the air, emit greenhouse gasses, and have the risk of nuclear meltdowns.[2] Renewable resources have many advantages that fossil fuels cannot compete with, which makes them essential for the environment.

B. Renewable Energies

Renewable energy is making its way into the mainstream of power suppliers faster than was anticipated only a few years ago. It is predicted that by the year 2020, 10-15% of the world's energy will be supplied by renewables.[8] Although renewables were our primary focus, other alternatives were researched to be impartial.

Energy efficiency, cleaner air fuels, and renewable resources were all considered. Energy efficiency, which uses appliances and equipment that reduce costs and have minimal impacts on the environment will certainly help by cutting down the amount of fuels used to run power plants, but this is not enough.[7] This will only prolong the inevitable, by slightly increasing the amount of time until all of the world's fossil fuels are expended. Clean air fuels are also a consideration, but only aid in cutting down air pollution. These oxygenated fuels have been proven to reduce carbon monoxide emissions in several cities in the U.S., but are still limited in supply.[9] This will certainly help to reduce emissions of carbon monoxide and smog, but is not a permanent solution. Renewable resources seem to be the most viable solution, being independent of fossil fuel supplies and inherently cleaner than traditional energy resources. The focus of this section is on renewables due to their superiority over energy efficiency and clean air fuels.

Renewable resources are those that do not use up the world's natural resources. There are many different kinds of renewable technologies, some of which include wind, solar, biomass, and geothermal. Each of these different technologies uses resources that can be renewed and replaced. This, among other reasons, is why renewables will be such an invaluable part of energy for the future.

In general, renewable resources have little negative effect on the environment. They do not emit toxins into the air, they produce only a minute amount of greenhouse gasses, and they have an unparalleled advantage over burning fossil fuels: they can be replenished. There will never be a day when there is no more sun or no more wind;

renewables are thus a valuable technology for the world's future. Even a technology like biomass, despite its few disadvantages, has the means to re-grow all the natural resources that it consumes.

Not all renewable resources are environmentally hazard-free, however. Some renewable technologies are too aggressively implemented, and produce a small amount of greenhouse gases as well.[10] For example, biomass is using up more trees than it should when not properly managed. There are even instances were it is being overexploited when management techniques are in place. It is burning more than can be replenished, thus making it less environmentally helpful.[11] Overuse of biomass resources is also bad because living trees absorb carbon dioxide, so the trees that are not replaced will be unable to absorb greenhouse gasses. Technologies like biomass are not yet perfected, but when properly managed, will be able to help sustain the world's energy needs.

C. Wind Energy

Renewables are good for the environment, particularly wind energy. Wind energy does not require anything to be cut down, depleted or burned. Wind flow and consistency will not be altered by the presence of wind farms. Wind energy is not prohibitively expensive, and is free from many of the hidden social costs related to traditional energy resources.

1. Advantages and Disadvantages

Wind farms are possibly one of the cleanest sources of energy that exists today. Wind energy does not emit carbon dioxide into the air and it does not need to be replenished. Having a source of energy that does not need to be managed as biomass does is a vast improvement over the way fossil fuels are used up today. This, along with the lack of greenhouse gasses produced by wind farms, makes them an invaluable technology for the future. All of these facts make wind energy one of the most economical and environment-friendly ways available to generate power today.

The use of wind farms today show just how far wind energy has come since its uses in the early 1900's. While wind farms are used for direct production of power today, earlier applications included pumping water as well as grinding grain.[12] Another application that predates even these, but is still widely in use today, is the sailboat. This is one of the most simple and effective uses of the wind that reduces the use of gasoline by powerboats. Although our society is beyond using the wind to pump water, it is important to see how far we've come from such simple applications.

It is also important to realize that while early uses of wind energy had minimal drawbacks, more modern usage of the wind has created a few problems socially as well as environmentally. These may be a problem at the present, but they are all correctable with time and effort.

The noise wind farms produce and current costs, have been the cause of some controversy. The noise caused by the spinning of the blades and the generators can be bothersome to residents living near wind farms. This makes locations hard to find, since they must be somewhat distanced from populated areas.[13]

The cost of wind farms is also, for the time being, an issue as we will discuss further in the next section. It is currently cheaper to burn fossil fuels, and fuel-burning plants can keep up with the demand of energy needed. However, the technology is being pursued now more than ever. As a result, costs will go down over time, and more efficient wind generators will be developed, which will be able to keep up with the growing demand for power.[7]

An issue of some concern to environmentalists is the increased death of birds in wind farm areas. Birds have been killed from flying into the propellers of wind turbines. This situation is being looked into. Researches have found that making some simple modifications can decrease avian mortality rates. One option is to make the center region where the blades meet larger, since this is where the blades move the slowest. Painting the blades with highly visible colors will also help with this problem.[14]

While these drawbacks may cause some controversy, the positive aspects of wind energy are undeniable. This is why the research is being pursued now more than ever, and not only by the United States, but in many other countries as well.

2. Developments in Other Countries

In addition to the United States, wind energy is being pursued in many other countries. China, Russia, India, and especially Denmark, have all initiated and developed numerous wind energy projects, and are focused on using wind energy as a primary renewable resource.

Some countries have independently planned and erected wind farms, while others have received assistance or materials from outside sources. For example, The Gujarat Energy Development Agency in India set up a 1.1-MW demonstration wind farm in 1986. As of 1999, 130 MW of wind power existed in Gujarat, 117 MW of which were added since 1993.[15] In contrast, Europe's largest wind farm in Carno, Wales supplies electricity to 25,000 homes, and its turbines were built in Denmark. Wind turbines are Denmark's fourth largest export commodity, which was worth $525 million in 1997.[16]

Denmark is leading the world in wind energy production. All countries are making progress in wind energy at different rates, and it is encouraging to see that more developments are being made every year. These help to ensure that globally, wind energy will have astounding advancements through the 21^{st} century.

Detailed information on wind energy developments in other countries is included in Appendix A.

3. Economic Considerations

Wind energy has, since 1980, gone from being a fairly costly experimental resource to a practical, affordable and commercially competitive source of energy.[13] The issue of wind energy application is no longer how to apply the technology, but when and where. Because financial considerations will no doubt be of great importance to both state and private investors, it is necessary to be aware of the various economical aspects of wind energy.

Installing wind farms can be costly in the short term. Locating a sufficiently isolated site, constructing the installation and connecting to the power grid are all more prohibitive than in the case of traditional fossil fuel plants. These costs, however, are not nearly so considerable in the long run, and there are several social and environmental benefits that are directly relevant to the investor and the economy.[17] Wind energy installations require a minimum of maintenance comparatively. Money saved on maintenance is enough to balance the initial investment required for wind energy. Furthermore, equipment failures do not entail the dangers of a nuclear plant.

The fuel for wind energy, being fundamentally different than fossil fuels, cannot respond to demand. Wind is intermittent, more so in some places than others. Power is not necessarily a constant from any given wind farm. Batteries can be used to some extent as a solution to this problem, but are adequate only for short-term intermittencies.[18]

However, as wind energy does not depend on an external fuel supply (unlike gas/oil resources), it is not subject to the rapid fluctuations in price that have been seen in the oil market, notably the oil crisis of the mid-to-late 1970's. As such, wind energy offers a relatively dependable return to investors, independent of foreign political climates.

Socio-economically, the greatest benefit of wind energy is that it is a very clean energy resource. As such, it does not carry with it the hidden costs related to polluting resources. As stated above, the use of wind energy will not increase the release of greenhouse gases, deplete domestic natural resources, or lead to higher disease rates as a result of energy production byproducts, all of which lead directly to societal and investor costs (that is to say, lawsuits).[19] Wind energy reduces the risks related to power production, and thus the economic responsibility of those producing the power.[20]

4. State and Federal Government Involvement

There exists a profound and highly relevant link between governmental support of energy technology and the widespread application of that technology. For wind energy to see continued growth, it is important that investors are given good reason to believe that wind energy is going to be supported by local and federal government. The federal government has directly involved itself with wind energy for several years now through funding and research. Many state governments have contributed as well.

Wind energy, like any other energy resource, is funded largely by private investors and investor-owned utilities (IOU). Federal and state government aid in energy projects is often an incentive to get involved in a specific energy resource. Utilities (municipal and IOUs) benefit more from energy investment than non-utility developers, often due directly to the criteria for government aid.

The United States federal government has involved itself in wind energy in a variety of ways, including turbine and wind research as well as direct funding and co-funding of various wind energy installations. The U.S. Department of Energy (DOE) has established the National Renewable Energy Laboratory (NREL) and the Wind Turbine Verification Project (TVP) specifically to advance the state of wind turbine technology. The NREL has been active in locating prime sites for wind farm placement as well.[21]

The DOE/TVP has been involved in co-funding wind energy installations. In Iowa, the TVP funded $1.3 million of a $2.8 million 2.25-MW installation in 1998. In Texas, the DOE provided $1 million to a 6.6-MW project. Another $4.4 million was provided by EPRI, the Electric Power Research Institute, a non-profit research company.

One important incentive currently being offered to wind energy developers by the U.S. government is the Federal Production Tax Credit (PTC) for wind energy. This PTC grants utility-scale wind energy developers a $0.017/kWh credit, a considerable number considering the small discrepancy between wind energy costs ($0.05/kWh) and competing fossil fuel costs ($0.015-$0.03/kWh). The potential expiration of the PTC on June 31st, 1999 actually spurned a period of rapid wind energy growth in early 1999 in order to match the deadline for tax credit. The PTC has since been extended to December 31st, 2001.[22]

State government involvement has also been notable and a few states have shown well above-average wind energy growth thanks largely to state involvement. California is currently leading the U.S. in wind energy deployment. The California Energy Commission (CEC) has established a variety of programs to encourage utility and private installations of wind energy. The state had seen well over $3.2 billion in private investments toward wind energy by 1991, and in 1995 produced approximately 30% of the world's wind energy.[22]

Minnesota has similarly encouraged the private employment of wind energy by limiting or eliminating state taxes on energy income from private installations under 5 MW. Minnesota has also seen very active discussion and advancement of green taxes to discourage polluting energy resources in favor of wind power and other clean energy resources.[18]

For its share, Massachusetts has been involved in both research and application, directly and through tax incentives and energy regulation. The state's Division of Energy Resources (DOER) has helped fund the Renewable Energy Research Laboratory (RERL) at UMASS. DOER has also funded wind energy installations in the state, including the towns of Beverly and Hull. The RERL currently operates the largest wind turbine in the state, a 250-kW turbine owned by UMASS and located on Mount Tom in Holyoke.[17]

Massachusetts also offers several tax incentives to promote the application of renewable energy resources. These incentives cover a wide variety of state taxes. There exists a 15% income tax credit on system installation and use costs for individuals installing renewable energy systems in their residences, state sales tax exemption on the sale of solar, wind, or heat power system for a person's primary residences, local property tax exemption for up to 20 years, and a corporate income tax deduction for business installing wind or solar-powered heating and climate control units.

Finally, through the Massachusetts Electric Utility Restructuring Act, the DOER established the Renewable Energy Portfolio Standard (RPS). The RPS requires that electricity suppliers provide customers with a minimum amount of renewable energy. By 2003, the RPS requires 1% of all energy being provided to be renewable, increasing thereafter by 1% per year until disbanded by DOER. Clearly, Massachusetts has been taking a proactive stance on the implementation of renewable resources projects.

5. Physical Characteristics

In order to intelligently utilize wind energy, it is essential to understand the characteristics of wind and the way in which turbines harness it. The physical qualities of wind, its causes and dynamics, the manner in which wind interacts with the Earth's surface in a local context, and turbine technology are all relevant aspects to any analysis of potential wind farm installations.

a. Physical Qualities of Wind

Wind is caused by the heating and cooling of the Earth's surface as the planet rotates. Geostrophic winds occur at altitudes 1,000 meters or higher above ground level. These winds, for obvious reasons, are not influenced by discontinuities on the Earth's surface. Instead, they are influenced mostly by temperature differences, which create pressure differences high above the earth's surface.[23]

b. Interaction with the Earth's Surface

While global wind patterns are observable from a localized perspective, wind levels are very much dependent on terrain, elevation, surface roughness, and a myriad of less influential variables. These all affect the overall wind speed and consistency in a given area, parameters that are central to wind energy production.[24]

Terrain has a very considerable effect on wind speed. Flat or rolling areas, like the planes of the Midwest, in general see very little discrepancy between locally measured data and what could be predicted from the movement of the jet stream. More mountainous terrain sees greater variation, with accelerated wind speeds near ridges and lower wind speeds on the sheltered side of sharp terrain.[24]

Surface roughness, expressed in terms of ground cover, can also have a profound effect on local wind speeds. Cropland and grassland have very little effect on wind speed. Areas of mixed woodland and cropland tend to slow wind slightly, but not prohibitively. Heavy woods and urban areas have significant slowing impact on wind speed, and forest areas so significantly decrease wind speeds that wind energy sites in such locations aren't generally feasible. (Bodies of water have nearly no slowing affect on wind, but are obviously unsuited for wind energy installations as they hardly offer a solid foundation for multi-ton turbines.)[25]

Wind speed also varies greatly based on the distance from the ground. Over fairly smooth terrain, wind speed decreases steadily as the height decreases. This translates to higher efficiency for taller turbine installations, as well as data discrepancies for wind measurement devices installed at different elevations. In mountains and on the wind-facing side of ridges, the height from the ground is less of an issue as the angle of slope tends to cause acceleration of the wind near the ground. Once we have a clear understanding of how the Earth's surface influences the wind, we need to study how wind power is harnessed by turbines.

c. Turbine Technology

It is vital to base turbine placement on the various characteristics discussed earlier, because a difference of some percent in wind speed has much larger effect on efficiency than a merely linear relationship. The amount of power that can be collected by using wind turbine generators is actually not linear with increasing wind speed, but exponential. In general, at 15°C with an air density of 1.225 kg/m^3, the formula for power in W/m^2 is $(1/2)(1.225)(v^3)$ where v is the wind velocity in m/s.[26] This shows that getting every extra meter/second of wind goes a long way for producing power, as a 10% increase in wind speed yields a nearly 30% increase in energy production.[24]

Turbine technology has been developed and refined over the years to take advantage of wind characteristics. There are two main types of wind power generators: horizontal and vertical. The type that most people think of when they picture a wind farm is the horizontal. This type has blades that spin like that of an airplane propeller, with its main shaft horizontal to the ground. The other type, the vertical or eggbeater type, works similarly, only the blades spin parallel to the ground, with the main shaft perpendicular to that.

The way horizontal wind towers work is somewhat basic, but still effective for the purpose they serve. Wind towers are typically very tall, some even up to ten stories high, and each has a large fan at the top of it, typically equipped with two or three blades. Their large height reflects the fact that the wind is usually stronger and more consistent high above the ground. For a smaller wind power generator to work, the wind speed needs to be at least 3.5 m/s, and up to 6 m/s for larger generators.[12]

The blades, or rotors on the tower, catch the wind and turn. The main shaft that the fan is attached to rotates, and this shaft is attached to a generator, which in turn rotates, creating power. Wind turbines convert the kinetic energy of the wind into mechanical power by the physical turning of the generator. This power can go directly to the home, business, or whatever the turbine is powering. If it is generating more energy than is needed, the surplus can be stored.[7]

Vertical generators operate very much the same as horizontal generators do, but are structured differently. The eggbeater generator looks exactly like it sounds, with multiple blades curved outward around a central shaft that rotates to generate power.

III. Methodology

The objective of this project is to assess wind energy potential within Eastern Massachusetts. To facilitate this assessment, we use software and gather wind data to produce wind maps. We analyze and compare these maps with social and geographic data to determine the most ideal locations for wind farms. This process is divided into the following four distinct tasks, as described in this chapter:

- Software Review
- Gathering and Manipulating Wind Data
- Producing Wind Maps
- Analysis of Wind Maps

A. Software Review

Several software packages are available that can be used to address the various aspects of wind energy. As our goal is to produce accurate, useful data, it is important that we acquire and use the tools best suited to our work. A review of existing software is therefore an important task that defines the direction of this IQP. For the purposes of our project, we need the capacity to process Geographic Information System (GIS) data, as well as a means to create a map of wind patterns over the area of Central and Eastern Massachusetts. This section describes four packages relevant to addressing aspects of wind energy.

1. IDRISI

IDRISI is a GIS program with a wide range of data-processing features. In general, IDRISI takes a bitmap and vector data as input, and through any number of data transformations produces a raster file as an output. This raster file is an array of numerical values of some specific set of data (be it elevation, roughness, etc.). IDRISI offers several tools that are very well suited to the tasks that this project involves.[27] Though not directly related to wind calculations, IDRISI provides useful features for determining social factors regarding our wind data, allowing comparisons and calculations between several layers of geographic information.

2. WindFarmer

WindFarmer is designed to analyze in detail the physical layout of turbines in a wind farm. It is able to calculate such wind turbine characteristics as noise and power output, while also considering loss of wind energy in the wake behind the turbine.[28] WindFarmer proves to be a powerful tool in wind analysis. However, as the task of placing wind turbines on wind farms is beyond the scope of our project, we do not utilize WindFarmer.

3. WindMap and WAsP

WindMap and WAsP are two software packages that are commonly used to evaluate wind energy potential. Both programs can perform terrain-sensitive wind interpolation. WindMap, the end product of years of wind research by Michael Brower, is suited to larger geographic areas on the scale of our project area. WAsP, by contrast, focuses on more site-oriented details.

WindMap has the ability to predict wind speeds, wind power density, and turbine output across an entire region. It can also accurately show the effects of terrain obstacles on wind flow. For WindMap, no GIS is required because it allows the display and query of terrain, roughness, and wind maps from within the program.[29]

WAsP (Wind Atlas Analysis and Application Program) is able to calculate wake effects on wind farms, wind flow in complex terrain areas, and loss of wind flow caused by three-dimensional objects. The program allows the user to specify different obstacles and terrain height differences when performing detailed wind turbine siting.

For our purposes, WindMap is desirable for simple economic reasons. The DOER has donated a copy of the software to WPI for wind energy projects. Considering the high price of many software packages, having access to software for free is a boon.

Unfortunately, WAsP is priced at $2,420, which is a prohibitive cost in this project.[30]. WAsP would be more suitable for the analysis of individual wind farms, rather than in the large-scale siting on which this project focuses. For these reasons, we decided against purchasing this software.

B. Gathering and Processing Data

Initially, several data types are needed to produce the maps that we use. Digital Elevation Models (DEM), wind data from anemometers, and upper air data are among the different types of data that we collect.

1. Wind Data

Our wind data consists of direction and speed information from several sources. These include data from airports, weather services, buoys, and other resources. These data cover various time-spans, many of which are six to twelve month or longer periods, with updates every hour or less. The data comes from points across Massachusetts, with the majority of stations located near the Eastern border of the state.

Wind data is taken from several distinct anemometer stations. These stations are Beverly, Boston, Buzzard's Bay, Fairhaven, Halibut, Hyannis, Lawrence, Martha's Vineyard, Nantucket (2), New Bedford, Norwood, Otis, Plymouth, Provincetown, Worcester, Yarmouth, and Providence, RI. These data come from a variety of sources, including TMY (Typical Meteorological Year) CD-ROMs, NCDC (National Climate Data Center) CD-ROMs, airports and weather services. The data files come in Microsoft Excel, Microsoft Access, or plain text file format. The locations of these stations are shown in Figure 1.

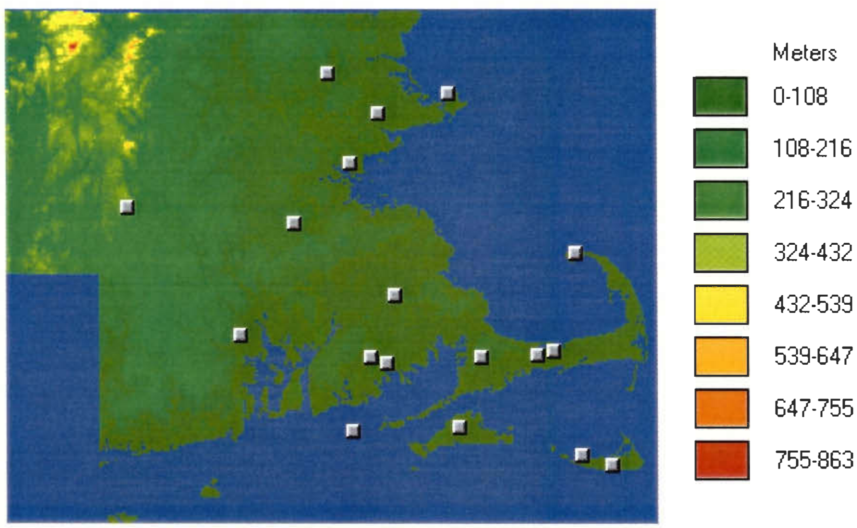

Figure 1. Digital elevation map showing location of all 18 stations

There are several reasons why we use the provided wind data. Most importantly, wind data is one of the required inputs of WindMap, and calculations are impossible without it. In addition, the more stations used in WindMap's calculations, the more accurate its results are, and a better representation of the analyzed area is formed.

Overall, the provided wind data spans a variety of time periods. For this reason, we must decide which data to use that represents a fair and accurate model of a particular area's wind patterns. Therefore, we attempt to use data that cover identical or similar time periods.

a. Producing Wind Roses

From each of these sources of anemometer data, we calculate mean speed and frequency. This is done by sorting all data points into 12 bins of 30 degrees each, based on the measured wind direction for each point. These bins are 346-15 degrees, 16-45 degrees, and so on for the remaining bins. Any two consecutive data points with measured speeds of zero are considered frozen data and are excluded from calculation. For each bin, mean speed is calculated by dividing the total bin speed by the number of data points in the bin. Frequency is calculated by dividing the number of data points in the bin by the total amount of data points in all 12 bins. The result of these calculations is an average wind speed and frequency for each of the 12 bins. These 24 values are referred to as a wind rose, which is a visual representation of wind information for a particular anemometer (see Figure 2).

Figure 2 is a wind rose for Nantucket. The window on the left displays the frequency information, while the right depicts the mean speed. The dominant direction can be identified by the point with the highest magnitude in the frequency window. Nantucket's dominant direction is approximately 240 degrees. The mean speed shows consistency in all directions, with speeds varying from approximately 5.5 to 8m/s.

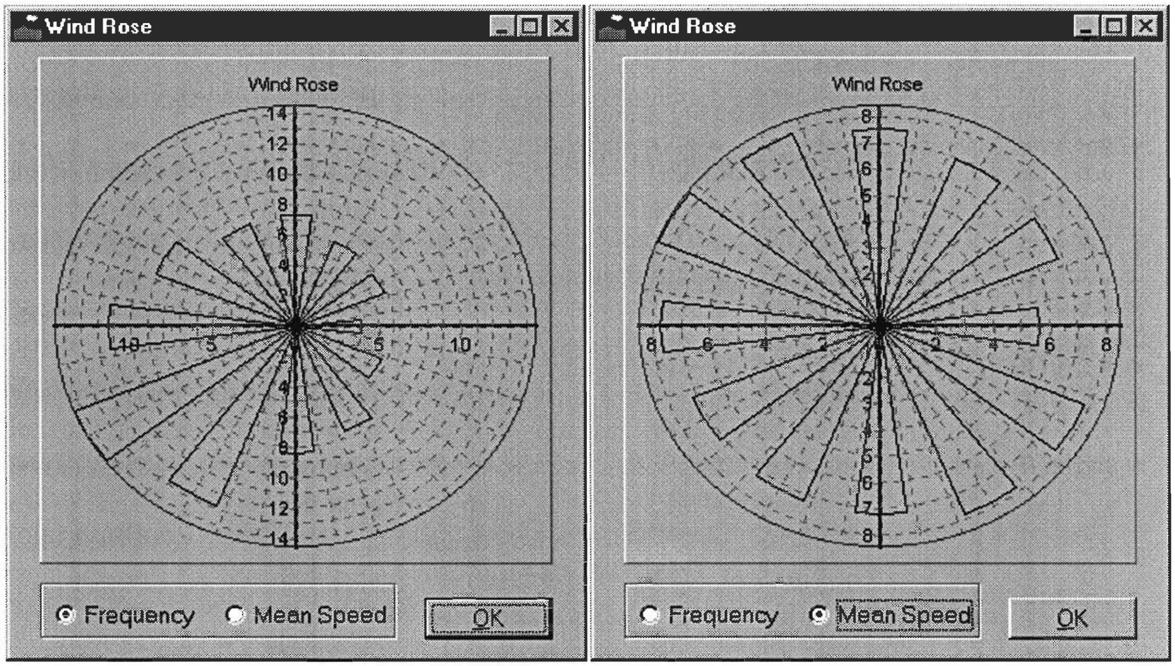

Figure 2. Wind rose for Nantucket anemometer A

b. Upper Air Data

In addition to the data listed in section 1, upper air data for Chatham, MA is provided from http://raob.fsl.noaa.gov/. These data, gathered by a weather balloon, include measured wind speeds and directions at various elevations higher than those measurable by typical anemometers. To calculate the wind rose, we first select a focal point elevation value. This upper-air value has been chosen largely for consistency with the work of the Western Massachusetts project. For our purposes, this value is 1,500 meters. Next, values within a certain range above and below the focal point – 500 meters - are selected as potential data points. Finally, the wind rose is calculated as described in the previous section. Once we have all the upper air and ground station data, the next logical step is to convert the DEMs into a format usable by WindMap.

2. DEM Processing

In order to analyze wind speeds with WindMap, we need to have some information about the topography of Massachusetts. WindMap can determine, from such information, the effect of terrain variations on interpolated wind patterns. This information takes the form of a Digital Elevation Model (DEM). The DEM is a map that expresses the terrain elevation at every point (to a certain resolution) in a mapped area.

To create a DEM for use in WindMap, we use freely downloadable USGS DEM maps. These maps are at 250,000:1 scale, culled from satellite photos. The maps are approximately rectangular, organized into "quadrangles," with each set of maps (the quadrangles are split into east and west halves) labeled according to the notable geographic area contained therein. These files are available from USGS either in uncompressed format or compressed with the gzip utility (a common compression/decompression standard on UNIX systems). The quadrangles that contain portions of Massachusetts are Albany, Boston, Chatham and Providence.

Once downloaded, these maps must be converted into a form usable by IDRISI. The simplest way to do this is a two step-process. First, the files must be converted to some sort of graphical bitmap (that is, a format where the data is organized as a linear series of discrete, same-size chunks). They must then be imported into IDRISI.

To convert the files, we use the DEM2tga utility. This simple utility, written by Jon Larimer, parses the USGS DEMs and outputs a targa (.tga) graphics file. Targa is a fairly common, open standard, and is supported in many graphics applications, utility of which is important: the converted files can be easily checked for corruption by examining them in an image viewer. DEM2tga also yields the latitudinal and longitudinal bounds of the

DEM in decimal degrees (where hours and minutes are converted to a decimal fraction), as well as the minimum and maximum elevation of the image.

Having converted the DEMs to the targa format, we import these into IDRISI32 using the PARE utility. PARE, available in the "File >> Import >> General Conversion Tools" menu, is fairly straightforward. It requires an input filename, an optional header size, and the dimensions, elevation range and latitudinal/longitudinal bounds of the data. PARE then strips from the file a number of bytes corresponding to the given header size and translates the remainder of the file into an IDRISI .img file of the given dimensions, according to the given bounds. For our targa files, the header size is 786 bytes, the dimensions are 1201 pixels square, and the elevations and bounds are those provided by DEM2tga for each respective file.

Note that it may be simpler in some cases to convert the USGS DEMs to a raw bitmap file, rather than a .tga or other graphics formats, as PARE strips whatever format-specific information is available. In fact, it is trivial, with a working knowledge of C programming, to modify the DEM2tga.c code to do exactly this. However, it may be useful to view these images in a context other than IDRISI. In cases where converted versions of the DEMs are distributed, there should be no difficulties so long as the header-size of the format is known. The DEM2tga.c code is in the public domain.

It is also necessary to invert the resulting IDRISI along the Y-axis, as the targa files seem to hold an upside-down image of the USGS DEMS. This is a trivial procedure in IDRISI, thankfully; were it more difficult, we would consider editing the DEM2tga.c code to rectify the problem.

Having successfully imported the USGS DEMs into IDRISI, our next step is to create a single large map of the Massachusetts area. To do this, we use the CONCAT utility (available in the "Reformat" menu in IDRISI32). We take advantage of the "Automatic Placement Using Reference Coordinates" option. This option causes IDRISI to line input files up according to their degree coordinates. The output is a seamless DEM map of the Massachusetts area.

For WindMap to use our DEM, we need to convert the coordinate system to a meters-based format. We use an IDRISI utility, PROJECT, to convert the map from its somewhat distorted degrees-based format to IDRISI's spc83ma1 space-plane coordinate format. The resulting projection is less distorted and readable in WindMap.

At approximately 6400 by 3000 pixels, our DEM is far too large for practical use. Calculations on the data would take a prohibitive amount of time, assuming our system doesn't crash outright. We therefore reduce the size of the DEM. To do this, we use IDRISI's CONTRACT utility. We reduce the map by a factor of 10 in both the X and Y directions.

Furthermore, as our focus is on the eastern portion of Massachusetts, we can crop much of the bordering area. We use IDRISI's WINDOW utility, specifying an area from the easternmost tip of Cape Cod, west approximately 300km (400 pixels at what is about 750 meters per pixel resolution). The resulting cropped DEM is approximately 300 by 400 pixels in size. The DEM is now ready for use in WindMap.

C. Generating Wind Maps

Once all the data are collected (wind roses, upper air (UA) data, DEMs, and roughness maps, which are described later in this section) we begin to use WindMap to output wind profile maps of Eastern Massachusetts. While only the DEM and one wind rose are necessary for WindMap to operate, we gather as much data as possible to ensure the most accurate map possible. Once WindMap is open the options for importing data are available, as we discuss in the following sections.

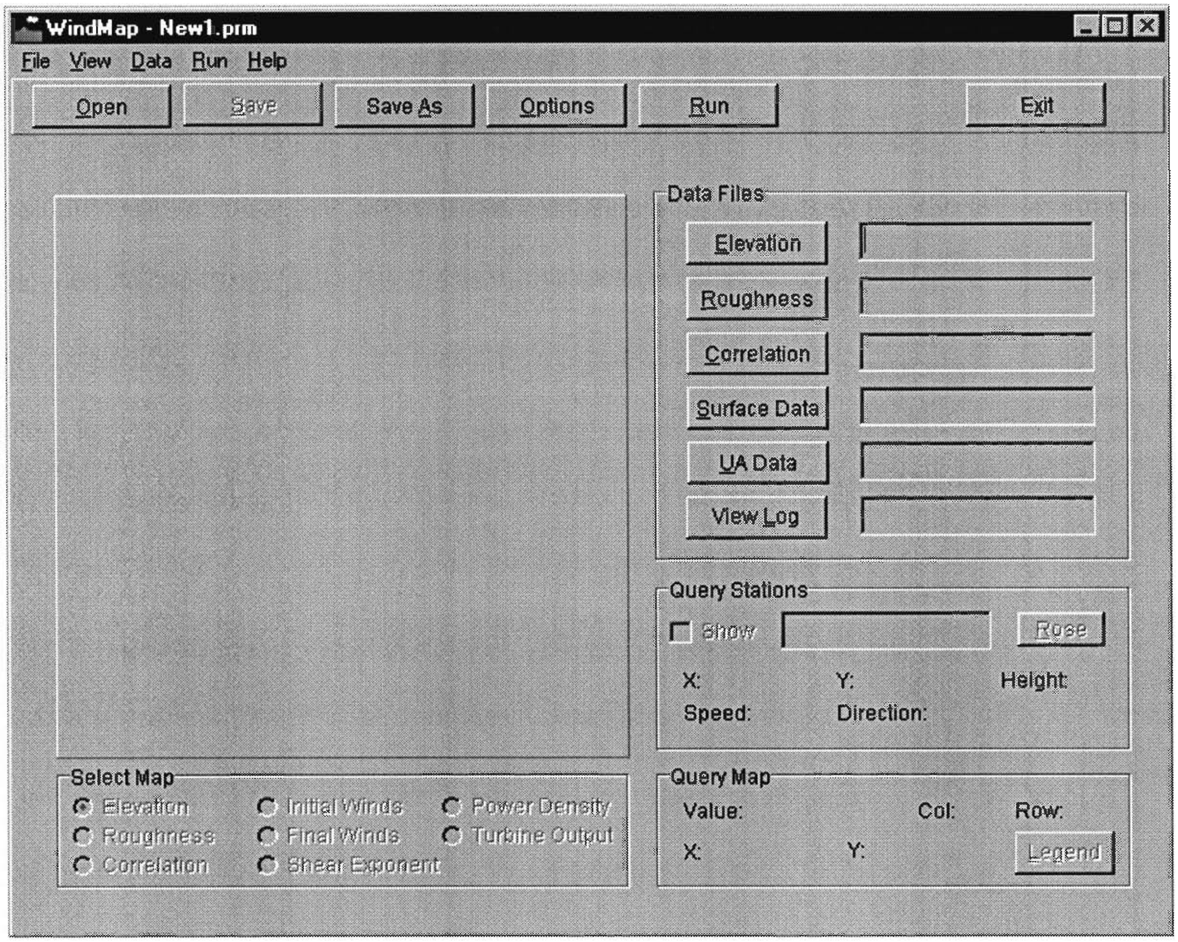

Figure 3. WindMap main screen

1. Elevation Map

On the right-hand side of the main screen (see Figure 3) there are several different buttons used for importing the data mentioned above. The first of these is the elevation data, used for importing the preformatted DEMs of the area that the user is profiling. Once this is done, there exists a map of the section being profiled in WindMap's main window on the left. The "Legend" button, on the bottom-right corner of the main screen, can be used to display the color-coded values for either the elevation maps, as well as any of the other maps that are displayed in WindMap, such as Initial Winds, Final Winds, Power Density, Turbine Output, or Roughness.

2. Roughness Map

The next item to import is a roughness map. This is a map that gives the relative roughness (trees, bushes, or anything other than smooth ground) for the area being profiled. Typical values on a roughness map range in length from zero meters up to three or four meters. Bodies of water have values near 0, forests and small towns have values between 0.5 and 1, and large cities have values around 3. Although the roughness map used for this IQP was purchased from Brower, the user can make one of his or her own with the proper resources.

If the user does not wish to input a roughness map at all, or does not have access to one, there is an option described later in this section under the "Options" menu that allows for that situation.

3. Surface Data

The surface data button is where the wind roses (that were calculated using the procedure listed in section **a** of "Gathering and Processing Data") fit into WindMap. Once this field is open, the screen shown in Figure 4 appears.

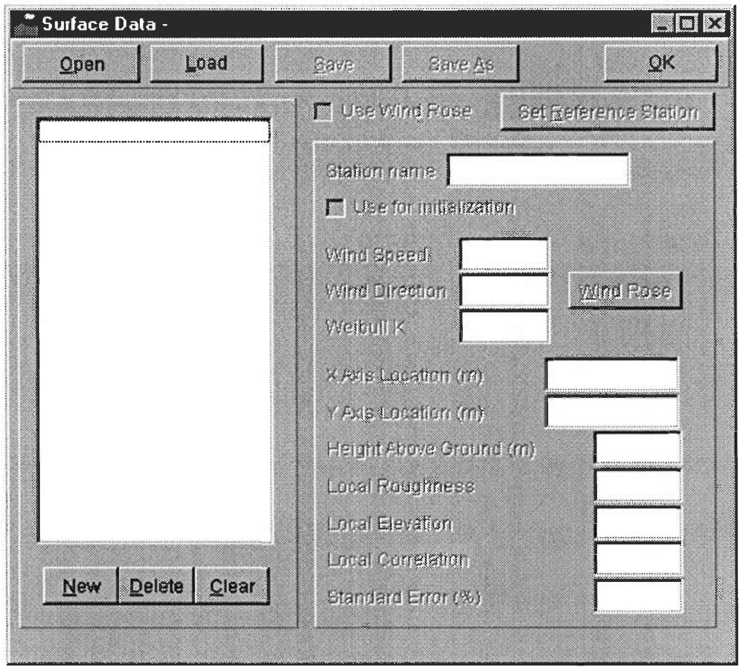

Figure 4. Surface data window

At this window, the user can create a new station and enter data for it by clicking on the "Wind Rose" button. There, the wind rose data, mean speed and frequency (if applicable) are entered for the 12 bins. Frequency may not be applicable in most cases since WindMap will only allow the frequency for one station to be entered. At the screen showed above, the user enters the station name, height in meters, as well as its X-Y location in meters. The process for converting decimal degrees into WindMap's X-Y system is outlined in section E. This can be done for as many wind roses as the user has data for.

Another option that this screen has is the "Use For Initialization" button. This is used for all of the stations, such that all the stations will calculate the initial speeds across the entire area. The initial winds at every point on the map are expressed as an average of each station's data.

4. Upper Air Data

Once all previously discussed information has been entered into WindMap, an optional input is the UA data. The data for this field is entered much the same way as the surface data is: in wind rose format. Likewise, the user can enter as many sets of upper air data as are available. If the user does not wish to enter, or does not have, upper air data, the "Constant Profile" box can be checked, in which case WindMap assumes the upper air wind speeds and directions are constant. One difference between the upper air data and surface data is that there are no latitude or longitude coordinates entered for the upper air data. This data is assumed to be the same across the entire map.

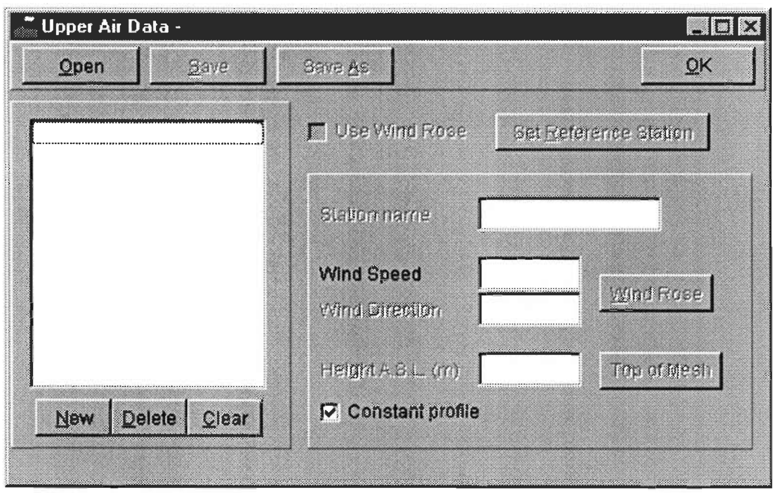

Figure 5. Upper air data window

5. View Log

The last field, "View Log", is only applicable after all the data that the user wants to enter is imported and WindMap solves all the continuity equations with the given data. Once this is done, the "View Log" button can be used to see the various measured and predicted wind speeds at each station and for each direction (bin).

6. The Options Menu

Another important part of WindMap is the "Options" menu. Within this field are six different tabs: Geometry, Atmosphere, Power, Initialization, Roughness, and Iteration Control.

The "Geometry" tab is used to set up the size of the map that WindMap will display. It sets the X, Y, and Z sizes, where X and Y are the two-dimensional sizes of the DEM being entered, and Z is the number of vertical cells. To get a map with the finest possible resolution, a maximum of 25 levels can be used in the Z (vertical) direction.

In the next tab, "Atmosphere," the user specifies the Boundary Layer Height, which is the depth of the layer where surface roughness begins to affect wind shear. This setting is left at the default height of 100 meters, which is a typical value. The transition layer height is another feature that can be adjusted. At the transition height, the wind speeds and direction from the top of the boundary layer begin to affect the upper air data. We enable this option and leave it at the default height of 500m.

The "Power" tab is used for adjusting the air density options, elevation adjustment, and the type of turbine that would typically be used at the location. We use the standard default values for this part since they are best suited to our purposes. The air density option is left as "Adjusted for Elevation" while the elevation adjustment is left at "Standard Temperature Profile." These two options allow WindMap to adjust each setting to the standard air density/temperature for our map. The turbine type is also left at the default setting, which is a "Generic 750kW." The type of turbine that is used at the wind farms is beyond the scope of this project, making the most typically used turbine the best-suited choice.

The next tab, "Initialization," is where the user can determine if the UA data or surface data is used to initialize WindMap. We use the surface data, since we only have one set of upper air data and two are required for initialization. The user can have the initialization depend on elevation and also use a form of data weighting. This is the "$1/r^2$ Weighting" button, which is used to adjust how each stations data affects the wind profile around it. When the box is checked, a distance can be entered that determines how much weight the stations data has in that radius around it.

Another part of the initialization section is the "Adjust For Elevation" box. The WindMap help file suggests that this option is best used when the user knows the approximate effect of speed on the elevation. Since that type of information is beyond the scope of this IQP, and since two upper air stations are required for this to be automated by WindMap, we set this option to zero. While this is not utilizing the option to its potential, it still helps create a more accurate wind map, absent the elevation information needed.

There is also a "Roughness" tab that is necessary if not using a roughness map. If the user does not have a roughness map, a constant roughness can be entered instead. This simulates a constant roughness, entered by the user, over the entire area of the map. The default setting is .03, although we are not using this, as a roughness map has been acquired from Brower to input.

Finally there is the "Iteration Control" tab. This control tab is primarily used to "Match Surface Data" and "Optimize Stability Ratio." The "Match Surface Data" is enabled and set to zero which, according to WindMap documentation, "on each iteration, it adjusts the wind field to ensure that the predicted wind speed and direction match the measurement at the … station[s] … marked 'Use for Initialization.'"[31] The "Optimize Stability Ratio" button is another way to cause WindMap to make a best fit between the predicted and measured speeds across the map. This option, however, cannot be utilized since the "Link To Vertical Profile" option is used, and both cannot be simultaneously.

D. Wind Map Analysis

Thorough siting analysis is not as simple as locating areas of particularly high winds. There are a variety of social and environmental and geographic features that affect the viability of a potential wind farm site. For example, most urban, residential, and recreational areas will be unpopular candidates for large turbine installations. Proximity to the power grid and to existing roads affects the initial cost of a wind farm. Our societal analysis examines, quantifies and weighs the influence of these various factors via GIS data processing.

1. Societal Factors

Essential to a responsible analysis of potential sites is the discrete identification of the discouraging and outright prohibitive features of the land under examination. Some factors, such as land type or settlement, strictly disallow the installation of a wind farm. Other considerations, including distance from population centers and existing power lines, affect the value of a particular site in more subtle ways. Both sorts of impacts are represented in the construction of a societal map for analysis.

Land use is a primary issue. All else aside, it may simply be unreasonable or prohibitively expensive to build a wind turbine on unstable ground or on water. Wetlands, marshes, bogs, and large bodies of water may be unrealistic choices for wind farms. Furthermore, many sensitive areas, including state and national parks, wildlife reserves and reservoirs, are unlikely candidates due to the potentially disruptive impact of a wind farm installation.

Urban areas and non-rural residential zones are a poor choice, largely due to resident response to the aesthetics of a wind farm installation. Turbines are very large and potentially noisy. These attributes will likely be very unattractive to residents and property owners, constituting both a noise pollutant and a possible financial burden if property values in the vicinity are driven down. Likewise, recreational parks and golf courses would almost certainly be refused as potential development sites.

Connecting a new wind installation to the existing power grid will constitute a significant financial responsibility. One must take into account both the linear cost of covering the distance to the nearest transmission lines and the additional cost of building a new substation. Similarly, any new roads required for the project will add to the cost as well as increase potential objection from environmental preservation groups.

It is imperative to the validity of our wind analysis that we make some attempt to model and quantify the relationship between our wind data and these various social factors. To do so, we utilize the IDRISI software package to process publicly available GIS data for Massachusetts. We create a series of maps that can be layered and weighted in such a way as to add socially relevant data to our wind maps.

2. Processing the Societal Data

Our analysis depends on a quantification of available societal data. We use the image-processing features of IDRISI to create several societal maps from publicly available data. For step-by-step details regarding the creation and manipulation of the societal analysis maps, see Appendix C. Societal data discussed in this section include land use, population density, distance from power lines, and areas of critical environmental concern.

a. Land Use

Land usage data provides the bulk of our social analysis. The source of our land usage information is a series of ESRI Shapefile data files available for download from MassGIS at http://www.magnet.state.ma.us/mgis/ftplus.htm. These are vector files, containing arc and polygon information as well as a .dbf database tying in corresponding information about discrete areas in the maps. The files (named lusX.exe where X is a number between 1 and 351) are broken up by town, and vary in size depending on the complexity of the specific zone's land use.

To create a complete land use map from the MassGIS files, we use several of IDRISI's functions, in combination with some simple custom macros, to process and concatenate all the separate land use maps. The maps are downloaded, uncompressed, and converted into IDRISI-native vector file format. From there, the interesting data (which, in the case of this analysis, is the land use codes assigned to each polygon in each map) is extracted and associated with our converted IDRISI vector files. Finally, all 351 of these vector files are converted to a bitmapped raster format and projected onto a single map. The result is a cohesive, raster-format land-use map of Massachusetts.

b. Population and Power Maps

With the land use map having been generated, several new maps are derived. IDRISI's RECLASS function is used to create an "allowable land" map and a "population center" map. The allowable land map looks very similar to the original land use map, but excludes areas unsuited to wind farm siting, including residential, urban, recreational, environmentally threatened and hydrographic areas. The population center map consists of dense residential areas, commercial and industrial zones.

The population center map is further manipulated with IDRISI's DISTANCE function to create a map where each pixel's value corresponds to its distance from the nearest population zone. Similarly, power line data available from MassGIS is used to create a DISTANCE-produced power grid map expressing each point's distance from the nearest major transmission line. For the purpose of this analysis, nearness to power lines is considered valuable, whereas nearness to population centers is considered undesirable.

c. ACEC Map

We also create a map of Areas of Critical Environmental Concern (ACECs) from MassGIS data, to be added to the restricted areas of the allowable land map. The ACEC program is administered by the Department of Environmental Management and designates locating requiring environmental review for many kinds of development. Our ACEC map is a Boolean mask of all identified ACECs, and is combined with our land use map.

d. Final Analysis Maps

Once all the maps are created, they are combined with a wind speed map produced by WindMap, as discussed in section C, to create a weighted analysis map of both wind and societal features. The ACEC map is subtracted from the allowed land map to assure that no restricted areas are represented, and the resulting map is used as a base for the analysis. The power-distance and population-distance maps are normalized to a 0-to-1 range, as are the wind maps, and each is weighted according to chosen factors.

Finally, the maps are combined into a single analysis map, each factor being weighted to express its influence on potential wind sites. Our analysis considers those areas with the greatest total sum values to be most attractive for potential sites. While the maximum possible value for any point is a sum total of 1, it is unlikely that any area will receive a perfect score, and so the analysis maps we produce have a scale of 0 to slightly less than 1.

Wind speed:	84.5%
Power distance:	12.25%
Pop. distance:	3.25%

Table 1. Societal factor weighting values.

The choice of weighting is based on the choices of a previous IQP group responsible for performing a similar analysis on Western Massachusetts. It seems ideal to maintain consistency between this analysis and the preceding one, so that the results of each can be combined and compared without a great deal of re-interpretation of the data. The weighting values we use, shown in Table 1, were chosen by the previous group based on the existing research of Brower. These values, as well as various other aspects of our methodology, are discussed further and analyzed in Chapter IV.

IV. Results and Analysis

Having acquired the wind data, the DEM and roughness map, as well as the societal maps, we turn to a discussion of our results and the corresponding analyses. In order to qualify the worth of our research, the validity of the data needs to be considered, and the results must be interpreted. Our produced wind roses are examined for patterns and abnormalities, as are the maps we have created with WindMap. We consider the accuracy and consistency of our societal analysis maps, and present a discussion of potential wind sites according to our findings.

A. Wind Data

The first issues to consider are the nature of the wind at the anemometer stations and the accuracy of the data. Further, to examine wind patterns between stations, we compare the frequencies of various stations to those nearby.

The results of our wind rose calculations are shown in Table 2, along with each of the 19 station's anemometer height and elevation above ground level. While most of our stations were measured at 10 meters, some were measured at greater heights. The dominant direction varies clockwise from 210 to 30 degrees, although most coastal stations lie within the 210-240 degree ranges. Also, as the anemometer height increases, the mean speed increases, with the exception of Fairhaven.

In addition to these stations, we also obtained data for Hull and Salisbury, but neither were used in WindMap. The Hull data spanned a very short time period and had too many frozen data points to be considered accurate. The Salisbury data did not list wind speeds for each direction, but we still used its frequency data for comparison with our other stations. We notice that it concurs with the dominant direction of 210-240 degrees observed in our other wind roses.

Station	Mean Speed (m/s)	Dominant Direction (°)	Anem. Height (m AGL)	Site Elevation (m ASL)
Beverly	5.337496	330	10	~25
Boston	5.159676	240	10	~20
Buzzard's Bay	7.543667	240	24.79	0
Chatham (UA)	10.288663	300	1,500	---
Fairhaven	3.854250	210	39.61	~15
Halibut	5.870000	270	30.48	~20
Hyannis	4.775996	270	10	~15
Lawrence	3.937061	210	10	~20
Martha's Vineyard	4.942415	210	10	~20
Nantucket 1	6.722500	150	45.72	~1
Nantucket 2	5.189508	210	10	~15
New Bedford	4.327350	210	10	~20
Norwood	4.058847	210	10	~50
Otis	4.803825	240	10	~35
Plymouth	4.200954	210	10	~30
Providence	4.501450	30	10	~25
Provincetown	5.778738	210	10	~5
Worcester	4.752083	270	10	~250
Yarmouth	5.783167	240	30.48	~10

Table 2. Summary of calculations and station heights for all 18 stations

Recall that the reference frequency is the one frequency that WindMap uses in its calculations for each station. Since there are several different dominant directions, we created several trial runs using various stations' data as the reference frequency. The effect of these different reference frequencies was negligible. We chose Chatham on the basis that the data is for upper air patterns that are unaffected by terrain roughness and other ground effects.

B. WindMap Results and Analysis

Using the anemometer data from the previous section and following the options outlined in the methodology, we utilized WindMap to create maps of interpolated wind patterns. The results from this software indicated variance in the promising areas for potential wind farms. Variations were made to the run parameters to ensure the integrity of these maps.

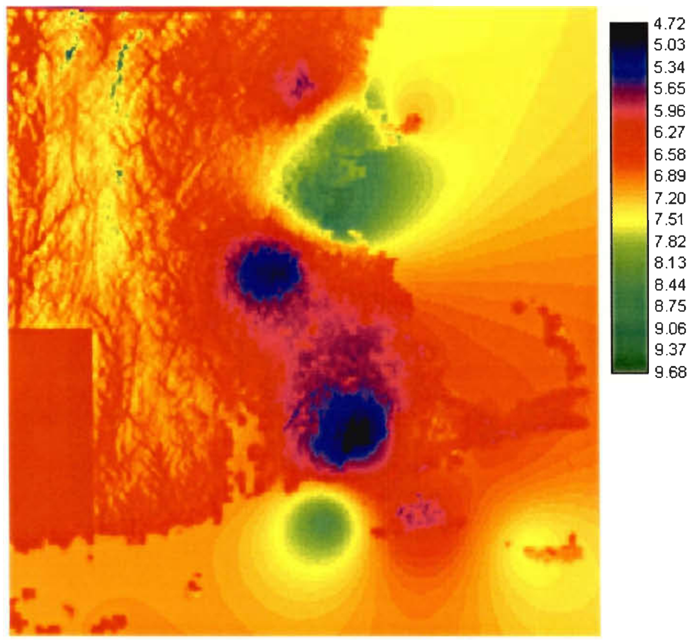

Figure 6. Final map produced by WindMap

1. Wind Speed Map

The map shown in Figure 6 is the final map produced by WindMap based on the specifications outlined in Appendix B and explained in section 6, chapter 3. The results suggest that the highest wind speeds calculated reside in and near Boston, Worcester, Buzzard's Bay, and Nantucket. The lowest speeds are localized near Fairhaven/New Bedford and Norwood. Most speeds in other areas of the map are between 6 and 7.5m/s.

The map shows radical changes in wind speed from one station to the next. These inconsistencies are localized around Norwood and Fairhaven/New Bedford. There are many factors that could lead to such effects. For example, the absence of a correlation map, which is used in situations where there are two or more distinct zones where wind conditions are different, could account for the pockets where WindMap predicted slow speeds. A correlation map allows the user to set the wind influence in each zone so they do not influence each other directly. There is clearly a difference in wind speeds on and off the coast of Massachusetts. It may therefore be beneficial to construct a correlation map in future research.

Review of the final log for this map (see Appendix B) also shows that some of the largest discrepancies between the predicted speeds and measured speeds exist near Fairhaven and New Bedford. This indicates that WindMap interpolated the data incorrectly, possibly due to the influence of an offshore station (Buzzard's Bay), which supports the need for a correlation map. Another possibility is bad data and roughness effects.

Despite the possibility that the maps generated by WindMap are not as accurate as anticipated, we are still confident that they espouse a comparatively high standard of accuracy and detail in the context of previous work. In order to gain greater insight into the nature of our wind map data, we conduct a series of integrity tests.

2. Integrity Tests

To help guarantee the integrity of the wind maps being produced by WindMap, several options were changed to ensure that the discrepancies were as small as possible. We changed only one option at a time to isolate any discrepancies.

a. Frequency Variation

Since WindMap only uses the frequency for one station, we rotated the reference frequency between each station. By varying just the frequency for each run, we demonstrate that the frequency data we had was accurate and that the results from WindMap would also be as accurate as possible. Since the frequency is used throughout the entire map, if our wind rose was inaccurate there would likely be noticeable differences in the wind patterns across the entire map. The frequency for our upper air data was used as well in order to be consistent with our integrity tests. While the choice of a reference frequency didn't change the outcome of the map, we decided that the upper air frequency would be used for the remaining WindMap runs. The upper air data is taken from much higher altitudes than our anemometers, and is thus more immune from varying wind directions caused by ground effects.

b. Adjusting the Correlation

The $1/r^2$ weighting option was varied as well. We initially used 6.5km for the "weight," but we varied this parameter to ensure that the weight of each station does not stay too close, nor extend too far out from its immediate radius. Decreasing this value would create accuracy closer to the stations, with the estimated speeds between stations having less accuracy. Therefore we increased the weight to 30km, a map of which is shown in Figure 7. Increasing the weight has each station's data averaging with its neighboring stations to reduce the influence of any bad data. The result of using 30km length is that the wind speeds show smoother transition across the entire map, which seems more realistic than having pockets with high and low speeds. The wind speeds are still higher in the Boston area than in most areas on the map. However, the speeds near Buzzard's Bay decrease compared to the map from figure 6.

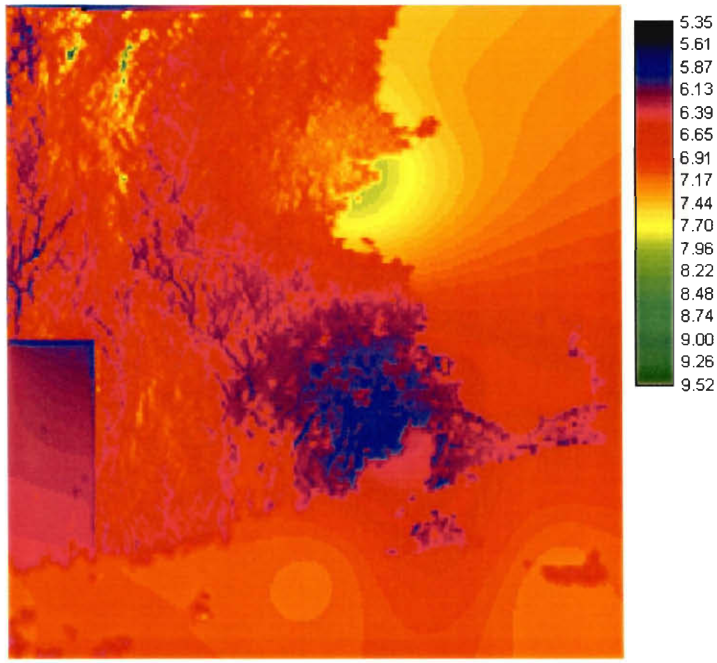

Figure 7. Wind map with correlation of 30km

A mathematical approach was used to determine the validity of this map. While the predicted speed and measured speed values are very close for our map shown in Figure 6, these values are not as consistent to our measurements for this map. We calculated a least-squares estimate with the difference of the predicted and measured speeds of this data as well as for that of the map in Figure 6. The map from Figure 6 had an estimate of approximately 1.44, while the map with the correlation of 30km had an estimate of 11.91. There is obviously a large discrepancy there, despite the fact that the latter map seemed most consistent. For this reason, we used both maps in our societal analysis and compare them in the next section.

Weights of 10km and 20km were used as well to compare with our previous two maps. The map with 10km weight had a wind profile and measured/predicted speeds very similar to that of the map with 6.5km weight. The map with 20km weight was similar to the map with 30km weight. This indicates that there is a cusp where a majority of the stations will begin to affect each of its neighboring stations. Again, a correlation map could help eliminate this, allowing the proper stations to affect each other.

c. Anemometer Review

Another factor that could likely have changed the final map is whether the wind speed data at each station is accurate or not. Investigating the accuracy of each station's data, however, is beyond our capabilities and time constraints for this project. For this reason, we continue to use the data available to us and try to isolate discrepancies based on the final wind map.

The station that seems most inconsistent with the rest of the map is Provincetown. Figure 8 shows a final map with the Provincetown station included. The predicted wind speeds around the Provincetown station seem to be unusually slow. The relative roughness in the area should be minimal since it is surrounded by water on three sides. We compensated for this by taking the station out to see how WindMap interpolated the data in that area without the station. The map produced seems much more consistent in that area and the wind speeds do not vary as drastically as they do on the map where the Provincetown station is removed (see Figure 6). For this reason we decided to leave this station out for the remainder of this project.

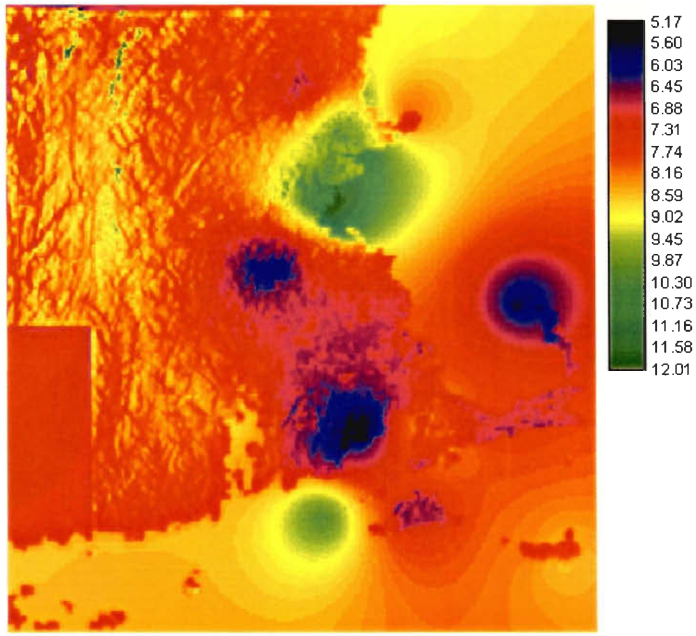

Figure 8. Final wind map with Provincetown included

Another cause for concern with the map from Figure 6 is the inland stations Plymouth and Norwood. These stations exhibit slow speeds in relation to the speeds predicted by WindMap around them. Removing these stations was taken under consideration. However, the low number of inland stations prohibited this. Without these stations, there would be little data for WindMap to use for calculations inland.

d. Comparison with Existing Wind Atlas

The wind maps from Figures 6 and 7 are compared with another map that is an assessment of the wind profile around Massachusetts.[28] This map, made more than 10 years ago, is used only as a general outline of wind speed patterns against which we can consider our own wind maps.

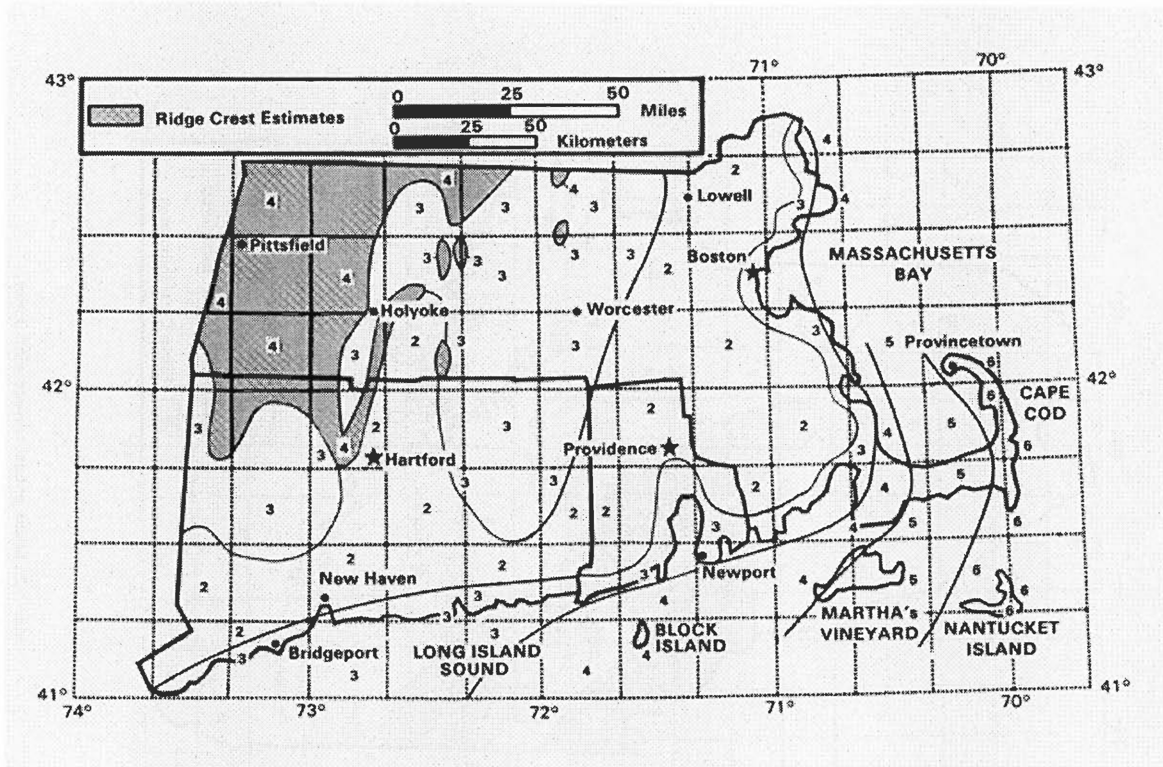

Figure 9. Wind class assessment for Massachusetts

The map in Figure 9 portrays the wind classes around the coast and throughout Massachusetts. For the scale of this map, class 6 winds are equivalent to approximately 8.5m/s and class 2 winds are approximately equal to 6m/s.[28] Based on this scale, the map in Figure 9 shows the highest speeds around the easternmost regions of Massachusetts, with the winds slowly decreasing as they move west.

The map from Figure 6 shows similarities to Figure 9 above Boston, outside of Buzzard's Bay, and inland near Norwood and Fairhaven/New Bedford. Areas inside Buzzard's Bay and Boston, and near Worcester are higher than speeds shown by the map from Figure 9.

The assessments shown in Figure 9 are inconsistent with our map from Figure 7. The speeds in the Boston and Worcester areas are higher than those shown in Figure 9, and most other sections are lower than those speeds shown in Figure 9. Figure 9 shows class 4-6 winds around the coastline, however winds of this magnitude are not apparent in our map in figure 7.

There are similar discrepancies between each of our maps and Figure 9. Reasons could include the use of anemometer data from different time periods, data from limited time periods, or differing means of calculation. Future research would benefit from a detailed assessment of these factors.

Regardless of the differences between our maps and Figure 9, we feel confident that our wind maps are substantially informative to provide the groundwork for further examination and siting. The concluding step in our analysis is a consideration of our wind results in the context of societal factors.

C. Societal Map Analysis

An analysis of the social aspects of potential wind sites is essential to a useful, holistic understanding of our wind data. This societal analysis focuses on the relationship between produced wind maps and a combination of infrastructure and land use factors. We examine and discuss the applicability of the various factors in order to establish the meaningfulness of our analysis.

This analysis considers two wind maps. The maps' attributes are identical except that one was produced using a correlation value of 6.5km, the other with 30km. As discussed in the previous section, there is a significant disparity between these two maps. The map with the smaller correlation value has localized areas of highly contrasting wind speeds (see Figure 6), while the other map's larger correlation leads to a much smoother map (see Figure 7). It is not immediately clear which map is more appropriate a representation of wind in eastern Massachusetts. We will attempt to analyze both and consider the similarities and differences between the two maps.

Aside from our wind map data, three other factors will be considered in the analysis. These include distance from the power grid, distance from centers of population, and land use restrictions. We have used IDRISI to create raster maps representing each of these maps, as discussed previously in the methodology. Each of these factors bears examination for validity and meaning in our societal analysis.

1. Power Grid Analysis

Our power-distance map (see Figure 10) represents the financial impact of the distance from the existing power grid to a potential wind site. Because of the linear relationship between distance from the power grid and the cost of connecting a site, in this analysis we consider proximity to existing power lines ideal. Areas closer to the existing power lines therefore receive larger values.

Examining Figure 10, we see unexpectedly poor values for much of the Boston area. This result is questionable, considering that the Boston area is highly populated and likely has a well-developed infrastructure. It is reasonable to assume that the original power grid data used is at fault, not properly representing the power line configuration in Boston's surroundings.

The power grid map is weighted as 12.25% of the total analysis. This weighting was chosen largely for consistency with previous work in Western Massachusetts, and expresses that the cost of connecting remote areas to the current power infrastructure in Massachusetts entails a significant financial commitment. It is, however, worth considering that Eastern Massachusetts in particularly is thickly developed, such that no area is very remote from the power grid. Considering that, a lower weighting for the influence of this factor could be justifiable in future research.

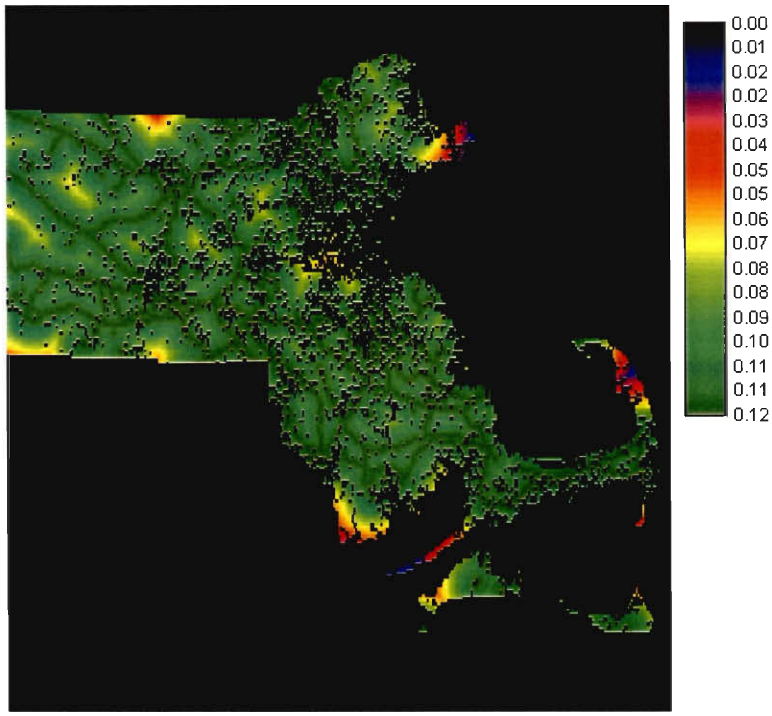

Figure 10. Normalized map of distance from power grid. Weighted value is 12.25% of total analysis

2. Population Distance Analysis

The margin by which a potential wind site is proximal to residential, commercial and industrial zones may influence the desirability of that site. Residents and landowners have historically been reluctant to allow the construction wind turbines for reasons of aesthetic concern that include unsightliness and noise concerns. This analysis therefore considers greater distance from population centers to be ideal.

Population centers considered are those zones with land use classifications of commercial, industrial, and residential lots of up to a quarter acre. We consider these areas to be sufficiently populated or developed such that the aesthetics of a wind farm would raise objections with the residents. Further analysis of population center influences might consider the applicability of one-eighth acre or one-half acre residential lots as appropriate cut-off values.

Our population map (see Figure 11) has been assigned only 3.25% of the total weighting. This is, again, consistent with previous work in Massachusetts. Furthermore, it reflects the fact that population concerns are also addressed in our land use map, which we will discuss briefly. This map is important in that it provides a sliding-scale quantification of population-distance in addition and contrast to the Boolean nature of our land use data. It is clear from Figure 11 that the majority of ideal locations are toward the western end of our target area, while much of the Boston area hardly registers at all.

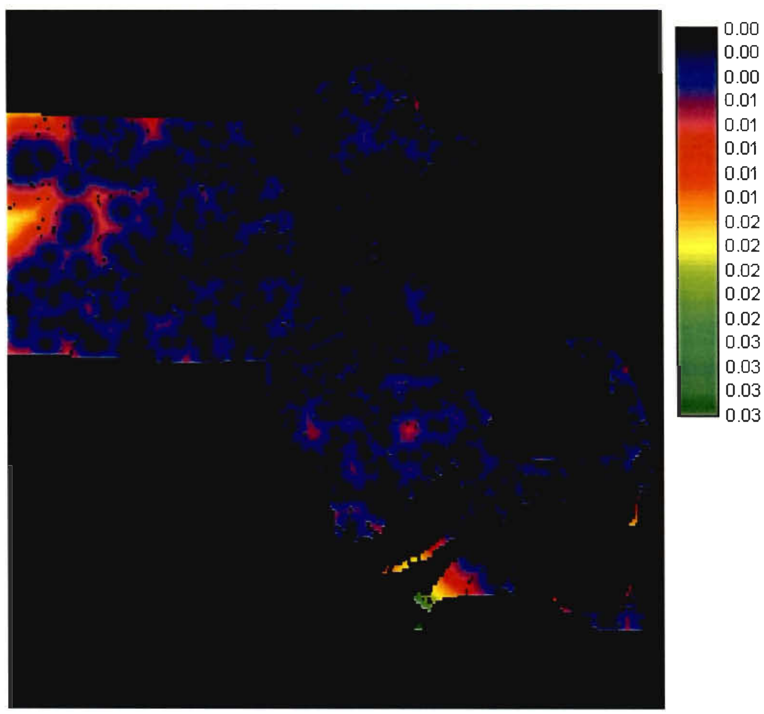

Figure 11. Normalized map of distance from population centers. Weighted value is 3.25% of total analysis

3. Land Use Analysis

Our land use map (see Figure 12) is used to mask off any areas considered by this project to be restricted from potential wind farm development. As discussed in our methodology, these areas include urban, dense residential and recreational zones, as well as protected national park areas, wetlands, and environmentally restricted land. While these areas may in some situations be feasible for wind development, research in the specific location would be necessary to determine such fitness. Residential zones are restricted at the same quarter-acre cut-off as in our population centers map, and future analysis could benefit from an exploration of different values as discussed previously.

The land use map is not weighted on a percentage like our other factors, but is expressed as a Boolean mask. Any restricted region receives a value of zero, any non-restricted region receives a value of one. This filter is multiplied by each of other analysis maps to eliminate restricted areas from consideration. The choice of this mask is, as with our other factors, largely a matter of consistency with the Western Massachusetts project. Future research may benefit from changing to a scaled range of values, in order to express the severity or consistency of land restrictions.

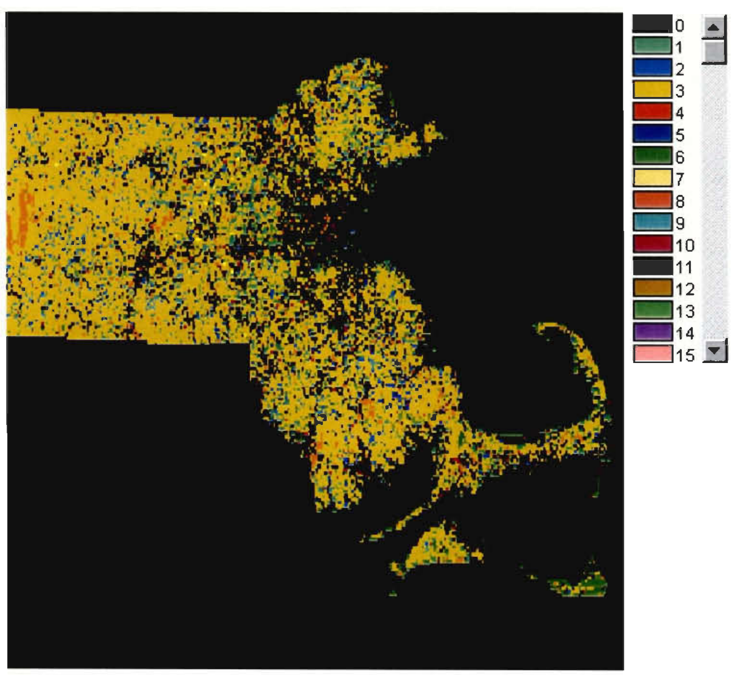

Figure 12. Land use map. Black areas are considered restricted from wind farm development

4. Societal Analysis Map

To analyze these factors, we combine our wind, power, population and land use maps into a single analysis map expressing each factor as a weighted influence. The procedure for creating the analysis maps is simple. The maps are first normalized with IDRISI to convert from any arbitrary scale to a scale of 0-max where max is the weighting of a given factor. The maps are then combined with IDRISI's "overlay" function. The resulting map is expressed on a scale from 0 to some value slightly less than 1.

The analysis maps produced with the wind maps of values 6.5km and 30km yield notable differences, but look generally the same (see Figures 13 and 14). The differences manifest mostly in mediocre areas, which are of less interest to this project than desirable areas. However, the inconsistencies between our wind maps, and the corresponding analysis maps, are indicative of a need for cautious interpretation of any of these results.

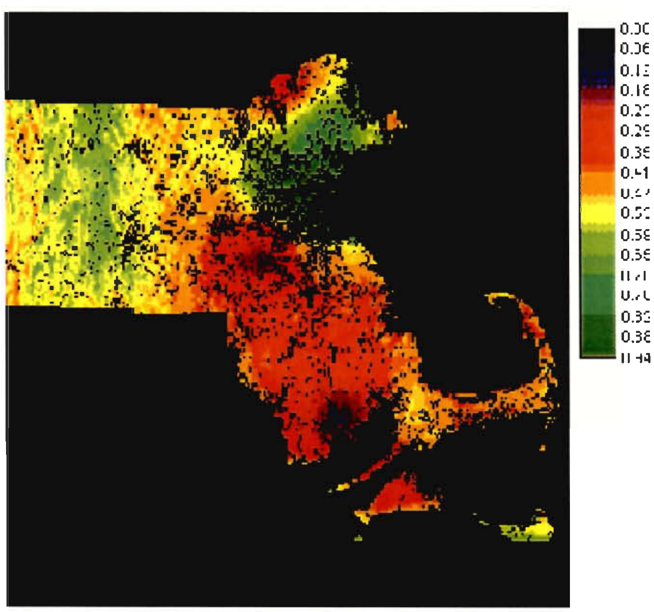

Figure 13. Analysis map produced from 6.5km correlation wind map

From the maps, Boston appears to be a desirable site, but considering population density in that area, a wind farm construction would not be plausible. However, the land to the north of Boston is the largest area of highly desirable sites. Much of the coast looks good, and Nantucket is very attractive. Portions of Central Massachusetts in the Worcester area look good as well.

The primary areas of discrepancy between the two analysis maps are the southeastern region of the state (from south of Boston down towards the Cape) and the southern portion of Central Massachusetts. Further analysis directed specifically toward these areas would be prudent before any definite conclusions are drawn about their viability as wind farm locations. An in-depth clarification of the cause of these discrepancies is not within the scope of this project.

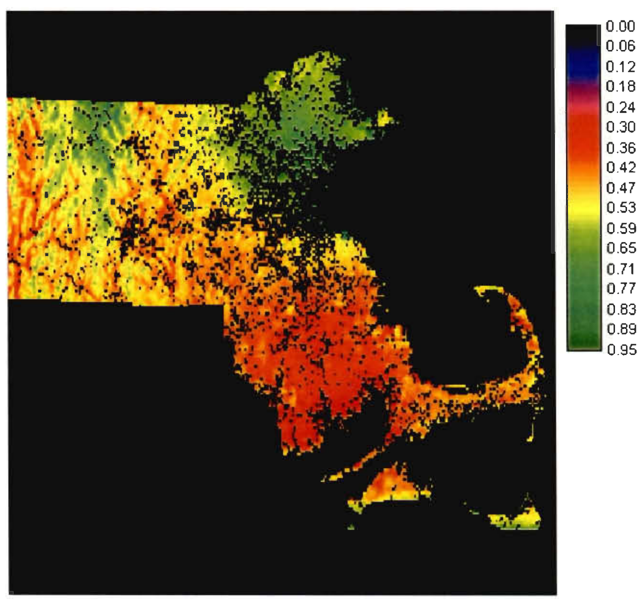

Figure 14. Analysis map produced from 30km correlation wind map

The final analysis maps are not scaled from precisely 0 to 1 because no areas of the maps which are "perfectly" ideal. That is, if any spot on the map yielded maximum wind power, was situated negligibly close to a power line, and was as far from a population center as any other point on the map, that spot would have a weighted sum of 1. No points on our analysis maps are so ideal, however, and so the maximum is actually somewhere upwards of 0.9. Our scale is arbitrary, however, so this is hardly a concern.

It is, unfortunately, quite relevant to our siting that Nantucket and other coastal locations, while very attractive by these analyses, may be difficult to target as good sites due solely to strong objections by the local residents and landowners. For the time being, it may be realistic to leave possibility of wind farm development in these areas to further research. Having said that, portions of the state to the north of Boston and areas of Central Massachusetts are by far the most desirable locations for wind farm siting, as is indicated by Figure 15. By our analysis, these areas deserve more site-specific attention and analysis.

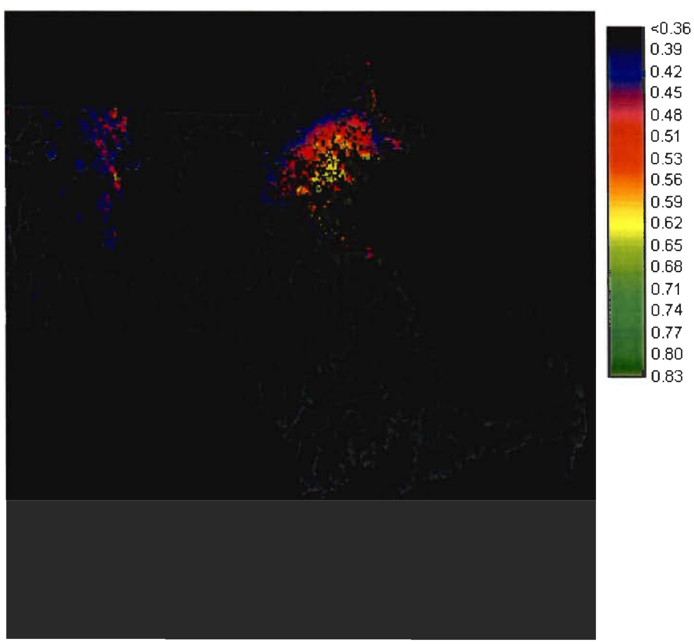

Figure 15. Desirable areas for wind farm placement, with town boundary overlay. Values are taken from mathematical product of 6.5km and 30km correlation analysis maps. Shown are sites rating better than 0.36

V. Conclusions

Our research suggests several ideal sites for wind farm development in Eastern Massachusetts. While these areas bear further investigation for potential development, an in-depth assessment of the data used to produce these results would also be prudent. Future research in this area may well benefit from an understanding of the scope and limitations of our project.

The most productive areas seem to appear along the coastlines, which makes sense since the lack of roughness along the ocean will result in faster winds. Boston and the area to the north show particular promise. There are also a few areas of high wind in the Worcester area, although the higher speeds along the coastline are much more abundant.

Bearing in mind the boundaries of this project, the production of our analysis is an important step in advancing the state of wind energy in Massachusetts. Our new data, while certainly not perfect, has the advantage of newer technology fueling it than any previous work on this region. We can say with confidence that this project stands as a useful milestone, though hopefully not the definitive one. There is much room for improvement in siting technology and technique.

While WindMap is much more advanced than older forms of wind siting, it has its limitations. It is not perfect, capable only of interpolated estimates that must compromise between localized accuracy and long distance prediction. The number of data points available for wind calculations limits WindMap's accuracy. While this project had utilized significantly more data than the preceding Western Massachusetts project, we still depend on points that are distant from one another and very sparse in areas such as Central Massachusetts. An ideal project would have access to a much denser lattice of data points for WindMap calculations.

We are also limited by accuracy of our data. While efforts were made to avoid large batches of zeroed-out data attributed to malfunctioning anemometers, and to verify the height and location information of the anemometers, errors in data processing remain a concern and a possible explanation for unexpected results. There is no apparent means of data verification available to our group if an anemometer seems to produce unusual data. Also, much of our data is taken from airport anemometers. These locations tend to be flat and open, leading to higher wind speeds in these areas. Our roughness map is not of high enough resolution to account for the local contrasts between an airport and surrounding land. The result may be inappropriate interpolation by WindMap. If any data used in the analysis is deeply flawed, the influence this has on the results must be considered.

Another reasonable concern is the choice of societal factors and their respective weighting in the final analysis. For this project, we chose to remain consistent with the factor and weighting choices of the previous IQP group, in order to produce a map consistent with that produced for Western Massachusetts. The precedent set in Michael Brower's research in New Mexico, the Midwest, and other areas influenced these attributes. It is not unreasonable to think that, in a heavily developed state like Massachusetts, power grid concerns may be lessened and population concerns amplified from what was appropriate in larger, more sparsely developed and populated states in the Western and Midwestern US. Future projects would certainly do well to evaluate these issues.

Our land use evaluation was similarly conducted with consistency to the previous project in mind. While the restrictions applied to land use seem fairly reasonable, a more in-depth consideration of each land use type and its role in Massachusetts would likely be beneficial to future siting research. In this project we chose to absolutely disregard unfavorable land use types. In the case of some types of land, it may be more appropriate to apply some fractional weight to areas that are somewhat restricted but still viable should other factors make the site desirable.

These considerations aside, our project has taken advantage of powerful developing technology to improve the available knowledge of wind energy potential in Massachusetts. Extending this sort of research to other locations should be very straightforward, and the evidence of this project's success may very well empower others to initiate such projects. This mode of research could easily be applied to the rest of New England and, in that spirit, to the rest of the country and continent.

This advancing line of research capability, coupled with still-developing wind mapping technology and wind energy technology, signifies great hope for the growing implementation of wind energy resources in the near future. If such progress can be made, the need for fossil- and nuclear-fueled power supplies will be diminished, and in turn both the environment and world energy consumers will benefit from a cleaner, more stable means of energy production.

Appendix A. Wind Energy Developments in Other Countries

I. China [26]

The increasingly serious issues of environmental pollution and global warming have influenced the Chinese government to push large-scale wind energy commercialization development. By the year 2000, a total capacity in the range of 300-400 MW is anticipated.

In 1997, there were 19 wind farms in China, the largest being in Xinjiang with a 10-MW capacity. The table below summarizes China's wind energy developments from 1989 to 1997.

Year	Annual Installation (MW)	Accumulated Installation (MW)
1989	4	4
1990	0.85	4.85
1992	2.7	7.6
1993	2.5	10.1
1994	9.2	19.3
1995	16	35.3
1996	22.1	57.4
1997	109	166

In addition, several ongoing wind farm development projects have been initiated in China:

- **The GEF/World Bank Project.** This project's objective is to develop the first large commercial wind farm and to encourage large-scale investment in other wind farm projects.
- **The Ride Wind Project.** This project has been initiated to expedite wind farm commercialization and local manufacturing.

II. Japan [32]

Japan has few indigenous energy supplies, and as a result, imports much of its energy. The country has shown very high rates of energy consumption due to high economic growth from 1960 to 1970, and after the oil crises of the 1970s, it has shown a great deal of interest in renewable energy.

Wind turbines began appearing in Japan in the mid-1970s. In the 1980s, conspicuous installations were made in mountain ranges, which were isolated from the commercial power grid. From the late 1980s onward, capacity increased and reached 18 MW in 1997.

Electric companies and local governments have installed most turbines in Japan. The largest one is Wind Park in Tappi cape, which houses 11 turbines, and has a total output of 3,375 kW.

Recently, Japan's increased wind turbine capacity has reduced the cost to approximately ¥20 per kilowatt-hour (18 cents in U.S. dollars), depending on wind speeds. This amount is much closer to ordinary electricity prices, and cost-wise, wind power generation is reasonably close to commercialization among new forms of energy.

Additional installations are being made frequently, aiming at Japan's targets of 20 MW of wind power in the year 2000, and 600 MW in 2010. However, in comparison to Germany and the US, these numbers are very small, due to Japan being restricted by natural conditions. The country's geography is complicated, and locations where stable wind energy can be gathered are limited. In addition, windstorms caused by typhoons are common.

III. Russia [33]

Renewable energy is appealing in Russia because it can help contribute to the conversion of military, idle, or under capacity factories to useful manufacturers of commercial technologies.

Several large regions of Russia and the Ukraine have an annual average wind speed which exceeds 7 m/s at or near ground level, although most available wind speed data seldom gives the measurement height. These areas include the far-northern and far-eastern coastal areas of the Arctic and Pacific oceans, areas adjacent to the Caspian, Azov, and Black Seas, and several high plains and mountain regions. Most of these areas have low population densities and are far from electric power networks. Consequently, wind power would have to exist in decentralized off-grid systems.

More precise wind speed data is available from several wind farm sites under active development. For instance, measurements made at a site in Kalmykia showed average annual wind speeds of 7.6 m/s at a height of 38 m. In addition, a site in Karelia showed average annual wind speeds of 8 m/s at a height of 10 m.

In general, favorable regions for grid-connected wind farms are those which possess excellent wind resources, flat terrain subject to agricultural use, high population densities, and electric power deficiency in the regional electric grid. Potential investors in grid-connected wind systems in Russia include regional electric power utilities, the national electric power utility RAO EES Rossii, municipal electric distribution utilities, and private power developers.

Several domestic technology developments have occurred in Russia in the early 1990s, involving collaborations of research institutes, design bureaus, and science-production associations. The national electric power utility, RAO EES Rossii, has been supporting many of these developments:

- In cooperation with the Tushinskiy production enterprise, an aerospace factory located near Moscow has developed a commercial 1,000-kW turbine, and prototypes have been built. These turbines will be used in a planned 22-MW wind farm, to be built in Kalmykia by the regional electric power utility.
- Vetroen, a science-production association and longtime wind turbine developer in Russia, and the Yuzhnoye factory in the Ukraine jointly developed a 250-kW turbine

and installed several in the Crimea in 1994. The Ukrainian government financed the project.

In 1995, several wind farms with capacities in the range of 2-5 MW were being planned in Russia, one being a test station for turbines in arctic weather conditions. A few direct imports have also taken place. For instance, Germany funded ten 30-kW turbines to be imported and installed in Saratov.

IV. India [15]

Gujarat, a western territory of India, has a large demand for power, but faces problems of fuel shortages because of long traveling distances from the eastern coal mines.

The Gujarat Energy Development Agency (GEDA), established in 1979, first became interested in wind energy in 1984 as a method to reduce the territory's reliance on fossil fuels. They initiated a wind mapping program, which assessed the wind potential within Gujarat to be approximately 5,000 MW. In 1986, GEDA set up a 1.1-MW demonstration wind farm, the first ever in India. As of 1999, over 130 MW of wind power exist in Gujarat, 117 MW having been added since 1993.

Wind farm performance in Gujarat has shown average annual capacity factors lower than the expected 20%. This was initially due to purchasing foreign or inferior second-hand machines which were unable to operate efficiently within the Indian system. They were given little maintenance and spare parts were often hard to find. Since then, however, joint-venture projects have allowed the development of local manufacturing and modification of turbine design to facilitate operation under local conditions.

Despite turbine technology improvements in Gujarat, poor performance persists, due to a number of factors:

- The wind mapping project is said to have been inadequate, not measuring wind speeds at a sufficient number of locations or different contours.
- Wind farms are located on the coast where demand is very low, and therefore the power must be transported over long distances to areas of high demand. As a result, frequent grid outages occur, due to overloading of substations. To prevent these failures, restrictions are imposed on wind farms at certain times, which do not allow them to operate at full capacity.
- In an attempt to avoid sales tax, many investors rush to develop projects quickly before the end of the financial year. As a result, not enough time is spent carefully planning the project, and consequently, wind farms are not sited in the most optimal locations.
- Many developers are inexperienced in power production, and rely on manufacturers for assistance in the operation and maintenance of turbines. This is worsened by there being a large number of small-capacity wind farms in Gujarat.

Overall, the poor performance of wind turbines in Gujarat has reduced the level of confidence policy-makers and investors have in the technologies. Still, the capabilities for manufacturing, operating, and maintaining wind turbines exist in Gujarat. In addition, a wind energy association has formed to provide a discussion forum, dissemination of information, and to exert political influence.

V. Sudan [34]

Wind turbines are used for two different methods in Sudan. Small-scale machines are used for pumping water or generating electricity, and large-scale machines and wind farms are used for generating electricity.

Wind data is obtained from the Sudan Meteorological Department Office in Khartoum. Measurements are made with a cup anemometer connected to a chart recorder for selected wind stations. Collected data was used to prepare a map which shows the distribution of wind across the country. The annual average wind speed was calculated at over 4 m/s along the main Nile, and exceeds 5 m/s at the costal area along the Red Sea.

Grid electricity is generally not available in most rural areas of Sudan. Diesel fuel is expensive, and its supply is sometimes doubtful, especially during the rainy season. In addition, there are no natural oil reserves, so it must be imported. Because of these conditions, Sudan must consider the potential of alternative sources of renewable energy to provide power to operate water pumps, which lift and supply water to rural areas. In the past, wind power has been used for water pumping, corn grinding, and stipulation of power for small industries.

VI. Korea [35]

A non-profit group from California, the Nautilus Institute for Security and Sustainable Development, has initiated the Democratic People's Republic of Korea (DPRK) Renewable Energy Project, in order to bring energy activity to the famine-ravaged country. It is the first non-governmental development by a US group in Korea.

In May of 1999, a bi-national team of Americans and Koreans manually erected a small 11.5-kW wind plant in cabbage fields near the village of Unhari in North Korea. Construction took five weeks, and the plant was electrified on October 5. Nautilus supplied seven turbines for the project, which now supply electricity to 20 homes, a medical clinic, and a kindergarten. Doctors can now refrigerate medicine, farmers can operate electric pumps, and the kindergarten now has fluorescent lighting.

Before the Nautilus project, rural North Korea was in an economically dysfunctional state. The electric grid was operating at 50% capacity, and power was only available regionally and intermittently and with wildly fluctuating voltage. Most of the area's electrical equipment was old and inefficient, and the electric system had been ruptured due to North Korea being hit hard by a tidal wave in 1997.

VII. Denmark [16]

Denmark has become the world leader in wind power and wind turbine manufacturing. Currently, 4,900 turbines supply 7% of the country's electricity, a proportion higher than anywhere else in the world. The largest wind farm in Europe is at Carno in Wales, which supplies electricity for 25,000 homes, and whose turbines were built in Denmark. Of Denmark's export commodities, wind turbines are the fourth largest, worth $525 million in 1997.

By 2030, Denmark hopes to produce 50% of its electricity from renewables. The Danish Energy Agency performed a major study which concluded that wind farms erected out at sea could produce power just as inexpensively as on land, and their first offshore wind farm will be installed in the near future. In addition, 4,000 MW of offshore wind capacity in Denmark is anticipated by 2030.

Appendix B. WindMap Final Log

This is the log for the WindMap output with the following options set:

Geometry:

Zones (X, Y, Z)	= (300, 240, 25)
Z Axis Spacing	= Geometric
Mesh Size (X)	= 690.346667
Mesh Size (Y)	= 925.191667
Mesh Size (Z)	= 30
Origin (X)	= 127890
Origin (Y)	= 753508
Distance to Mesh Top = Auto	

Atmosphere:

Boundry Layer Height	= 100
Transition Layer Height	= 500 (Disable Transition Layer – unchecked)
Stability Ratio	= Link to Vertical Profile
Vertical Profile	= Neutral

Power:

Air Density Options	= Adjusted for Elevation
Elevation Adjustment	= Standard Temperature Profile
Turbine Definition	= Generic 750KW

Initialization:

Initialize from Surface Data	
Surface Data Initialization	= Adjust for Elevation (checked) set to zero Use $1/r^2$ Weighting (checked) set to 6500m

Roughness:

Roughness Map used

Iteration Control:

Maximum Iterations	= 10000
Maximum Residual	= 1.00E-5
Over-Relaxation Parameter	= Auto
Match Surface Data	= (checked) Set to 0%
Optimize Stability Ratio	= (unchecked)

- 17 of 18 stations included and used for initialization (Provincetown removed)
- Chatham frequency used

Direction 1 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 410 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	4.750	4.566
2	Providence, R	4.360	4.403
3	Worcester	3.810	3.810
4	Nantucket	7.290	7.360

Direction 2 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 426 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	6.740	6.244
2	Providence, R	5.300	5.282
3	Worcester	4.730	4.703
4	Nantucket	6.700	6.725

5 Halibut	7.590	7.617
6 Yarmouth	5.750	5.882
7 Fairhaven	4.010	4.854
8 Beverly	4.950	4.799
9 Marthas Vineyard	4.510	4.611
10 Hyannis	4.390	4.548
11 New Bedford	4.000	3.708
12 Norwood	3.020	3.116
13 Plymouth	3.820	3.797
14 Otis	4.900	4.577
15 Lawrence	2.850	3.069
16 Nantucket2	5.850	5.695
17 Buzzards Bay	8.050	7.700

RMS Error (m/sec) 2.78E-01
Mean Bias (m/sec) 6.06E-02

Direction 3 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 683 iterations.

# Station Name	Measured Speed	Predicted Speed
1 Boston	5.530	5.245
2 Providence, R	4.460	4.471
3 Worcester	4.400	4.382
4 Nantucket	6.000	5.939
5 Halibut	6.920	7.104
6 Yarmouth	5.900	6.114
7 Fairhaven	4.290	5.158
8 Beverly	5.440	5.244
9 Marthas Vineyard	5.850	5.703
10 Hyannis	4.990	4.971
11 New Bedford	4.220	3.828
12 Norwood	3.370	3.478
13 Plymouth	3.470	3.563
14 Otis	5.070	4.713
15 Lawrence	4.460	4.517
16 Nantucket2	3.800	3.975
17 Buzzards Bay	6.280	6.314

RMS Error (m/sec) 2.89E-01
Mean Bias (m/sec) 4.00E-02

5 Halibut	7.810	7.972
6 Yarmouth	5.530	5.900
7 Fairhaven	4.700	5.521
8 Beverly	5.440	5.356
9 Marthas Vineyard	5.330	5.297
10 Hyannis	4.730	4.720
11 New Bedford	4.360	4.089
12 Norwood	2.920	3.190
13 Plymouth	4.400	4.333
14 Otis	5.120	4.792
15 Lawrence	3.650	3.850
16 Nantucket2	4.710	4.815
17 Buzzards Bay	7.480	7.350

RMS Error (m/sec) 2.91E-01
Mean Bias (m/sec) 7.42E-02

Direction 4 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 784 iterations.

# Station Name	Measured Speed	Predicted Speed
1 Boston	4.290	4.083
2 Providence, R	3.240	3.275
3 Worcester	3.540	3.523
4 Nantucket	5.020	5.203
5 Halibut	4.620	4.834
6 Yarmouth	5.050	5.205
7 Fairhaven	3.690	4.032
8 Beverly	4.610	4.300
9 Marthas Vineyard	4.150	4.167
10 Hyannis	4.390	4.267
11 New Bedford	2.920	2.858
12 Norwood	3.210	3.186
13 Plymouth	2.810	2.862
14 Otis	3.590	3.473
15 Lawrence	2.790	2.959
16 Nantucket2	4.080	3.915
17 Buzzards Bay	5.420	5.343

RMS Error (m/sec) 1.52E-01
Mean Bias (m/sec) 1.33E-02

Direction 5 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 709 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	4.420	4.177
2	Providence, R	3.310	3.363
3	Worcester	3.250	3.250
4	Nantucket	7.080	6.980
5	Halibut	3.630	4.042
6	Yarmouth	5.640	5.288
7	Fairhaven	3.760	4.390
8	Beverly	4.840	4.456
9	Marthas Vineyard	4.780	4.754
10	Hyannis	3.650	4.063
11	New Bedford	3.460	3.209
12	Norwood	2.430	2.561
13	Plymouth	2.630	2.756
14	Otis	3.940	3.745
15	Lawrence	2.590	2.780
16	Nantucket2	5.140	5.035
17	Buzzards Bay	7.180	6.865

RMS Error (m/sec) 2.64E-01
Mean Bias (m/sec) 7.42E-02

Direction 6 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 654 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	3.700	3.594
2	Providence, R	3.700	3.718
3	Worcester	3.700	3.658
4	Nantucket	5.440	5.399
5	Halibut	4.830	5.015
6	Yarmouth	6.120	5.431
7	Fairhaven	3.490	4.235
8	Beverly	4.620	4.304
9	Marthas Vineyard	5.080	4.876
10	Hyannis	3.410	3.989
11	New Bedford	3.470	3.172
12	Norwood	2.230	2.363
13	Plymouth	2.560	2.684
14	Otis	3.850	3.686
15	Lawrence	2.430	2.613
16	Nantucket2	3.830	3.907
17	Buzzards Bay	6.640	6.407

RMS Error (m/sec) 2.97E-01
Mean Bias (m/sec) 8.04E-02

Direction 7 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 472 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	4.480	4.249
2	Providence, R	3.840	3.870
3	Worcester	4.340	4.261
4	Nantucket	5.860	5.899
5	Halibut	5.120	5.290
6	Yarmouth	5.820	5.381

Direction 8 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 413 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	4.920	4.646
2	Providence, R	3.820	3.887
3	Worcester	4.530	4.463
4	Nantucket	6.610	6.489
5	Halibut	5.720	5.840
6	Yarmouth	6.080	5.677

7	Fairhaven	3.840	4.274
8	Beverly	4.630	4.395
9	Marthas Vineyard	4.350	4.342
10	Hyannis	3.570	4.031
11	New Bedford	3.140	3.107
12	Norwood	2.270	2.442
13	Plymouth	2.870	2.946
14	Otis	4.230	3.967
15	Lawrence	2.420	2.627
16	Nantucket2	4.400	4.437
17	Buzzards Bay	6.940	6.652

RMS Error (m/sec) 2.24E-01
Mean Bias (m/sec) 7.40E-02

Direction 9 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 751 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	5.070	4.798
2	Providence, R	3.840	3.904
3	Worcester	4.720	4.655
4	Nantucket	7.160	7.190
5	Halibut	5.060	5.447
6	Yarmouth	6.390	6.434
7	Fairhaven	3.920	4.627
8	Beverly	5.170	4.857
9	Marthas Vineyard	3.990	4.244
10	Hyannis	5.090	5.133
11	New Bedford	3.400	3.318
12	Norwood	3.100	3.209
13	Plymouth	3.550	3.572
14	Otis	5.210	4.791
15	Lawrence	3.010	3.221
16	Nantucket2	5.430	5.341
17	Buzzards Bay	8.790	8.263

RMS Error (m/sec) 2.72E-01
Mean Bias (m/sec) 7.04E-02

7	Fairhaven	3.860	4.583
8	Beverly	4.590	4.428
9	Marthas Vineyard	4.540	4.581
10	Hyannis	3.810	4.289
11	New Bedford	3.540	3.374
12	Norwood	3.010	3.091
13	Plymouth	3.390	3.414
14	Otis	4.700	4.353
15	Lawrence	2.720	2.919
16	Nantucket2	4.590	4.664
17	Buzzards Bay	8.050	7.634

RMS Error (m/sec) 2.80E-01
Mean Bias (m/sec) 6.25E-02

Direction 10 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 807 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	5.440	5.093
2	Providence, R	3.390	3.492
3	Worcester	4.850	4.777
4	Nantucket	7.930	7.645
5	Halibut	5.820	6.287
6	Yarmouth	5.660	5.624
7	Fairhaven	3.160	4.408
8	Beverly	4.870	4.684
9	Marthas Vineyard	4.150	4.319
10	Hyannis	4.290	4.437
11	New Bedford	3.900	3.384
12	Norwood	3.220	3.324
13	Plymouth	3.650	3.625
14	Otis	4.380	4.122
15	Lawrence	3.620	3.753
16	Nantucket2	5.330	5.340
17	Buzzards Bay	8.490	7.989

RMS Error (m/sec) 4.69E-01
Mean Bias (m/sec) 1.12E-01

Direction 11 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 721 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	5.390	5.153
2	Providence, R	4.330	4.372
3	Worcester	5.240	5.164
4	Nantucket	7.740	7.543
5	Halibut	7.930	8.058
6	Yarmouth	5.280	5.218
7	Fairhaven	4.020	4.951
8	Beverly	5.660	5.405
9	Marthas Vineyard	4.340	4.485
10	Hyannis	3.730	4.079
11	New Bedford	4.020	3.675
12	Norwood	3.770	3.804
13	Plymouth	3.670	3.695
14	Otis	4.390	4.127
15	Lawrence	3.690	3.890
16	Nantucket2	5.350	5.360
17	Buzzards Bay	8.940	8.427

RMS Error (m/sec) 3.30E-01
Mean Bias (m/sec) 6.08E-02

Direction 12 started
Transforming to conformal coordinates...
Calculating initial divergence...
Beginning iteration...

Converged after 628 iterations.

#	Station Name	Measured Speed	Predicted Speed
1	Boston	4.840	4.673
2	Providence, R	4.220	4.254
3	Worcester	4.630	4.573
4	Nantucket	7.840	7.598
5	Halibut	5.410	5.810
6	Yarmouth	6.180	5.688
7	Fairhaven	3.520	4.360
8	Beverly	5.730	5.364
9	Marthas Vineyard	4.430	4.493
10	Hyannis	3.630	4.181
11	New Bedford	3.450	3.256
12	Norwood	3.410	3.436
13	Plymouth	3.460	3.466
14	Otis	3.960	3.843
15	Lawrence	3.630	3.759
16	Nantucket2	5.220	5.326
17	Buzzards Bay	8.270	7.807

RMS Error (m/sec) 3.44E-01
Mean Bias (m/sec) 8.46E-02

Summary

#	Station Name	Measured Speed	Predicted Speed
1	Boston	5.108	4.849
2	Providence, R	3.971	4.025
3	Worcester	4.653	4.595
4	Nantucket	7.262	7.144
5	Halibut	6.137	6.411
6	Yarmouth	5.826	5.707
7	Fairhaven	3.762	4.627
8	Beverly	5.177	4.928
9	Marthas Vineyard	4.373	4.485
10	Hyannis	4.174	4.435
11	New Bedford	3.704	3.435
12	Norwood	3.216	3.300
13	Plymouth	3.523	3.539

14 Otis	4.530	4.251
15 Lawrence	3.299	3.477
16 Nantucket2	5.140	5.142
17 Buzzards Bay	8.242	7.810

RMS Error (m/sec) 3.02E-01
Mean Bias (m/sec) 5.80E-02

Appendix C. Land Use Map Creation with IDRISI

The first step in processing these files is to download the relevant town's data. Unfortunately, the files are ordered alphabetically rather than by any sort of geographical order, so determining which files fall into the central and eastern portions of Massachusetts is, in terms of time-efficiency, more troublesome than it is worth. We will, therefore, simply acquire all 351 data files and process all of them. The fastest way to obtain the files is via a command-line ftp connection; instructions for connecting and locating files is available on the site.

After downloading the data, it must be extracted, as the files are all contained in self-extracting zip archives. The contents of any given land usage archive are two .shp, two .shx, and two .dbf files, one each corresponding to an arc-based file and a polygon based file. Because we are interested in features of specific areas of these maps, we will be using the polygon files.

Due to the number of files that we must process, we will utilize IDRISI macros wherever possible to automate our actions. IDRISI macros are straightforward to create, consisting of single lines of plain text. IDRISI's help files provide extensive coverage of macro syntax for various functions, which simplifies the task considerably.

The first step is to convert the shapefiles (.shp) into IDRISI's native vector (.vct) format. We will use a simple macro call to the SHAPEIDR function, which perform precisely the conversion we want. The conversion creates a .vct file, as well as a corresponding Vector Documentation file (.vdc) and a Microsoft Access database file (.mdb).

Next, we must produce useful attribute information to tie our land use data to the vector files. The land use data including in these files encodes every portion of land according to the current LU37 scheme as well as the older LU21 scheme. Both of these describe a polygon as one of several enumerated sorts of terrain (including forest, residential, urban, wetland, etc). LU37 has the advantage of breaking some of the categories in LU21 into a larger number of categories. We will be making use of the LU37 codes.

We will create Attribute Value Files (.avl) for our various vector files. An .avl is simple a 2-field key-value database. The key is an IDRISI_ID number corresponding to each polygon in a given land usage file; the corresponding value describes the sort of terrain by which the respective polygon is classified. We will use IDRISI's Database Workshop module to open our .mdb files and create these .avl files for each land usage vector file. Unfortunately, there is no apparent macro support for Database Workshop functions. As a result, all 351 of the .avl files must be created manually. Each .avl takes about 15 seconds to create, but with such a large number of files to process, the procedure of creating all the .avl files may, by itself, take more than three hours total of constant clicking and menu navigation.

After the .avl files have been created, we must link them to their corresponding .vct files. We can accomplish with IDRISI's ASSIGN function. We will again take advantage of a simple macro file to automate our use of ASSIGN for all 351 .vct and .avl pairs.

As a minor detail, we must next change the type of data stored in our vector files from the default of Real to Integer, so that we will be able to convert them properly from vector to raster. As opposed to vector data, which specifies shapes in terms of points and arcs in geometric relationships to one another, IDRISI requires the use of bitmapped raster data for many of its more useful operations. A raster file is a matrix of pixels tied to specific values which can be interpreted as appropriate to the situation.

To accomplish the change from Real to Integer, we will use a macro file calling IDRISI's CONVERT function. Once that is done, we can use IDRISI's POLYRAS function to convert our vector files to raster projections. By projecting each of the vector files onto a single large raster file, we will end up with a raster file containing the sum of all 351 land usage files. In other words, we will have a complete land-usage map of the state of Massachusetts, in a raster format that will facilitate our the creation of several maps useful for our social analysis.

References

1. http://www.epa.gov/globalwarming/impacts/index.html
2. http://www.eia.doe.gov/cneaf/electricity/pub summaries/renew es.html
3. Rashad, S. M.; Hammad, F. H.. "Nuclear Power and the Environment Comparative Assessment of Environmental and Health Impacts of Electricity-Generating Systems." Applied Energy. Apr 2000, Vol. 65, Issues 1-4, pp. 211-229.
4. S3. Norman, Colin. "Anatomy Of An Accident." Science. 5 Apr 1985, Vol. 228, pp. 32
5. Rosenzweig, C.; Hillel, D.. "Predicting Global Change Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture." Trends in Ecology & Evolution. 1 Nov 1999, Vol 14, Issue 11, pp. 454-455.
6. Ackerman, Frank; Biewald, Bruce; White, David; Woolf, Tim; Moomaw, William. "Grandfathering and Coal Plant Emissions: The Cost of Cleaning up The Clean Air Act." Energy Policy. 29 Dec 1999, Vol. 27, Issue 15, pp. 929-940.
7. http://www.eren.doe.gov/
8. Sayigh, Ali. "Renewable Energy – The Way Forward." Applied Energy. 30 Nov 1999, Vol. 64, pp. 15-30.
9. http://ethanol.state.ne.us/bgca.htm
10. FitzHerbert, David. "Electricity generating renewables and global warming emissions." Renewable Energy. 4 Jan 1999, Vol. 16, pp. 1057-1063.
11. Moxnes, Erling. "Overexploitation Of Renewable Resources: The Role Of Misperceptions." Journal of Economic Behavior & Organization. 30 Sept 1998, Vol. 37, Issue 1, pp. 107-127.
12. http://solstice.crest.org/renewables/re-kiosk/
13. http://www.awea.org/
14. Tucker, V. A. "Using A Collision Model To Design Safer Wind Turbine Rotors For Birds." Journal of Solar Energy Engineering. Nov 1996, Vol. 118, Issue 4, pp. 263-269.
15. Amin, A-L. "Liberalization of the Indian Power Industry: Wind Power in Gujarat". Renewable Energy. 4 Jan 1999, Vol. 16, pp. 977-980.
16. "Greenpeace Ship Sails to Climate Solution – Wind Power Comes of Age". June 22, 1998. http://www.greenpeace.org/pressreleases/climate/1998jun22.html
17. http://www.magnet.state.ma.us/doer/programs/renew/renew.htm#wind
18. http://www.awea.org/faq/cost.html
19. http://rredc.nrel.gov/biomass/doe/rbep/ethanol/seven.html
20. http://www.ee.rochester.edu:8080/programs/399Projects/TMIStudy/TMIConseq.html
21. http://www.nrel.gov/research/wind/index.html
22. http://www.energy.ca.gov/wind/windfacts.html
23. http://www.windpower.dk/tour/index.htm
24. Brower, Michael C.; Tennis, Michael W.; et al. Powering the Midwest. Union of Concerned Scientists. 1993.
25. Brower, Michael. "New Mexico Wind Resources." 9 Sept 1997, p. 9.

26. Junfeng, Li; Zhuli. "Wind Power Commercialization Development in China". Renewable Energy. 4 Jan 1999, Vol. 16, pp. 817-821.
27. http://www.sbg.ac.at/geo/idrisi/wwwtutor/tuthome.htm
28. http://rredc.nrel.gov/wind/pubs/atlas/atlas_index.html
29. http://www.browerco.com/program.html
30. http://www.wasp.dk/MainFeatures.htm
31. WindMap help file. "Executing The Sample Run"
32. Ushiyama, Izumi. "Renewable Energy Strategy in Japan". Renewable Energy. 4 Jan 1999, Vol. 16, pp. 1174-1179.
33. Martinot, E. "Renewable energy in Russia: markets, development and technology transfer". Renewable and Sustainable Energy Reviews. Mar 1999, Vol. 3, pp. 49-75.
34. Omer, Abdeen Mustafa. "Wind energy in Sudan". Renewable Energy. Mar 2000, Vol. 19, pp. 399-411.
35. "Building a political bridge with wind". Windpower Monthly. May 1999. http://www.nautilus.org/dprkrenew/wpowerarticle.html