01D064I

42

Project Number: 42-PPM2013

A GIS-Based Analysis of Wind Energy Potential in New Hampshire

An Interactive Qualifying Project Report

Submitted to the Faculty of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

By

Scott R. Byers

John E. Crowley John E. Crowley

Sergey M. Kaplan

Date: May 2, 2001

Approved:

Professor Paul P. Mathisen, Advisor

Professor Steve Pierson, Co-Advisor

Executive Summary

As fossil fuel resources continue to be depleted, developed nations will have to seek out renewable sources of energy. The United States and New England in particular have recognized wind energy as a viable alternative to fossil fuel sources. Wind energy is one of the more cost-effective sources of renewable energy and is a clean source as well. In order to promote renewable energy, the government has offered tax incentives to renewable energy suppliers on both federal and state levels. The interest in wind energy is strong, and it is an excellent time to take advantage of that interest.

However, making wind energy possible requires careful consideration of siting. Wind speeds have to be sufficient to cover the operating costs of a wind farm, and typically over 6 m/s on average. In addition, there are many important social, economic, and environmental factors to take into account as well. The goal of this project is to develop a model by which candidate sites can be identified, and then apply that model to New Hampshire. This state has been assessed for wind speed potential in the past, but the methods used to determine the best sites are now outdated, while the neighboring states of Massachusetts and Vermont have had extensive modern analyses carried out upon them.

Therefore, this project carries out the first modern analysis of the wind speed potential of New Hampshire. Our approach has three basic elements: a wind speed assessment of the state of New Hampshire, a Geographical Information System (GIS) based analysis of relevant factors, and a qualitative analysis of other factors that affect the feasibility of wind farms conducted through interviews. These factors include accessibility issues and other concerns which affect the economic viability of a site, and

also the social and environmental issues that appear as a developer seeks approval for the construction of a wind farm.

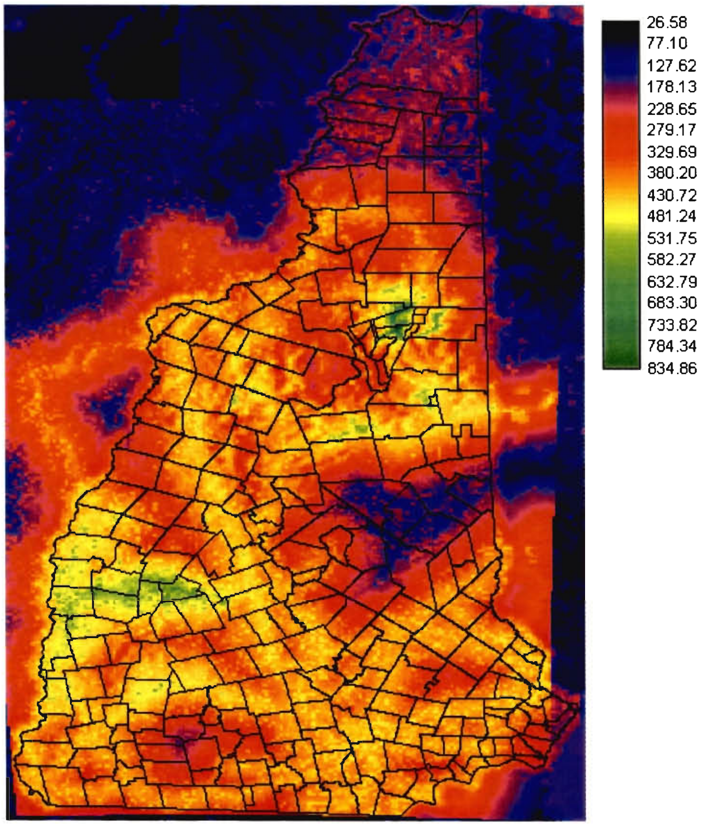
WindMap, developed by Michael Brower, is the program used in this project to predict wind speeds over the state of New Hampshire. Given an elevation map and observed wind speeds at several points on that map, maps of the wind field in New Hampshire were produced at a height of 40 meters. A careful analysis of the various parameters that affect the wind field was conducted, comparing an extensive set of maps to determine the most accurate description of wind speeds. This analysis produced two final maps, one describing the wind speeds over the entire state, and one highlighting the areas where the minimum speed (5.5 m/s) required for a profitable wind farm existed.

The GIS package IDRISI was used to provide a quantitative assessment of the effect issues such as distance from power lines and roads will have on a site's suitability for development. Additionally, the wind speed maps were incorporated into this GIS analysis, allowing candidate sites to be identified by applying a weighting system to all of the factors. Using IDRISI, suitability maps were drawn up on a scale from 0 to 1000, with wind speeds providing 60%, distance from power lines providing 25%, roads providing 10%, and surface roughness providing 5% of those 1000 points.

Many individuals were also interviewed by phone to gain a better understanding of the issues surrounding wind farm development and development in general. Representatives from groups such as the Sierra Club, AWS Scientific, and various developers gave their own perspective on issues ranging from the environmental impact of wind turbines on the surrounding environment, to the economic issues that determine how expensive it is to build and maintain a wind farm.

The two wind speed maps produced were in turn combined with the accessibility map to produce two final maps representing the suitability of New Hampshire for wind farm development. The primary areas where wind speeds are above the minimum required speed and the distance from roads and power lines is minimal are located near Mt. Washington (the Presidential Range), and the region surrounding Mt. Sunapee.

Both of these areas contain suitability rankings numbering in the range of 400 to 835. For comparison, the average suitability of a site in New Hampshire was 180. The higher suitability rankings represent areas of extremely high winds, prevalent near Mt. Washington. Speeds approach 14 m/s in parts of the mountains, which is extremely high for any region of the world.



Final Suitability Map for All Wind Speeds

exist. These barriers include the opposition of environmental groups to construction in undeveloped areas and any concerns that people living in nearby towns may have. Also, future investigations of these potential sites must take into account the effects a wind farm will have on any surrounding forests or protected regions. Regardless, the suitability maps created during this project give an idea of the relative suitability of sites in New Hampshire, and with more time further enhancements could be made to the model which would produce even more accurate results. These enhancements could be decided upon on a state by state basis.

The current model, however, is easily adaptable to other states, as it takes into account factors that are important in any location. For instance, in areas like the Midwest, where extremes of wind speeds are not as common due to lack of mountains and valleys, wind speeds will not play as large a factor in the suitability rankings. A uniform wind map will cease to cause variation in the final suitability map, allowing other factors such as distance from power lines to determine what sites are more suitable. In this manner we have created a very versatile model that can be applied to any region with few adjustments, and opening the way to further analyses.

Table of Contents

Abstract

A model was created for assessing the suitability of wind farm sites based on economic, social, and environmental factors, and applied to the state of New Hampshire. A map of wind speeds was created using WindMap. Accessibility issues were evaluated with the Geographical Information System (GIS) based program Idrisi. These two factors were combined to identify two regions of high energy potential. Interviews with various parties identify the strengths of this analysis, and help determine recommendations for future refinements of the model.

1. Introduction

In the past century, the world's energy needs have been met primarily by non-renewable energy sources. These sources include conventional tools such as fossil fuels plants, hydroelectric plants, and nuclear plants. Eventually the supply of fossil fuels will run out, and renewable sources of energy will have to be utilized. Environmental concerns such as global warming also support a shift towards renewable energy.

Over the past few decades, environmental concerns have pushed industrialized nations into seeking renewable energy sources, such as wind power. Rising levels of emissions from fossil fuel plants have introduced problems such as acid rain and ozone depletion. An environmentally friendly alternative was necessary, and wind power is one such alternative. However, in the beginning of the wind farming industry, the operation of wind turbine sites was more expensive than conventional energy plants. Hydroelectric and nuclear power were explored instead, even though nuclear power was expensive and had environmental concerns of its own.

With improvements in technology wind became a more affordable and environmentally attractive source of power. Today, with the costs of running a wind farm lower than ever, many industrialized nations are putting great efforts into the construction wind farms. The operation of a successful wind farm requires careful site analyses that take into account a number of factors that will determine if a site is viable, however. Among these numerous factors are the wind speed and direction at a particular location, the type of wind turbine used, proximity to existing roads and power transmission lines, and possible impacts of the wind farm on the surrounding wildlife. Therefore, in-depth research must be done before a specific area of land can be used to produce wind energy.

In the 1980's the Wind Energy Resource Atlas provided a basic map of wind speeds across the U.S. Although the map gave a general idea of wind resource potentials, it was not highly accurate, and was only useful in providing a rough idea of where to build wind farms. In more recent years, more detailed site analyses have been conducted using GIS (Geographical Information Systems) methods. More accurate information on the wind speeds and directions was now provided to those seeking to identify eligible sites. As the wind farming industry began to expand, many states began looking to wind as a renewable source of energy. New England states, with their especially high demand for energy due to high population density and their history of polluting industries, became especially interested in building wind farms.

Although New England states are interested in renewable energy resources such as wind power, some of its states are behind. New Hampshire's wind resource assessments are outdated. Therefore, no major wind farming projects have been considered due in part to the lack of new and accurate data regarding the surface wind speeds. The greatest part of a modern wind farm's cost comes from the initial installation of the facility. However, no wind resource assessments have been conducted in New Hampshire since the Wind Energy Resource Atlas.

The goal for this project is to devise a model by which candidate sites can be identified, and then apply that model to the state of New Hampshire. The model will make use of the modern GIS methods utilized in other recent projects, and will take into account the factors outlined above to determine the overall cost effectiveness and feasibility of a wind farm. The resulting suitability rankings from this model can be used as a basis for planning wind farm projects in New Hampshire by any industry that wishes to set up a cost effective wind farm.

2. Background

The industrialized world is reliant on a large supply of affordable energy. With fossil fuel supplies decreasing, the need for cost effective renewable energy sources is increasing rapidly. In past decades, wind power has become a viable renewable energy source, a source worth pursuing to replace current fossil fuel power plants. However, it does not come without its own costs. Although wind energy has become one of the leading renewable energy technologies, there are other factors to consider besides cost effectiveness. Aside from economic concerns, wind energy involves some environmental issues as well as legislation from both federal and state governments, and has a complicated siting process. This chapter contains a general overview of the energy situation in the United States, then a specific discussion of wind power follows. This discussion includes environmental, economic, governmental, and siting issues.

2.1 Environmental Effects of Coal and Natural Gas Consumption

Presently, the majority of the United States' energy needs are met by coal and natural gas power plants. While being very economical, coal and natural gas are non-renewable resources. Eventually their supply will run out and alternative sources will have to be used. When they are burned they also emit many toxins and greenhouse gases into the earth's atmosphere.

The burning of coal and gas by electrical power plants emits 70% of the United States' SO_2 and 30% of the United States' NO_x total emissions (EPA, 1999), as well as a large amount of CO_2. The gases CO_2 and NO_x contribute to global warming. NO_x and

SO_2 also contribute to a reduction of air quality, an increase in acid rain, and a reduction in visibility. Wind power, on the other hand, burns no fuel, contributing no SO_2, CO_2, or NO_x into the atmosphere.

Acid rain has many ill effects towards plant and animal life. A survey done by the National Surface Water survey found that in over 1000 lakes and thousands of miles of streams suffering from chronic acidity, acid rain was found to be the cause of the acidity in 75 percent of the acidic lakes and 50 percent of the acidic streams. Acidity causes chemical conditions which endanger aquatic life, especially fish. Acid rain also contributes to forest degradation, impairing tree growth in several ways. Probably the most important of these ways is that acid rain increases the susceptibility of trees to winter weather (EPA, 1999). Additionally, acid rain causes the corrosion of metals, stone, and paint. Because of this, structures and vehicles must be built using corrosion-resistant materials, or else maintenance costs are increased significantly. Either way, expenses are increased.

Emissions from coal and gas power plants can also contribute to the greenhouse effect, where energy from the sun becomes trapped within the earth's atmosphere. Although there are many questions as to whether or not the greenhouse effect is the cause of recent temperature increases globally, it is widely accepted that even small increases in temperature could have harsh effects. Sea levels could rise; amounts of precipitation, humidity, and other climate conditions could be affected. These factors, in turn, could change water supplies, crop yields, human health, and many types of ecosystems (EPA, 2000). A White House report issued in June of 2000 predicted an average increase in temperature of between 1.8 and 6.3 degrees Fahrenheit globally by 2100. In the United

States, temperatures were modeled to rise between 5 and 10 degrees. The report predicts increased periods of drought and flooding, significantly lower amounts of snowfall, an increase in frequency and intensity of heat waves, and other adverse effects (Chandler, 2000).

Regardless of the relationships between greenhouse gases and global temperatures, the presence of these gases in the atmosphere decreases air quality. Sulfur dioxide, when exposed to the atmosphere, form sulfate aerosols, which compose 25% of airborne particles in the atmosphere in the United States. According to recent studies at Harvard and New York Universities, higher levels of sulfate aerosols are associated with increased sickness from lung disorders. These sulfate particles also account for more than 50 percent of the visibility reduction in the eastern United States. Farther west, nitrogen and carbon play larger roles, so this percentage is significantly lower (EPA, 1999).

2.2 Economic Viability of Wind Power

Despite the negative environmental impacts of electrical production through coal and natural gas, power companies will not invest in wind energy unless it is economically competitive. Advances in wind turbine technology have made wind energy competitive with other forms of energy production (United States Department of Energy, 1996), but a blanket statement about their comparative prices is difficult to make. In some cases, utilization of wind resources by private citizens will save them money in comparison to their electric bills. At sites with lower wind speeds or where accessibility is a problem, installation of wind turbines would not be a good idea. In the past, the drive towards wind power has been a matter of environmental concern, not economic benefit.

There are a variety of ways energy costs can be calculated. The most common way of comparing energy costs is on a price per kilowatt-hour basis. A kilowatt-hour is a set amount of energy (in this case, electricity) that is produced or consumed. In 1980 the cost of wind energy was about 24 cents per kilowatt-hour, decreased to 8.5 cents in 1992, and was projected to decrease to between 5 and 6 cents by 2000 (Painter, 1992). Those projections have been met, making wind energy competitive with gas and coal. Nuclear power, which was originally projected to cost less than any of these given proper research and funding, costs roughly 15 cents per kilowatt hour. These prices are based upon initial installation costs, fuel costs, and maintenance costs predicted over the lifetimes of respective plants. From this perspective, wind energy seems financially to be about as profitable as coal or gas. A report done by The California Energy Commission came up with prices for various types of power on a per-kilowatt-hour basis:

Table 2.1 Relative costs of various energy sources

Fuel	Cost (cents/kWh)
Coal	4.8-5.5
Gas	3.9-4.4
Hydro	5.1-11.3
Biomass	5.8-11.6
Nuclear	11.1-14.5
Wind (without PTC)	4.0-6.0
Wind (with PTC)	3.3-5.3

Wind energy is competitive with, but not necessarily less expensive than the other major sources of power in the United States. Coal and natural gas, which are the two primary sources of energy today, have costs close to those for wind energy. PTC refers to the United States federal production tax credit of 1.5 cents per kilowatt for the first ten years that a site is operating. If a thirty year life span is estimated and the credits accrue interest over the life of the plant, the credit is an average of 0.7 cents per kilowatt hour over the entire thirty year period (AWEA, 2000). When this federal tax credit is supplemented by state subsidies and tax breaks, wind energy looks even more economically attractive.

The economic downside of wind energy is the high installation cost of a turbine. One turbine typically costs between five and seven hundred thousand dollars (Krohn, 2000). Even if the price per kilowatt hour for energy at a particular site is very low, that site will not actually produce profits until well into its operational lifetime. Over 85 percent of the cost to operate and maintain a wind farm is the installation cost, so for the majority of a wind farm's lifetime it is earning back the installation costs, and the very last years almost all energy produced can be sold as pure profit. Many claim that since the installation costs are much lower for other forms of energy (especially coal and gas), that wind power is actually more expensive. Wind energy is a long term investment which in the long run will produce profits comparable to gas and coal, but due to the fact that all the profits are earned at the end of the plant life, the profits at a wind farm cannot be reinvested as quickly (NWCC, 1997).

Whether or not wind energy is more economical, people are largely willing to pay more to have their energy come from an environmentally friendly, renewable source. In some cases, as in the Sacred Heart Monastery in Richardton, ND, erection of wind turbines saves money. Here the nuns are very pleased with both the money they are saving (over ten thousand dollars annually) and the fact that the only negative environmental effect is that they can often hear the hum of the turbines since they were built so close to the monastery (Nicholson, 1999). In other cases, such as the town of Hull, the cost isn't really an issue, and the environment is the overriding impetus for wind energy. As the town manager put it, "To be able to point to a street light and tell my son and daughter that that light is powered by a windmill, I don't think there's anywhere else in the country that can say that," (Daniel, 2000). A survey done by The Sustainable Energy Budget Coalition found that 60% of households were willing to pay six dollars more per month on electric bills if the energy came from a cleaner source, 40% would pay eleven dollars more, and 22% would pay twenty-one dollars more. The Electric Power Research Institute did a similar study, but posed the question differently. They assumed that green power will soon be sold at today's discount energy prices, and asked consumers how much savings they were *willing to give up* in order to have a green energy source. 71% of Americans said they would give up 15% savings to use wind energy or some comparable renewable source (NWCC, 1999).

Environmental concerns are still the overriding factors contributing to the need for wind energy. If the cost of wind energy continues to decline as quickly as it has in the past few decades, wind energy will be actively pursued for economic benefit as well. But, for the time being, public and government support is needed to keep power companies interested in renewable resources.

2.3 Government Support of Renewable Energy Sources

In order to get the support for installing wind farms, people and power companies look up to the state and federal governments for tax credits and legislation. The federal government acts as a motivator and an advocate for wind energy, while the state government fills the role of a host and an actual supporter of wind power through numerous financial incentives and regulatory laws. The government will try to satisfy the needs of both the consumer public and the energy provider, while at the same time trying to safeguard the environment. Therefore, the policy that is created is a result of research and tries to acknowledge all of these concerns. In the end, local and state governments dictate a policy that either supports or opposes wind energy development.

Although some states provide their own Renewable Portfolio Standards, the federal government also proposed a system that encourages the best renewable sources to advance in the energy production market. This system is called the Renewable Portfolio Standard (RPS). The RPS requires that some minimum share of the generated electricity during the year by a certain utility company is produced from a renewable energy source, such as wind energy (www.nrel.gov/docs/, 2000). Because the "RPS applies equally to all competing electricity providers, it is competitively-neutral" (www.awea.org, 1997). If electricity providers fail to produce a certain amount of power, a severe penalty is applied to them. This penalty is often much larger than the actual price of either producing or buying the energy from a renewable source. In order to help out the states with this new approach, specialists in the Department of Energy Wind Program are providing advice, analysis support and testimony to the state legislatures and public utility commissions about the economical and technical aspects on developing wind energy (www.nrel.gov/docs/, 2000).

At the basis of the RPS, a system called Renewable Energy Credits (REC) is designed to keep track of amount of energy produced from renewable sources. "The RPS boils down to a requirement that every generator possess a number of RECs equivalent to a determined percentage of its total annual kWh generation (or sales)" (www.awea.org , 1997). This keeps an accurate account of the usage of renewable energy and keeps industries such as wind power in competition with other power sources. "Because the RPS creates a market for renewables, it will help to close the gap between the cost of pre-commercial technologies and the renewables-market price"(www.awea.org, 1997). Although the federal government provides plenty of help for starting wind farms, some states go to even greater measures to encourage the energy industry to fully utilize renewable energy sources.

States provide their own legislation for the promotion of wind energy. For example, New York state sets its own RPS where it requires 0.5% of all retail electric sales to come from non-hydroelectric renewables (650,000 million kWh; equivalent to about 300 MW of installed capacity, or enough for 90,000 homes). New York also has net-metering for wind laws and a Clean Energy Fund which establishes a buy-down program for small renewable generators funded by the .1 cents per kWh. New York also has the Wind Energy Tax Credits system and also prohibits electric utilities from imposing exit fees and back-up charges for small wind generators (www.awea.org/wpny, 2000). Along with New York five other states have adopted the Renewable Portfolio Standard. Texas was the most aggressive state, as electricity providers must generate

2000Mw of renewable energy. Because Texas has a lot of wind potential, it produces 200MW of power just from wind turbines (www.nrel.gov/docs/, 2000). The Minnesota state legislature required its utility company, Northern States Power, to install 425MW of wind capacity by 2002 and another 400MW by 2013 in order to grant permission for storing the waste fuel at its nuclear power plants (www.nrel.gov/docs/, 2000). However, New Hampshire is also trying to create an opportunity for the renewable power sources in its state.

The state of New Hampshire also provides multiple incentives for research and development of renewable energy resources. One of those incentives is a tax exemption for the property owners who setup their own wind turbines (www-solar.mck.ncsu, 1976). This not only cuts down on the landowner's utility bill, but also reduces the demand for the power supply, which in turn helps keep electricity prices down.

Another law that was created and implemented by New Hampshire requires power companies to buy some of the excess energy from private wind turbine owners and forces the companies to research the possibility of using renewable power sources (www-solar.mck.ncsu, 1997). This piece of legislation creates competition between the use of current and renewable energy sources. The system works similarly to the federal Renewable Portfolio Standard, where power companies have to produce a certain amount of energy from a renewable source. Therefore, instead of buying renewable source energy from expensive privately owned small businesses and homeowners, power companies have to compete to create or research their own production from a renewable energy source. Wind power is relatively inexpensive, which makes it a good potential source.

However, this New Hampshire regulation was not passed without a battle. It was challenged by the New Hampshire Renewable Energy Committee, which concluded that the law was unfair, since the power companies' foremost concern was providing the consumers energy, and researching for the alternative sources of power was their last priority and possibly not their responsibility. Although this regulation does not provide any figures or specific projections on renewable energy use, it creates a push in the right direction.

New Hampshire also provides grants of up to ten thousand dollars for research concerning renewable energy sources. This is open to any educational, commercial or even private organizations that are interested in providing useful data to the state regarding the use of solar and wind power (www-solar.mck.ncsu). This grant is an indication that the state is willing to support the expansion and modernization of the wind farming industry.

Clearly, public opinion regarding wind energy and other renewable energy sources makes a great impact on deciding where to site possible wind farms. It is also understandable that legislation of a particular state is an excellent representation of whether that state is willing to look into the renewable energy portfolios. Therefore, in the end, the government serves as an indicator of the public's opinion and therefore the atmosphere surrounding the issue of using renewable energy sources.

2.4 Factors Involved in Wind Farm Siting

Wind farms require large investments in time and capital. In order to decide where a wind farm should or should not be built requires investigation into the potential costs and profits at a specific site. No site will meet every siting criterion, and because of this decisions must be made concerning the importance of each factor. These factors can be categorized into three basic groups: building costs, environmental factors, and wind speeds.

2.4.1 Building Costs and Accessibility

The type of a wind turbine being put up, accessibility of a site, insurance costs, the amount and cost of labor, and safety at a site must all be taken into consideration at potential sites. All these issues are important since they will decide the cost efficiency and the value of potential sites. If these costs are too high, the wind farm will be more expensive to erect and maintain.

An energy-producing facility is very expansive to install. Because of this, many loans are often taken out in order to set up the power plant. The biggest concern that a contractor has is the amount of time it takes to build an energy producing facility and make it operational because the interest on the project accumulates until the loans are paid in full. Therefore, the amount of time that it takes to put up a wind farm on-line is very important. Conventional power plants, such as hydroelectric, nuclear, or even fossil fuel burning power facilities take years to build and start operating. This is why their initial costs are extremely high. However, since most modern turbines can be built within nine months of the order, the project interest will not increase too much (Swift-Hook, 1989). This means that compared to the alternative power plants, wind farms are less expensive in respect to borrowing money and taking out new loans.

Another big expenditure from the beginning and through the rest of the operating life of the wind farm will be insurance. This insurance should not only cover the project, machinery and supplies, but also the potential hazards that are associated with maintaining, operating and most of all building the wind farm which can exceed twenty percent of the initial building costs (Gipe, 1993). The insurance costs are dependent on the state in which the site is located, and on the level of safety required for the labor workers building the wind farm. Obviously if the location of the site is very remote and the safety of the construction site is compromised, the insurance will increase substantially.

Accessibility to a site is also a big issue. If the site is located in a very remote area, such as on the very top of the mountain, the transportation of supplies will be significantly costlier than the supply line price for a wind farm located in flatter terrain. Even level areas can be far away from power lines and roads, which makes shipping materials to a site more difficult. Although a site distant from populated areas will meet fewer zoning and noise pollution problems, distant sites will be more expensive to build, operate, and maintain (EWEA, 1998). This is due to the fact that the transportation of workers and supplies will create additional expenses.

Because of concerns about noise pollution and environmental impact, off-shore wind farms are often considered (EWEA, 1998). However, the costs associated with setting up an off-shore power plant are much greater than the expenses encountered in establishing a land-based wind farm due to the accessibility of site. This increase of cost is due to the foundation development and the transportation of the entire wind farm to its permanent geographical location off shore.

Based on the power that wind turbines are going to be asked to deliver, a type of turbine will also factor into the equation. It might be more cost efficient to build a cheap but inefficient turbine than a state of the art turbine that will be costly to setup and expensive to operate even though it will perform with a greater efficiency. (Gipe, 1993) In this case the ability of a wind turbine to produce power at a certain wind speed is irrelevant compared to the amount of profit that will be made from wind energy later, depending on what turbine is chosen and its operating and maintenance costs.

2.4.2 Environmental Siting Factors

Compared to other forms of energy production, wind energy is environmentally friendly. It produces no carbon dioxide, requires no fuel, and has no waste products. There are other environmental considerations that should be taken into account before a wind farm is built, however. These concerns include disruption of wildlife, electromagnetic interference, and noise pollution.

The movement of metal rotors used for wind power can interfere with electromagnetic signals. Because of this interference, potential wind farm sites should not be considered if they are close to major transmitters of radio and television signals. In addition, anyone living near the site should be informed that they may have difficulty with reception if the site is installed (Swifthook, 1989). Fortunately, turbines are increasingly being built out of composite plastics and fiberglass, which cause much less interference. Satellite reception and cable signals would not be affected by wind turbines, and would be a good alternative for people living close to a wind farm (Krohn, 2000).

Wildlife may be affected by the installation of a wind farm. "After more than a decade of wind power plant operation in California, the only discernable negative impact on wildlife involves rare, but fatal interactions between birds of prey and wind turbines." (United States Department of Energy, 1996). In Denmark, some studies were done on the flight patterns of birds around wind turbines, which showed conclusively that birds shifted their flight patterns well ahead of the turbines, usually flying safely above them. The power lines, in fact, are more of a risk to bird life than the turbines themselves (Krohn, 2000).

Chance bird deaths occur at all wind farms, either because of collisions with turbines or electrocution by the wires leading to the generator. These deaths can also occur when birds collide with windows of buildings, cars, poles, and numerous other objects, so one should not be quick to claim that a wind farm is unsafe for the bird population of an area. The only wind farm where high bird mortality rates have been reported as a severe problem is the installation in Altamont, California. Here "a 'wind wall' of turbines on lattice towers is literally closing off the pass." (Anderson, 1999). Birds can have difficulty flying around the turbines because of the layout of the wind farm. Farms where the turbines are sparse should pose little or no threat.

In addition, the threat to birds is species specific. The Altamont installation, which is shown to be a threat to birds, has a large number of raptor deaths in particular. Different species may or may not have difficulty seeing the turbines and may or may not have trouble avoiding them once they are spotted. Some species tend to fly close to ground level and would tend not to collide with turbines that are higher up. And, depending on the type of tower the turbine sits on, there have been reports of birds nesting in the towers themselves (Krohn, 2000).

When a turbine is turned by the wind, the mechanical turning of the rotor as well as the aerodynamic movement of the air over the blades create. Generally speaking, the aerodynamic sound produced by a turbine is only slightly louder than the ambient sound in the area caused by the wind. The mechanical sound tends to be masked by the wind as well, but can be a problem at lower to middle wind speeds (between 5 and 10 meters per second). In the past, some complaints have been reported at wind installations with speeds in this range, but advances in turbine technology have virtually eliminated any sound levels above the ambient noise. Since housing is usually no closer than 1000 feet from any turbine, what little sound remains is negligible as observed from the housing around the installation (Krohn, 2000).

While environmental concerns cannot be neglected during the siting process of wind farm planning, it is fairly easy to predict whether or not these problems will occur. As long as a potential site is clear of major transmitting towers, electromagnetic interference is not a problem. It is recommended that turbines be placed at least 1000 feet from housing, and if so, any noise pollution is negligible, especially so at sites where wind speed generally stays above 10 meters per second (Swifthook, 1989). Disruption of wildlife is not a severe threat unless a site is home for an endangered species of birds or a major migratory zone. These factors should be looked into before a site is constructed, but at most sites they will have little or no negative impact.

2.4.3 Wind Speed Estimation

The methods by which wind speeds are predicted have changed drastically in recent years. When wind energy was first being developed in the 1970's, methods were necessarily more primitive than today. At the early stages of wind energy resource development, assumptions had to be made in order to make calculations, yet these assumptions made the values for predicted wind speeds unreliable (Rohatgi & Nelson, 1994). As computers have increased in computational ability, however, the list of assumptions that are necessary to produce results has grown shorter. In recent times it has become possible to produce a usable map from these equations.

The most ambitious early attempt to identify areas in the U.S. with high wind speeds was the construction of the Wind Energy Resource Atlas. When the Wind Energy Resource Atlas of the U.S. was made in 1986, the methods for choosing most of the sites were fairly crude. There were three main methods used to gauge relative wind speeds: observed wind speeds from a limited number of stations, wind effects on vegetation, and certain topographical features.

The Wind Energy Resource Atlas relied on observation stations to obtain its results. The National Climactic Data Center provided a lot of information to the project. However, a lot of observations relied on anemometers that were already set up in various locations such as those at ranger stations run by the U.S. Forest Service. These types of stations often had incomplete data, measuring wind speeds only at one point during the day, and did not provide an accurate picture of wind speeds during the course of seasonal and annual changes. The stations were also distributed in such a manner that some areas were underrepresented. Other avenues had to be explored in order to provide a more complete picture of wind speeds across the U.S. To this end researchers turned to terrain and topological features (http://rredc.nrel.gov/wind/pubs/atlas/appendix_A.html#sources, 1986).

The most important terrain feature that indicated strong winds was vegetation. Flagged trees are an indication of high wind speeds and directions because they tend to deform in areas with high winds (Wind Energy Information Guide, 1996). The makers of the Wind Energy Resource Atlas surveyed residents in the Northeast to find such areas, and used aerial observations to find such deformed vegetation elsewhere. However, searching for flagged trees is not a foolproof method. First of all, areas without deformed trees can still support very high winds, when considering that wind may blow from multiple directions. So while the method can identify sites with strong winds, it can miss detecting others (Wind Energy Resource Atlas of the U.S., 1986).

Another useful, but a complicated siting method is seeking out sites with certain topographical features (Wind Energy Information Guide, 1996). The Wind Energy Resource Atlas used this method extensively. Mountainous areas are conducive to high wind speeds, especially when there are long, sloping valleys leading away from them. Coastal sites also generally have higher than average wind speeds due to temperature gradients existing between the land and sea. Additionally, some features indicate low wind speeds, such as areas of high roughness, including highly forested areas (Wind Energy Resource Atlas of the U.S., 1986). It is also possible to predict sites of high average winds by finding Eolian landforms, including sand dunes, playas, and scoured surfaces (Wind Energy Information Guide, 1996). The strength of this method lies in the fact that such landforms indicate strong sources in constant directions. However, it is difficult to compute rough wind speeds from these geographic features, because of their qualitative nature.

More complicated and quantifiable methods of siting have been developed over the last decade. One such method, which we will be exploring, is numerical modeling. The equations that could not be tackled in the early days of wind resource assessment are now easier to solve because computers are faster and can handle more calculations.

For any system, there are three basic equations that describe it: equations for continuity (mass conservation), momentum, and energy.

$$\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta z} = 0$$

This equation describes the conservation of mass flow in three dimensions. It essentially states that the mass exiting a system is equal to the amount of mass entering the system. Each term is the derivative of velocity in one of three Cartesian directions.

The momentum and energy equations make up the Navier-Stokes equations for the momentum of fluid flow. These equations are a great deal more complicated, and are only utilized in certain algorithms. There are various types of numerical models relying on different sets of assumptions and algorithms. The two most often used methods are the NOABL algorithm and the Jackson-Hunt method. Many software packages use one of these algorithms to predict wind speeds and directions.

The NOABL algorithm ignores everything but the continuity equation because of the complexity of the others. Programs using this algorithm solve the mass conservation equations over an elevation map provided something is known about wind speeds over that map, also taking into account the resolution of the grid placed over the elevation map. Changes in elevation are taken into account up to a certain ceiling, after which velocities are assumed to be constant, by using a power law or logarithmic expansions. A simple power law for wind speeds is the following equation:

$$(V_2/V_1) = (Z_2/Z_1)\ \hat{}\ (1/n)$$

In this equation the speeds at two different elevations, Z_1 and Z_2, are related through the constant n, which typically has a value between 5 and 7, depending on local atmospheric conditions. The final output is adjusted so that it fits the mass conservation equation as well as possible (Wind Characteristics, 1994).

The Jackson-Hunt method uses the mass conservation equations as well, but also attempts to find an approximate solution to the momentum equation, by linearizing the equations (Wind Characteristics, 1994). This allows for a fine-tuning of the results from the continuity equation.

These two methods have both garnered support in the commercial sector of wind resource analysis. Brower & Company's WindMap, the software we will be using for this study, utilizes the NOABL algorithm. One of its competitors is WASP, which uses the Jackson-Hunt algorithm. The two programs boast similar error values, both coming within 10% of actual wind speeds, so both models seem to produce fairly accurate results (Wind Characteristics, 1994).

As an alternative to numerical methods, there are experimental methods that can be used. A terrain map may be used to build a physical model of an area. This model may then be tested in a wind tunnel or other apparatus and relative wind speeds can be determined (Wind Energy Information Guide, 1996). However, this method is generally only practiced on small regions. For our purposes, the numerical methods are much more versatile and provide fairly accurate results.

A trend that shows a move from experimental to numerical methods of wind farm siting is clearly noticeable. More calculations reliant on human observations and assumptions were turned over to computers. This gave rise to the modern and more efficient way of predicting the best places for wind farm installation.

2.5 An Introduction to WindMap

Our analysis will rely largely on the use of Brower and Company's WindMap software. WindMap is a relatively new program that utilizes one of the numerical algorithms discussed in the section on siting. Whereas programs like WASP use the Jackson-Hunt theory to predict wind speeds, WindMap uses the NOABL algorithm, relying solely on mass conservation laws. Both the Jackson-Hunt method and the NOABL method produce results within about 8-10% of the actual values. WindMap is also fairly easy to use in conjunction with Idrisi, a GIS program, which makes it appropriate to our task. WindMap requires a Digital Elevation Map (DEM), which can be imported from Idrisi, and wind data from several observation points. It can then extrapolate wind speeds from these inputs.

WindMap inputs include both surface and upper air wind speed data. Both upper air and surface station wind speeds can be entered as an average wind speed or a wind rose. A wind rose displays the average winds in a certain number of directions, and covers a total of 360 degrees. The wind rose or average speed data is then used to initialize the wind field that WindMap uses to calculate the final predicted wind speeds. WindMap can initialize from either upper or surface air data. The wind field can be initialized from either the upper air levels or the surface stations, but only one station is required to initialize from surface data, while 2 levels are required to initialize from upper air levels. A weighting system can also be applied to each station to determine its relative importance in determining the initial wind field. Initialization as it pertains to our specific project will be discussed in future sections.

Another input that heavily determines what kind of results WindMap will provide is the stability ratio, which describes the ratio between the weight given to vertical and horizontal motion in the velocity field. These motions are determined by temperature differences in the atmosphere. A stability ratio of 1 indicates an atmosphere with no temperature differences at different altitudes. This allows air particles to move horizontally as easily as they move vertically. As the ratio becomes smaller, there are larger differences in wind speeds at different heights. This is especially noticeable in the case of mountains and valleys. By reading a Digital Elevation Map (DEM), WindMap can predict the wind field from initial values within a certain tolerance level.

2.6 The Anatomy of Wind Turbines

In order to be able to make judgements on where to set up wind farms, a certain level of understanding of the physics behind the workings of wind turbines is required. Wind turbines that are divided into three main categories: small turbines, medium-sized with rotor diameter ranging from ten to twenty five meters, and large turbines. However, all wind turbines are made up of the following main components: induction generators, rotors, transmissions, brakes, yaw drives, and controls.

Induction generators are necessary in order to transform mechanical energy, in this case torque, into electrical energy or electricity. They are basically the heart of a wind turbine. They are inexpensive and are extremely easy to set up and run. The induction generator works just like an induction motor, but in reverse. If the power from the wind is supplied to produce torque and spin the shaft, the inductor will start producing power. As the wind speed increases, so does the rotational speed or torque on the generator, since the turbine drives the shaft mechanically. However, as the load on the generator increases, its speed slips by between 2% and 5% (Gipe, 1993).

The rotor consists of blades and a hub, which transform the linear wind speed energy into the rotational movement or energy of the shaft. The blades of most medium-sized wind turbines are mostly made of fiberglass. Fiberglass is strong, relatively light weight and is less susceptible to fatigue or corrosion than metal or wood. This quality also makes it preferable for offshore wind turbines. Since the main spar of the blade is made using a filament winding process and the blade is assembled in a mold with a smooth fiberglass shell, the blades become both strong and flexible (Gipe, 1993).

The hub converts the blade's motion into torque. It is one of the strongest components of a wind turbine. Although most wind turbines on the market right now have the blades bolted to a rigid hub, "several manufacturers of medium-sized wind turbines for commercial applications, 25 meters in diameter and larger, reintroduced pitchable blades in early 1990s to control the rotor in high winds." (Gipe, 1993)

As wind turbines grow in size, a more efficient transmission is needed in order to increase the speed of the generator shaft. The larger the wind turbine and its rotor, the slower the rotation of the shaft. Since most generators are designed to operate in the 1200 to 1800 rpm range, a transmission gear box is needed to create optimum operating range for the generator. Therefore, most wind turbines with large rotors and low rotation rate use planetary or epicyclic gear boxes. (Gipe, 1993)

Some sort of brakes must be used in the wind turbine design. If the wind is higher than the rated speed for a specific turbine, the rotor can increase its rotation rate beyond the destruction point. Many wind turbines use aerodynamic stall as the means of slowing down the rotor. Since most wind turbines use fixed-pitch blades with induction generators, they produce a constant speed shaft. "In winds above the rated speed, the tip-speed ratio for these turbines declines because the speed of the rotor remains constant. The angle of attack increases with increasing wind speed for wind turbines operating at constant speed, lowering the performance of the blades below the optimum."(Gipe, 1993) Although mechanical brakes are used on many turbines as backups, they are expensive, unreliable and require a lot of maintenance. For variable speed wind turbines, passive brakes called pitchable blade tips are used to reduce the rotor speeds. "At higher than normal speeds, the tips of the blades are pulled to the outside of the rotor by the centrifugal forces along the curved and grooved shaft. The action decreases lift where it is greatest while dramatically increasing drag"(Gipe, 1993).

In order to keep the blades from experiencing too much stress due to thrust in high winds, devices were invented to keep the rotor rotating at the same speed. Most modern wind turbines use the concept of furling to slow down their rotors in high winds. At high wind speeds, a lot of thrust is produced by the increased airflow. While the pressure will stay the same on the upwind part of the rotor blades, the only way to change the force parallel to the airflow is to reduce the area of the rotor. This is usually done with an assist of gravity or springs. In a gravity control system, the center of pressure is slightly higher than the hinges of the rotor hub. As the thrust increases, the rotor hub is pushed up, which at the same time raises the tail (Gipe, 1993). As the wind speed decreases, the weight of the tail brings the rotor back to its normal to the airflow position. In spring loaded wind machines, springs act as resistors of the tipping motion. As the wind speeds increase the rotor is turned by the thrust against the force of the springs, which return it back to its original position with the decrease of airflow.

Although not used on many wind turbines, another method to control the speed of the rotor is through the change of the blade pitch. Two kinds of mechanisms for changing the blade pitch exist today. The first uses centrifugal force to push out weights, which are called flyballs, on the hub. These weights transmit their mechanical motion into the rotation of the blades through a gear wheel. The flyballs are pulled inside by the springs that are attached to the hub in lower wind speeds.(Gipe, 1993) This mechanism is called the flyball governor. Another mechanism called the blade-actuated governor uses the weight of the blades themselves. As the rotational speed of the blades increases, the centrifugal force pulls the blades away form the center of rotation. When the blades slide on their own shafts, the grooved rail permits them to change their pitch toward feathering. As the blades slow down, they are pulled back by the springs, which are attached to a triangular spider. (Gipe, 1993)

A simple understanding of the basic components of the wind turbine is necessary in order to make informed and sound decisions on the kind of systems that might be employed on the wind farm. Every component from the generator to the mechanism that slows down or controls the rotor speed deserves attention, since every part is critical in determining the efficiency and cost effectiveness of the wind turbine.

2.7 Past Wind Resource Development

Governmental regulations involving wind power show that there is concern for how the U.S. energy needs are going to be met. The mere fact that legislation exists shows that there is at least some public support for renewable energy resources, especially wind power. But is wind power viable? By examining the past attempts made to establish wind farms, it becomes obvious that wind farms are tenable.

One could say that the birthplace of wind energy in the U.S. is California. On the average more environmentally aware then other states, California has been the site of many wind energy projects. In fact, more than 90% of the total wind power in the U.S. came from three California wind farms in 1999 (Mother Earth News, 1999). Most of California's turbines were built in the 1980's. With the deregulation of the industry in 1998, however, new projects have once again been springing up. A plant built near Palm Springs in 1999 provides energy for 6000 households (Natural Gas Week, 1999). The success of wind energy in California, although helped by that state's commitment to the environment, shows that other states could do the same.

The biggest market for wind energy, in fact, exists in the Midwest. Called the "Saudi Arabia of wind energy" by some (Smithsonian, 2000), the plains of the Midwestern U.S. are ideal for wind power applications. It has been predicted that North Dakota alone could provide 36% of the annual energy needs of the U.S. (http://www.nrel.gov/wind/potential.html, 1993). Minnesota has seen a lot of development due to the activities of its "green" legislature. When Northern States Power wanted to find sites for dumping nuclear waste, the legislature took the opportunity to get

NSP to agree to develop 425 MW of wind power by 2002 (Newsweek, 1998). They opened the Lake Benton facility in 1998, the largest wind farm in operation in the U.S. At the time it was able to power 40,000 homes, with predictions that it would quadruple this output over the coming years. This is only the tip of the iceberg, however, with projects springing up in Colorado, Iowa, Wisconsin, and Texas (Newsweek, 1998).

There has also been some potential identified in the states of New England. The biggest operation in New England is currently the Searsburg facility in Vermont. This facility conducted tests over its first three years to determine the effects of cold climactic conditions on the operation of the wind farm. Because the Midwest has such great potential but experiences harsh winters, this plant had particular significance to wind energy proponents. Siting this plant was no easy task. The plant is located in a relatively sparsely populated area, and was built on private land. Before building the plant, Green Mountain Power (who runs the plant) conducted thorough studies. They mailed two general societal acceptance surveys to the residents of Searsburg, and they actually still make efforts to educate people about the facility. Ongoing avian studies are being conducted to find the impact on bird populations, even though the plant threatens no endangered species. A study was conducted to determine the effects on black bear populations as well. Most importantly, years of on-site observations were made for wind speeds before building began. The average wind speed is 8 meters per second, and it is expected that the plant can provide 14 GWh (GigaWatt-hours) annually, and provide electricity to 2,000 homes (http://www.eren.doe.gov/wind/green.html, 2000).

European countries, as concerned about the environment as the U.S., have made huge strides in developing wind power. Since the formation of the European Union, many tax breaks and incentives have been instituted to encourage the construction of wind farms (UNESCO Courier, 2000). Denmark is one of the leading countries in wind power, with 10% of its energy coming from wind energy (UNESCO Courier, 2000). The Danes are so committed to wind power, in fact, that more of their workforce is involved in wind power than in such industries as fishing (Skin Diver, 2000). Some estimates have predicted that 50% of Denmark's power needs will be met by wind energy by 2030 (Skin Diver, 2000). This type of dedication is rare, however, as there are no such expectations for other countries.

Germany is leading the pack in terms of wind energy development (UNESCO Courier, 2000). They still only supply 1.3% of their energy from wind energy at the current point in time, however, with hopes to reach 30% by 2030. There is, however, some fierce opposition to the development of wind farms in Germany. Although the Germans are vehemently anti-nuclear and have the political will to push wind energy, the electrical companies oppose the restrictions laid upon them by the government. In addition, some lawmakers are concerned that the growing numbers of turbines dotting the countryside are ruining it. In the U.S., this is analogous to the Appalachian Mountain Club's objections to some wind energy projects (AMC guidelines, 1996). If a country like Germany, with a populace historically concerned about their environment, has these problems, then developers in the U.S. should take note. Such problems have hurt wind energy development in other Western nations. Britain, for example, has one of the greatest potentials for wind power. However, local government officials have neglected to issue permits for commercial wind farm construction, and so Britain's potential remains untapped (UNESCO Courier, 2000).

Even so, Germany and Denmark are wind energy leaders. They provide incentives for other countries to get involved in wind energy. Third world countries such as India, and other countries with large rural populations like China, are very interested in wind power, but not for environmental reasons. Wind turbines are very useful for providing energy to villages, as a single turbine is able to meet a village's needs (Courier, 2000). But even if they are not taking advantage of wind energy for environmental reasons, the goals of environmentally minded nations are being met in these cases.

The success of sites in California and in Europe (especially Denmark) and the continuing development of wind power in the Midwest shows that there is both a commitment to wind power and an ability to make it work. Even in Vermont, which experiences harsh climactic conditions and is not as suitable as the flat plains of the Midwest for wind power development, wind power is being successfully implemented. Since New Hampshire has a mountainous terrain similar to Vermont's, it is also an area where profitable wind farms could be constructed.

3. Methodology

Many factors must be considered in the siting of a wind farm. Some factors, such as wind speed, accessibility, and surface roughness can be weighed to yield a good estimation of a site's economic viability. An effective procedure for analysis and weighting of these factors is required in order to assess wind development potential in over a given area. After some discussion with Michael Brower and Mike Markus concerning the importance of each factor we decided to weigh the factors as follows: average wind speed 60%, distance to power transmission lines 25%, distance to roads 10%, surface roughness 5%.

There were three main aspects to this project. First a map showing wind speeds across the State of New Hampshire was created. This required a variety of input data for the WindMap program that we used. The second aspect involved the calculation of distances from roads and power transmission lines using GIS software as well as an assessment of the roughness of terrain throughout New Hampshire. Third, interviews were conducted in order to find out what barriers exist for wind power in New Hampshire, and elsewhere, and how they may be avoided. The integration of these three aspects provides an approach for measuring the wind development potential of a given area

3.1 Acquisition of Data

A wide range of data was required for input into WindMap and Idrisi. Digital elevation and surface roughness maps were required for the wind assessment. Additionally, the wind speeds and geographic locations of sites within New Hampshire and immediately surrounding the state were required. Finally, digitized maps of roads and power transmission lines were required for the accessibility assessment.

3.1.1 Digital Elevation Maps

WindMap requires an elevation map for the area we are investigating. Digital Elevation Maps (DEMs) were downloaded from the United States Geographical Survey website (www.usgs.gov). These maps were in the 1:250000 scale, a 100-meter resolution, and divided into quadrangles consisting of an eastern and western half. The quadrangles are not true rectangles due to the curvature of the Earth, but the software we used compensated for this factor. The map files were then imported into Idrisi using the DEMIDRIS import command, located under Government Agency Data Formats. The eleven quadrangle halves were imported, including the following: Albany East, Boston East, Boston West, Glens Falls East, Lake Champlain East, Lewiston East, Lewiston West, Portland East, Portland West, Sherbrooke East, and Sherbrooke West.

After being formatted as raster files, the individual quadrangle halves were concatenated within Idrisi using the CONCAT command to make a single map for New Hampshire. Idrisi assembled the individual maps into one single raster file using the "Automatic Placement using reference coordinates" option, which found the points where the maps connected automatically. This procedure produced a single raster file that covered the area we were interested in studying.

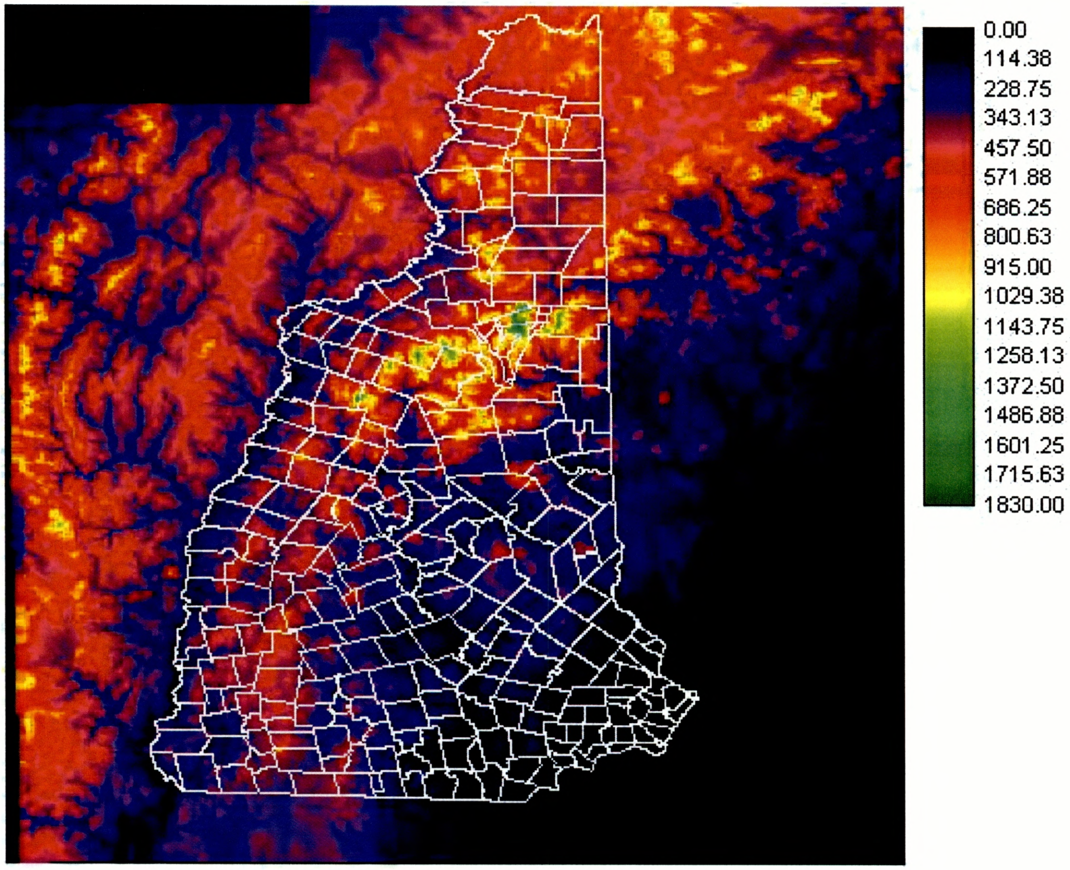


Figure 3.1: Digital Elevation Map (DEM) of New Hampshire in meters.

WindMap requires that the input maps and wind data be of a certain format. A suitable map had to fall under size and resolution limits. The DEM was in a latitude/longitude format, with degree units. This map needed to be reformatted into metric units. The maps from the USGS were in the "plane" reference system, a dated format that the current version of Idrisi does not support. However, because the "plane" system is essentially a latitude-longitude system, a simple transformation was possible using the RECLASS command. Because the coordinates of a point on the DEM could be multiplied by constant to gain latitude/longitude degrees, a correspondence file listing the old point coordinates with the desired new coordinates was easily constructed. The RECLASS command then quickly converted the map to a "latlong" reference system.

Within Idrisi, the PROJECT command was used to change the map projection from "latlong" to "spc83nh1", a metric projection specific to New Hampshire. Additionally, new bounds were chosen such that the resolution of each row and column of the map would be 912.9 meters per row and column. The final bounds ranged from 195000 to 427000 meters in the x-direction and 0 to 315000 meters in the y-direction. In order to have the proper resolution for these bounds, 254 columns and 345 rows were required. This map can be seen in Figure 3.1.

3.1.2 Roughness Maps

Roughness maps were obtained from Michael Brower, the man responsible for the WindMap software. The roughness map included a large area of New England, and was in the format "albers83", which required reformatting. The PROJECT command was once again used, to convert the map into "spc83nh1". Simultaneously, we were able to change the resolution of the map to 912.9 meters and choose the appropriate bounds (the bounds for the DEM). This was achieved using the 'Output reference parameters' option in the PROJECT menu. The roughness map used for our calculations can be seen in Figure 3.2.

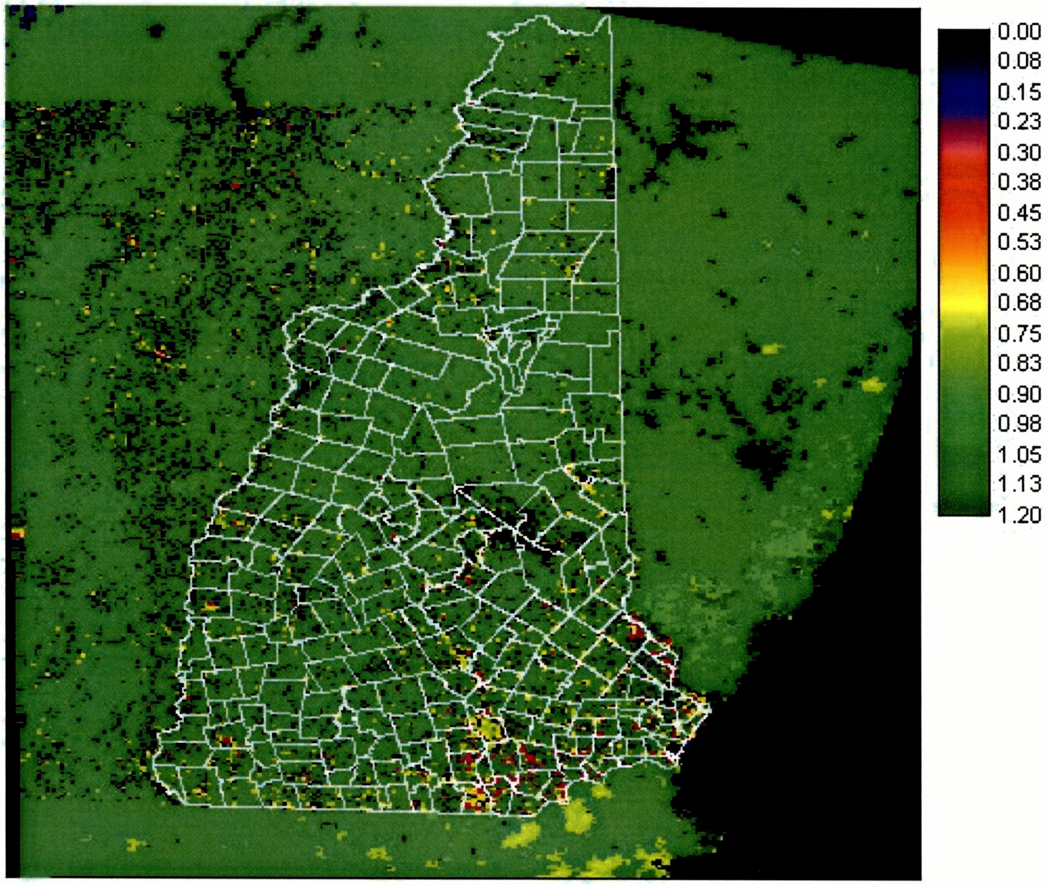


Figure 3.2: Roughness map of New Hampshire

WindMap uses 16-bit data such as that produced by Idrisi Version 2. Because we used the 32-bit version of Idrisi, the elevation and roughness maps had to be converted into the older 16-bit format. This was accomplished easily, using the Idrisi conversion tools. Idrisi easily converts between 16- and 32-bit file formats. This command produces a document file that WindMap can use to predict wind speeds.

3.1.3 Wind Data

WindMap requires wind speeds in each compass direction for a number of locations. Wind data were obtained from the National Climatic Data Center and quarterly reports of a study done by AWS Scientific. Ideally data for each station would range from January until December and data from the same year could be used for each station. Realistically data were simply not available for one particular year at a good sampling of stations. As a result the years 1998 and 1999 were used.

The data from the NCDC are given chronologically by station number with readings taken roughly every hour. The columns including the wind speed and direction were cut and pasted into a separate file. Each reading is given equal weight, making the assumption that there is no correlation between the number of readings taken on a certain day and the wind speed or direction. All of the wind data are then sorted into sixteen directions (22.5 degree increments), and the mean of each of these increments is taken using a computer program. The data are given by calendar year, so data ranges from either January 1998 to December 1998 or from January 1999 to December 1999. Data were available for the Concord, Jaffrey, and Berlin stations for both years. Comparisons of average wind speeds as well as wind speed and direction roses showed that data from the two years were very similar. In the case that data for more than one year were available the 1999 data were used. A listing of all the N.C.D.C surface stations used in this project can be seen in Table 3.1.

Table 3.1: NCDC sites used for analysis listed by state.

New Hampshire

Berlin
Concord
Jaffrey
Laconia
Lebanon
Manchester
Mt. Washington
Nashua/Boire Field
Pease AFB/Portsmouth
Rutland State
Sanford
Whitefield

Vermont

Barre/Montpelier
Morrisville
Springfield

Maine

Fryeburg

AWS scientific did a wind speed evaluation of four sites in New Hampshire: Berlin, Colebrook, Walker Mountain, and Mount Sunapee. This survey began in the fourth quarter of 1998 and ended in October of 2000. The data includes wind roses for each site over the course of each respective quarter. Data for the four quarters of 1999 were averaged to produce roses for input into WindMap with the same program used for the N.C.D.C data. Unfortunately, data were unavailable for the Berlin site during the month of February and for the Colebrook site between October and December due to the fact that the site was moved to Dixville Peak. Obviously it is best to have the same time period covered at all sites, but any error introduced by the missing months would have a minimal effect on the final wind speed map.

3.2 Wind Map Creation and Inputs

In order for a wind farm to be profitable, the wind speed at that farm must be above a certain level. If not, the site will not generate enough electricity. Wind speeds were analyzed using WindMap. In order to obtain accurate results in WindMap, data was required from a range of locations and altitudes. Each station had a wind rose associated with it that was entered into WindMap.

Within WindMap there are many parameters that can be varied to produce different results. These parameters are important because they reflect assumptions about the terrain, and can have drastic effects on the predicted wind speeds. The parameters must be tested in order to determine which ones best fit the available wind data. On the WindMap interface is an options tab, which when opened includes menus for Geometry, Atmosphere, Power, Initialization, Roughness, and Iteration Control. Each of these options has a different effect on the data, and the definition for each is presented in the following subsections.

Geometry and Roughness Menus

Two of the options are already accounted for by the data imported from Idrisi. The Geometry tab applies to the spacing of the map grid. The user can manipulate this directly, but since we are importing our maps from Idrisi, these values get entered automatically. Additionally, the roughness map automatically defines the fields under the Roughness tab. If there was no roughness map available, then a constant roughness must be assumed. Entering a roughness map into WindMap provides for much more accurate results.

Atmosphere Menu

The Atmosphere tab contains data about the boundary and transition layers and determines the vertical profile of the wind speeds. On the right side of the Atmosphere window is a graph showing the effects of the various parameters on the vertical profile, at three different roughness values. WindMap assumes that the typical boundary layer elevation is 100 to 200 meters, a range over which a logarithmic function can be used to calculate wind speeds based on surface data. The transition layer is also defined, and WindMap shows the point at which the upper air data and the surface data may be blended logarithmically. The transition layer can also be disabled, in which case this data is blended linearly. The next parameter is the stability ratio, which indicates how freely air particles are able to move in the horizontal and vertical directions. A value of 1 indicates motion is equally possible in either direction, while values less than 1 indicate more difficulty moving in the vertical direction. Finally, there is a box for choosing the stability characteristics of the vertical profile. The options include unstable, neutral, slightly stable, and stable, and these options reflect a stability length value L, which can also be entered manually. The more stable the atmosphere, the more wind speeds will change with height.

Power Menu

The Power menu contains three boxes that reflect parameters that will affect power output at a specific point. The air density box defines how air density changes over height. The value can be changed for elevation (the default), or made constant by user-defined value or given the value at sea level. The second box chooses how the temperature profile will change with elevation. WindMap uses the International standard for temperature profiles by default. Alternatively, if the temperature at the lowest point is known, and a rate of change for the temperature can be determined, these values can be used to make the temperature profile. Finally, the Power menu allows the user to define what kind of turbine is being used at a site. There is a drop down list of available turbine data, and is fairly comprehensive. It is also possible to edit the preexisting data or to enter new data. This option will remain largely unutilized in our study because we are more interested in locating sites with high wind speeds. Wind energy developers will have a better sense of what kind of turbine should be used at a particular site, and it is quite possible that the turbines available in WindMap are no longer the most technologically advanced.

Initialization Menu

The Initialization tab allows the user to tell WindMap how to initialize the wind data. Either upper air or surface data can be used to initialize the data, although the latter is preferred if possible. It is best to try initializing the wind field with several different combinations of stations if possible to determine which produces the best results. Additionally, some sites may experience unusual conditions due to specific surrounding conditions, and must be accounted for. An example would be a narrow valley. We will be initializing the wind field with surface data.

Iteration Control Menu

The final tab is Iteration Control, and determines how many calculations WindMap will perform in arriving at a solution. WindMap must conduct enough iterations to provide wind speed predictions that are accurate. The default number of iterations is 10000, although typically around 1000 iterations will be sufficient. The maximum residual can also be defined, and basically defines how much the final wind data will deviate from actual values. The WindMap help file demonstrates that with a 100x100 meter grid, each cell being 1000 meters long, and with the default maximum residual of 1E-5, wind speeds will be roughly 0.1 meters per second off from the true value. The other two options in the iteration control box help optimize the wind data.

Matching the surface data makes WindMap compare its predictions to the surface data entered, and forces it to make its prediction agree with the input. Optimizing the stability ratio also helps make WindMap's predicted wind speeds match measured wind speeds by varying the stability ratio during the iterations. This will increase calculation time dramatically, but also provides significant increases in accuracy. However, there must be a wide variety in the input data, including mountaintop data as well as airport data. If the time involved is not prohibitive, and our sites fit the criterion, we will employ this option.

All of the parameters must be tested to determine the best combination. A thorough examination of these parameters will produce the most accurate predictions possible. Discussion of the parameters chosen for the analysis of New Hampshire takes place in Chapter Four.

3.3 Calculations within Idrisi

As noted previously, Idrisi is GIS software that allows its user to import, digitize, calculate, evaluate, concatenate and analyze maps of different values and contents. It does this through the use of multiple functions, which are available from its menus. We used Idrisi to combine all our weighting system factors together to produce a final GIS image of the most plausible wind farm sites in New Hampshire. However, during this project we used only the following functions: Import, Idrisi Conversion Tools, INITIAL, LINERAS, Digitize, Distance, RECLASS, PROJECT, RESAMPLE and OVERLAY. In this section we will briefly describe what these functions do, what set of input parameters are required for each function, and the outputs that are produced by each procedure.

The Import function allows the user to import an already existing map in either digitized or desktop format into either a vector or raster file depending on the map itself. A vector file is already digitized and has practically no set resolution, giving it extreme accuracy. However, Idrisi uses a raster format to do most of its calculations. We also used a shape format from the GRANIT web site to import a road map into a vector format in Idrisi. This function requires a shape file to be inputted, a name for the resulting vector file, and a specific reference system to be established. Its output is a converted vector file that can later be used for our purposes in Idrisi. The greatest convenience of this function is that it will import a file into an already existing reference system in Idrisi, which is much easier to manipulate for analysis purposes.

Another import function in Idrisi is the ability to import any desktop format (in our case BMP) into a raster file. However, the file's parameters will stay exactly the same as they were in the original BMP file. This is less convenient, because the new raster file will require the assignment of appropriate parameters based on the georeference file.

The Idrisi Conversion Tools function allows the user to convert files from previous versions of Idrisi to the 32-bit version we use. Raster, vector, attribute or macro files can be converted with this function. For our purpose, we used only the raster file conversion option, as WindMap requires 16-bit versions of the maps we used. DEMs and roughness maps were converted to 16-bit for use in WindMap, and subsequent wind maps produced were converted into 32-bit versions.

The INITIAL function allows us to initialize a raster image. It requires an output filename and a specific set of output reference parameters, including the number of rows and columns of the image and its maximum and minimum parameters.

This image can be later updated with the help of the LINERAS function, which converts and at the same time concatenates vector files into one image. The final result of the LINERAS function is a raster file.

If the files were imported from a desktop format and have a poor resolution for the performance of distance calculations, it might be necessary to digitize the file manually. This is done with the help of the digitizing icon located in the toolbar, which requires the user to select the name of the file to be created, layer type and data type in order to be digitized. This function's output is a vector file, which again can be converted into a raster format through the use of the INITIAL and LINERAS commands.

After a file of an appropriate resolution is obtained, we can perform distance calculations on the file with the help of the Distance option. This function requires a raster file input and outputs a file that shows distances from lines which were either imported in a digitized format or were created manually using the digitize option.

In order to assign distances different values that will be compatible with the weighting system that we designed, we can use the RECLASS command in Idrisi. It requires the file to be reclassed and the new values, which must be inputted into the table manually for specific ranges of an already existing raster file. It also gives the option of saving the table so that it doesn't have to be reentered every time a new map is calculated.

Before we overlay the maps to get the final results, it is most of the time necessary to make sure that all maps have the same number of rows and columns and are in the same reference system. The PROJECT function can be used to convert a map from one reference system to another; for example, it can convert from a meter scale to latitude and longitude. This function requires an input raster file, its current reference system, and the output name of the new file along with the desired reference system. Output reference parameters are required; these may be automatically calculated by Idrisi or edited by the user.

If two maps are to be overlaid, the minimums and maximums of each file must match. This is accomplished with the help of the RESAMPLE option. However, a correspondence file must be created which contains a number of points to be compared with one another and the coordinates of old as well as new points. Once this file is created, the file to be resampled is entered along with the filename for the resampled image. The number of rows and columns should be the same as for all other maps so that they can be overlaid properly, but the minimum and maximum values should be inputted manually and equal to those of the new map.

The last function that was used in our GIS analysis was the OVERLAY option. It takes the values of two raster files and performs a mathematical operation with those values. It performs the operation pixel by pixel, so the number of rows and columns of the two maps must be the same. The result of this function is the combined value of the two files presented in a raster format.

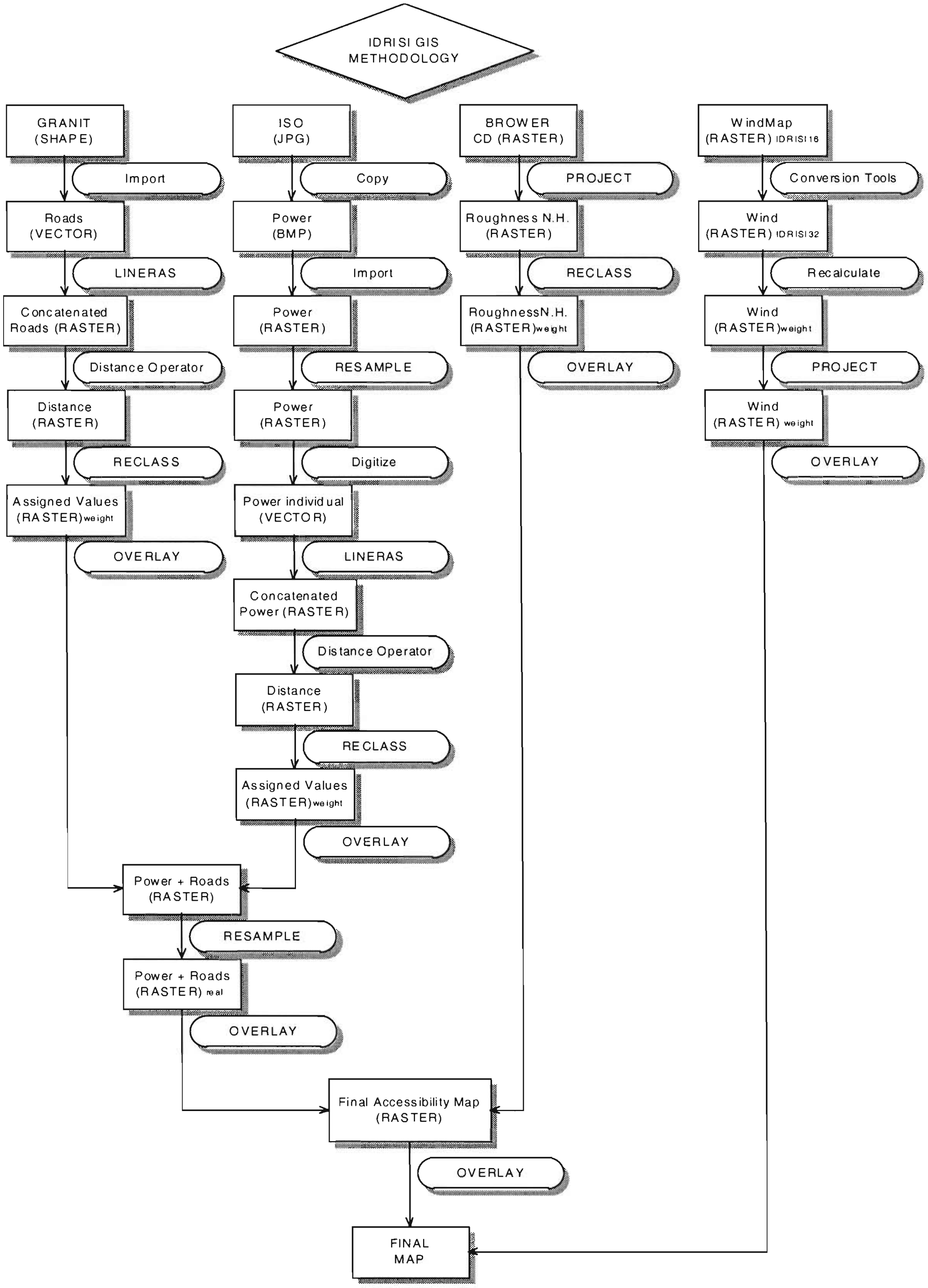


Figure 3.3: Flow Chart displaying the GIS methodology

Now that all the basic functions of Idrisi that we need to use have been explained, we can take a look at how we actually derived our final results by obtaining maps, digitizing them, assigning values based on our weighting system and combining these files using this software. This process is outlined in Figure 3.3, and each point in the flowchart is discussed below.

3.2.1 Calculating and Evaluating Distances from Roadways and Trails

Materials for the construction of a wind farm will be transported by automobile. As the distance from a potential site to suitable roadway increases, the cost of installation and the cost of maintenance increase. Additionally, special interest groups such as the Sierra Club and Appalachian Mountain Club frown upon the construction of new roadways to facilitate the construction of wind farms, so sites close to roadways are preferable. For these reasons the distance between potential wind farm sites and the nearest road or trail is a very important factor which deserves close consideration in the project.

Maps of suitable roadways were first obtained from the University of New Hampshire's GRANIT program (http://www.granit.sr.unh.edu/). GRANIT is the University of New Hampshire's GIS mapping program. There are 213 separate maps that must be concatenated in order to obtain a road map of the entire state of New Hampshire. Individual maps were downloaded and unzipped from the GRANIT web site. Next, these files were imported into Idrisi so that they would be converted from shape files into vector files. The vector file of the entire state that results from concatenation will be used for final distance calculations.

This was done by first creating an image of the roads with correct parameters to be later used in distance calculations. First a political boundaries map was downloaded from the GRANIT web site. When creating images, we selected the INITIAL option from the Data Entry menu and selected "defining special parameters individually". Under "output image" we used a random file name and "Output reference information" was selected. All of the values for the reference parameters were copied from the boundary file's Layer Properties. The number of columns and rows we selected produced a certain resolution. For a higher resolution, a greater number of rows and columns is needed. For a state the size of New Hampshire it is recommended that number of columns be more than 4000 and number of rows be more than 7000. The maps used contained 4978 columns and 9547 rows.

Next, the vector road files were converted into raster files, using the LINERAS command. In the "Vector line file" section each individual vector file of roads in New Hampshire was used, and under the "Image file to be updated", the image file that was created earlier from the parameters copied from the boundaries file was used. Idrisi automatically concatenates the files together into one raster file.

After Idrisi was done converting and concatenating, the distances from roads were calculated. Using the DISTANCE command, we selected the raster file of the entire state obtained from LINERAS. The output from the DISTANCE provided the desired distances.

After distances were calculated, the last step was to assign values to the specific ranges of distances. Since there was a total of 1,000 points and roads are worth 10%, a site's accessibility to the nearest road will be evaluated on a 100 point scale. A correlation was created between the distances such that 1 point corresponded to distance of 100 meters. A rating of 0 was presented to the sites with distances greater than 10 kilometers from the nearest road and a rating of 100 was given to an area where a road or trail presently exists within a 100 meter radius.

In order to assign the values to the file, the RECLASS function was used. For the “Type of file:”, “Image” was used, and for the “Classification type:”, “User-defined reclass” was selected. The “Input file” was the distances file and the “Output file” is the file that will finally be used in the OVERLAY function for the entire weighting system. For the “Reclass parameters” the same system that was described in the paragraph above was used. Namely, the “Assign a new value of:” went from 100 down to 0 in increments of 2 and the distances went up from 0 to 10,000 in increments of 200. The last assignment of 0 points was given to the range of distances from 10,000 meters to 1,000,000 meters in order to make sure that past 10 kilometers the values would be 0 throughout the entire map.

The final distance to roads map with assigned point values was used later in determining the total accessibility for different locations throughout New Hampshire. Besides the roads and trails map, a power line and roughness map was considered in this accessibility analysis.

3.2.2 Calculating and Evaluating Distances to Power Transmission Lines

Just as the distance from roadways is important, distance from power transmission lines to the potential site also matters a great deal. Once energy is created using wind farm, it must be transmitted through above ground or below ground power transmission lines. These power lines must be carrying a voltage of 69kV or higher otherwise they will not be able to transmit the power created by the wind farm safely or efficiently. Since the construction of new power lines is expensive, and since some special interest groups do not approve of their construction, sites close to existing lines are preferable. Also, because the connection cost to a power grid is virtually identical from site to site, there is only one factor, distance, that determines the accessibility to the power grid. Therefore, the distances between transmission power lines and potential wind farm sites must be closely looked at and evaluated. The distance to power lines calculations are very similar to the ones performed in the previous section.

A map of power transmission lines of New England was downloaded from the Independent Operators of New England web site and converted into a BMP file. This file was imported into Idrisi, using the appropriate values of New gained from the roads and trails map. The map was digitized and converted into a raster file. Lastly, distances to power lines were calculated and values for those distances were assigned based on our weighting system.

The actual map that was used in this analysis was obtained from the Independent Systems Operator of New England (http://www.iso-ne.com/FERC_filings/documents/FERC_715/1999_NE_Transmission_ Map.pdf). The image that was obtained from them was edited to include only relevant power lines and was later converted into a BMP file and then imported into Idrisi.

Values were assigned to the power line map from the boundaries map, as was done with the roads map. Subsequently, both maps had the same basic format. In order to assign the GRANIT values to the borders of New Hampshire of the imported file, the RESAMPLE function was used.

A correspondence file that contained the old and new coordinates of five points along the border of New Hampshire was created using a simple text editor (one is available in Idrisi as the Edit function). Distinct features of the New Hampshire border from the imported file were used to obtain sample coordinates for the power line map. To get the equivalent coordinates for the new map the same features were located on the roads map. Note that values that went into this correspondence file were in meters and in Spc83nh1 reference plane. Next, the RESAMPLE command was used. The file that was imported into Idrisi from the desktop format was used for the "Input image", and the correspondence file that was created earlier was specified. "Linear" was selected for the "Mapping function" and the "Resampling type" was "Nearest neighbor". The "Background value" was left at zero and under "Output reference parameters" the same number of rows and columns was used as for the roads, 9547 rows and 4978 columns. For maximum and minimum X and Y coordinates new values that were used in the correspondence file were inputted. The "Reference system" was Spc83nh1, "Reference units" were in meters and the "Unit distance" was left at 1.0.

The raster file produced needed to be at a higher resolution for further calculations. By zooming into the area that needed to be digitized, better accuracy was obtained for using the Digitize icon. Under the Layer type, a Line was selected, under the Data type menu an Integer was selected and a random name was used for the "Name of layer to be created:" menu. After each line was digitized, including those close to the border but outside of New Hampshire, a total of 58 vector files were created. However, a map of power transmission lines of 69 kV, 115kV, 138kV, 230kV and 345kV capacity that was received from the Public Service of New Hampshire was also used to compare the accuracy of the ISO map and the actual existing power lines. In some areas power lines were added manually to better map the existing power lines, especially in the Southeast part of the state.

The vector files that resulted from digitizing the power line map were then used for distance calculations. This was done by first creating an image of the power transmission lines with correct parameters to be used later in distance calculations. The parameters for the image file can be obtained from the Layer Properties.

First, to create an image, the INITIAL option was selected from the Data Entry menu and then "Defining special parameters individually" was specified. All of the values for the output reference parameters were copied form the vector file's Layer Properties. The number of columns and rows selected produce a certain resolution. In this analysis, the same number of columns and rows used in the roads map was specified: 4978 columns and 9547 rows.

Next, the vector file of power transmission lines in New Hampshire was converted into a raster file using the LINERAS command. In the "Vector line file" section the vector file of power lines in New Hampshire that was digitized from the map earlier was used, and under the "Image file to be updated" the image file that was created in the previous step was used. This procedure was used to update the new raster file 58 times, once for each layer. The convenience of the LINERAS function is that it also concatenates all the files that the image is updated with into one raster file.

After Idrisi was done converting the vector file, the distances from power lines was finally calculated. Using the DISTANCE command, the raster file that was converted from the vector files was input as the "Feature image". The output image is the file that will show the distances to the power lines from all points in New Hampshire.

After distances were calculated, the next step was to assign values to the specific ranges of distances. Since there was a total of 1,000 points and power lines were worth 25%, a site's accessibility to the power grid was evaluated on a 250 point scale. A correlation was created so that 1 point was equivalent to 0.24 kilometers or 784 feet. A rating of 0 was assigned to sites with distances greater than 60 kilometers from the nearest power line and a rating of 250 was assigned to an area where a power transmission line presently exists within a 240 meter radius.

In order to assign the values to the file, the RECLASS function was used. For the "Type of file:," "Image" was used, and for the "Classification type:", "User-defined reclass" was used. Using the distances file, this function outputs what will finally be used in the OVERLAY function for the entire weighting system. The "Assign a new value of:" went from 250 down to 0 in increments of 5 and the distances went up from 0 to 60,000 meters in increments of 1,200. The last assignment of 0 points was given to the range of distances from 60,000 meters to 1,000,000 meters in order to make sure that past 60 kilometers the values would be 0 throughout the entire map. After the power transmission lines map was prepared for the calculations of the plausible sites the next step was to prepare terrain roughness map.

3.2.3 Calculating and Evaluating Surface Roughness

After the distances to roadways and trails as well as to the power transmission lines were calculated, the map for the surface roughness of New Hampshire was the next step. Since many interest groups do not approve of clearing national forests or destruction of landscape, surface roughness has a profound impact on where potential wind farm sites might be built. The most preferable landscape is an open field, which is relatively clear of obstruction. The most undesired roughness is thick forests and cities in New Hampshire, because it is not plausible to build wind farms in thickly populated areas. However, because clearing land is a one-time expense, roughness will only represent 5% of the project.

The digitized map of the surface roughness used in the WindMap analysis was perfect for the task. This map represents the entire Northeast, so it had to be trimmed, since only sites located within New Hampshire are being considered. The map was then converted to a latitude/longitude system and had values assigned to it.

In order to trim the borders to encompass only New Hampshire, and to put the map into Latlong coordinates, the PROJECT function was used. For the "Type of file to be projected" "Raster" raster was selected, and under "Input file name" Brower's raster file was selected using the "albersus" reference system as the "Input reference system". The output file was specified as a latlong file. "Resample type" was chosen to be "Nearest neighbor" and the "Background value" was left at 0. The same values for the number of rows and columns, and the boundaries used for the roads and power lines were adopted. This procedure produced a map of surface roughness only for New Hampshire and in Latlong coordinates.

The values that were used in Brower's map for the surface roughness ranged from 0 over water to, 1.20 over forested areas of the state. Since this value system conflicted with our own weighting system, we had to assign different values to surface roughness map, so that it could be overlaid with roads and power lines. Because surface roughness was contributing 5% of the entire project, it was assigned a total of 50 points. We created a correlation between the roughness values and the weighted roughness map, such that 1 point corresponded to 0.024 units in the original map. A rating of 0 was presented to the sites with surface roughness greater than 1.20 of the original map and a rating of 50 was represented to areas where roughness was evaluated to be around zero.

In order to assign the values to the file, RECLASS was again used. For the "Type of file:", "Image" was used, and for the "Classification type:", "Use-defined reclass" was used. The "Input file" was the projected surface roughness. For the "Reclass parameters" same system that was described in the paragraph above was ; "Assign a new value of:" went from 50 down to 0 in increments of 2 and the roughness went up from 0 to 1.20 in increments of 0.048. The last assignment of 0 points was given to surface roughness from 1.20 to 1.21 in order to make sure that roughness values of greater than 1.20 would be 0 throughout the entire map. After the surface roughness map was finished, the next step was to convert the final wind map into the Idrisi 32 format with its appropriate values assigned to the wind speeds.

3.2.4 Calculating and Evaluating Wind Speeds

Wind speeds are the most important factor in the determination of plausible wind farm sites. If wind speeds are not high enough for the wind turbine to produce electrical power, then all accessibility factors are irrelevant. Therefore, it is clear that wind speed is overriding factor in the final evaluation of all the candidate sites in New Hampshire.

WindMap's outputs were designed for the older, 16-bit version of Idrisi, so they had to be converted to the current 32-bit format. Then values were assigned to the wind speeds and the final image was put into Latlong coordinates.

The Idrisi Conversion Tools command was used to turn the WindMap output into the desired format. For "convert from:" we used "Idrisi for Windows (16-bit)", "Idrisi (32-bit)" was implemented for "To:" and the "File type" was selected to be raster. After Idrisi converted the map to a 32-bit format new values had to be assigned to the map so that the appropriate percentage of the weighting system could be represented by the wind. Since wind contributes 60% to the weighting system, its values are converted to a 600 point scale. In order to put wind speeds in terms of the weighting system, the Calculator function was used for mathematical operations. Since the minimum wind speed calculated by WindMap was 2.85 meters per second and the maximum was 13.59 meters per second, solving a system of linear equations:

$$0 = 2.85 * M + B;$$

$$600 = 13.59 * M + B;$$

Yields $M = 55.86592179$ and $B = -159.2178771$. Therefore, the recalculating expression was "[mapname] * 55.86592179 – 159.2178771". This step gave us wind speeds on a 600-pt scale, whereby every 1 point, 0.0179 meters per second of wind increase was represented.

This new file needed to be converted to a latlong coordinate system using the PROJECT command. Under the "Type of file to be projected" raster was used. The file created previously was input, and Latlong was selected as the output reference system. Once again, the resample type was "Nearest neighbor" and the "Background value" was zero. In the Output reference information the same number of rows and columns as for all the accessibility factors was used, namely 9547 rows and 4978 columns, and new minimum and maximum X and Y coordinates were inputted manually, identical to the accessibility factors as well.

After this projection was complete, all the component maps for the final suitability map had been created. The next and final step was to combine all the accessibility maps and wind speeds together to obtain a map of suitable wind farm sites in New Hampshire.

3.2.5 Combining Accessibility Maps and Wind Maps

After obtaining all the accessibility and wind maps, the last step was to combine all four of them together. However, some of the maps did not have agreeing coordinates. The roads and power transmission line maps were converted into appropriate coordinates and overlaid, then were overlaid themselves with the surface roughness image. This procedure resulted in an accessibility map. Lastly the wind speed map was added to the accessibility map to produce the final map.

The power transmission lines and roads and trails maps were combined using the OVERLAY function. For the first and second images we selected roads and power lines respectively. Afterwards the addition function was used to get the accessibility factor due to only roads and power lines. Because the coordinates from GRANIT were not correct, or in an unrecognizable reference system, the roads and power line maps were converted to Latlong coordinates using the RESAMPLE function after they were overlaid. Using a correspondence file, five locations were utilized, in which old and new coordinates were specified based on the real coordinates that were consistent with both surface roughness and WindMap. For "Type of file to be resampled", the raster format was used, the "Mapping function" was selected to be Linear, the "Resampling type" was Nearest Neighbor and the "Background value" was left at zero. The number of rows and columns stayed the same, while minimum and maximum X and Y values had to be obtained according to the real, new coordinates in the output reference parameters. The reference system was selected to be Latlong, reference units were chosen to be in degrees, and the unit distance was left at 1.0. This procedure created a map that showed combined roads and power lines accessibility, which in turn was ready to be overlaid with the rest of the images.

The next image that was overlaid with power lines and roads was surface roughness. This map gave a complete picture of accessibility factors contributing to the weighting system. Again the OVERLAY function was used, combining the new roads and power lines map with the surface roughness map as the first and second image respectively. This addition of the three accessibility factors created the final accessibility map. It was a simple matter of using the OVERLAY function once more to add the weighted wind speed map to create the final suitability map.

The weighting system describes all the factors that can be explored quantitatively. However, there are further environmental and social factors to be explored. These factors do not have any specific values that can be interpreted by software and therefore have to be discussed outside of the weighting system.

3.4 Discussion of Environmental and Economic Restrictions

While many siting factors involved in the building of a wind farm lend themselves easily to weighting systems, some factors cannot be taken into account in this fashion. The disruption of wildlife, public opinion of wind farms, and many other factors can be estimated on a site by site basis. They are often too complex to be understood by a scaled map, and do not have a direct economic impact on a site. These factors are important to a number of special interest groups and organizations, however, and can be better analyzed through an interview or statement made by these organizations. The two main groups that have information on these issues are environmental interest groups and wind developers.

If and when a site is built, there will be some disruption to the environment. Trees will be cleared and some animals will be displaced. No matter how much siting is done before a wind project is started, loss of natural habitat as well as aesthetic beauty is unavoidable. Somehow it must be determined whether a proposed site will cause too much environmental disturbance. This project aims to do this through interviews with environmental interest groups to determine what constitutes a disruption and what constitutes an unacceptable disruption of aesthetics, habitat, and plant and animal life.

Although environmental restrictions severely limit the areas which wind farms may be built upon, a site will not be constructed unless the conditions there are favorable and the site will be profitable. The weighting system used to assess wind speeds and accessibility shows in a relative sense which sites in New Hampshire are most conducive to wind power. In order to test the validity of the system, interviews were conducted with wind energy developers. Questions were also asked concerning the general atmosphere for wind energy in New Hampshire as opposed to other New England states. These interviews provide a more complete picture of the barriers to wind energy in New Hampshire than the weighted map alone. Siting factors as well as economic and environmental restrictions must be considered in order to completely assess the plausibility of wind farm development in an area.

4. Results and Analysis

The model proposed in the previous chapter was applied to New Hampshire to detail which areas were most conducive to wind farms. The results obtained by this model showed that the areas in the White Mountains and Sunapee region were found to be the most suitable for wind development. This result is to be expected somewhat, as these locations experienced the highest observed wind speeds, especially in the case of Mt. Washington. These areas present barriers to development, however, due to being within national forests and protected land.

These results come from combination of factors, as discussed in Chapter 3. The weighting system detailed in sections 3.1 and 3.2 produced a series of maps that show how each factor we analyze affects the suitability index of a potential site. The results of our analysis of wind speeds in New Hampshire are discussed in section 4.1, while the results of our accessibility analysis are discussed in section 4.2. A discussion of environmental issues also took place with wind developers and special interest groups. That discussion suggested that the weighting system used was both applicable and reasonable, and that environmental concerns would ultimately make or break a proposal in the areas which were favored by the weighting system. Section 4.3 discusses the validity of the weighted maps as well as other restricting factors that are not included in the weighting system.

4.1 Creating Wind Speed Maps

We can estimate wind speeds over New Hampshire based on the data we have collected using WindMap, but there are many parameters that must be constantly adjusted to produce an accurate map. Multiple runs were executed in order to determine the optimal parameters for our final map. We varied surface roughness, the stability ratio, the vertical profile of the atmosphere, and initialization parameters in order to produce the best possible final map of wind speeds. Each parameter was varied over two different areas of New Hampshire. One area was centered on Mt. Washington, and the other included the area around Mt. Sunapee. These areas were chosen because there was a good concentration of observation stations in these two areas. Additionally, these areas consisted of both mountainous and flat terrain, which made it more representative of New Hampshire as a whole. Figures 4.1 shows the elevation map for the Sunapee region, which will be used as an example in the following sections.

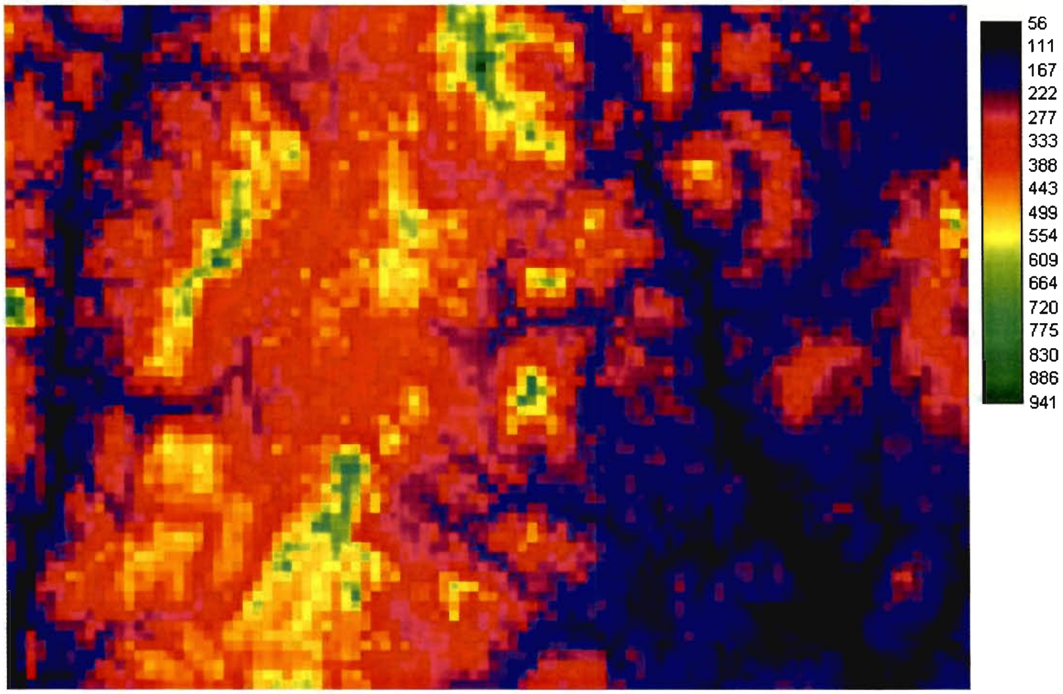


Figure 4.1: Digital Elevation Map of the Sunapee region (elevations in meters)

4.1.1 Surface Roughness and WindMap

From the beginning of the project it has been assumed that the roughness maps we attained from Michael Brower would provide the best picture of wind speeds over the entire state. However, it is possible to have WindMap assume a constant roughness over an area, and for the sake of testing our assumption out, runs were conducted that did not utilize the roughness map, and instead assumed a value of 0.4 over the entire state. This is a fairly good estimate of roughness for forested terrain, and urban centers as well, which covers a fair portion of New Hampshire. Below in Figure 4.2 the wind speeds over a constant roughness map and our roughness map can be compared. The map shows the difference between wind speeds calculated over the Sunapee region for a constant roughness and the roughness map. The maps are mostly in agreement, but the constant roughness underestimates speeds on mountaintops, and overestimates speeds in valleys (WindMap Helpfile). Comparison with the DEM in Figure 4.1 shows that the areas where the deviation is high occur in areas of extreme elevations. Therefore, our assumption that a roughness map would bear better results seems accurate.

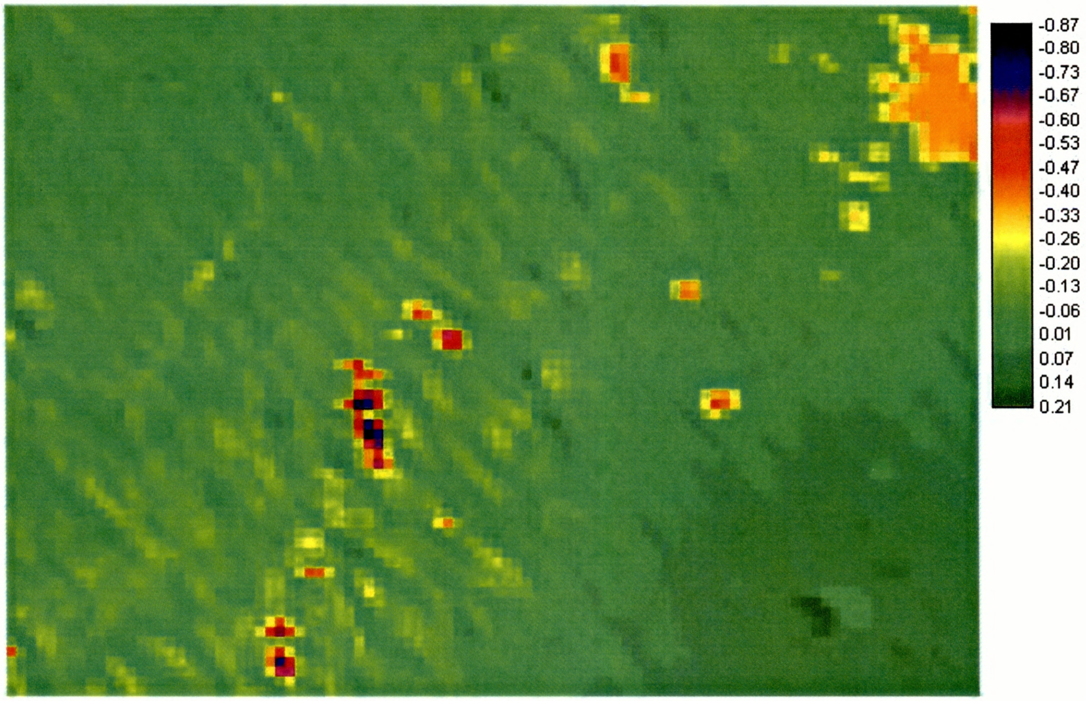


Figure 4.2: Differences in wind speeds for the Sunapee region for a constant roughness and roughness map, in m/s.

4.1.2 Vertical Profile

The vertical profile of the atmosphere essentially describes the wind shear over the terrain. Wind shear describes the relationship between wind speeds and altitude. There are four settings for the vertical profile within WindMap: Unstable, Neutral, Slightly Stable, and Stable. As the vertical profile moves towards more stable conditions, the wind shear increases. Subsequently, wind speeds will increase more as altitude increases. This effect is especially noticeable over areas of low roughness (where wind speeds tend to increase already), and over peaks to a lesser extent.

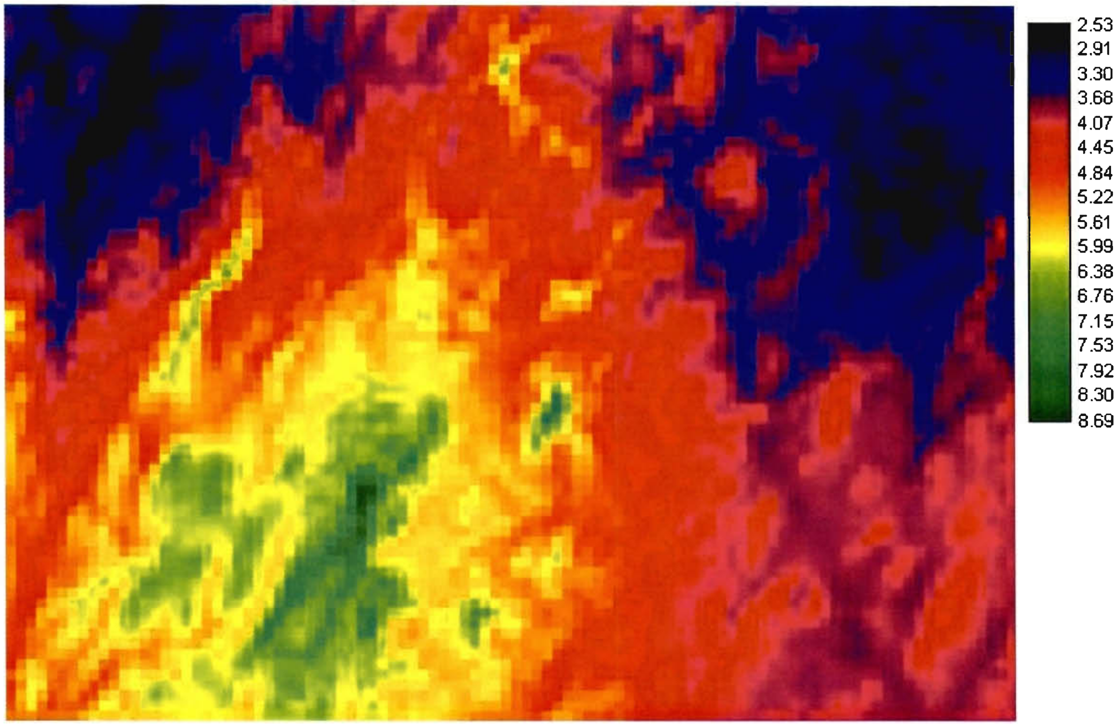


Figure 4.3: Wind Speeds over the Sunapee region for a neutral atmosphere in m/s.

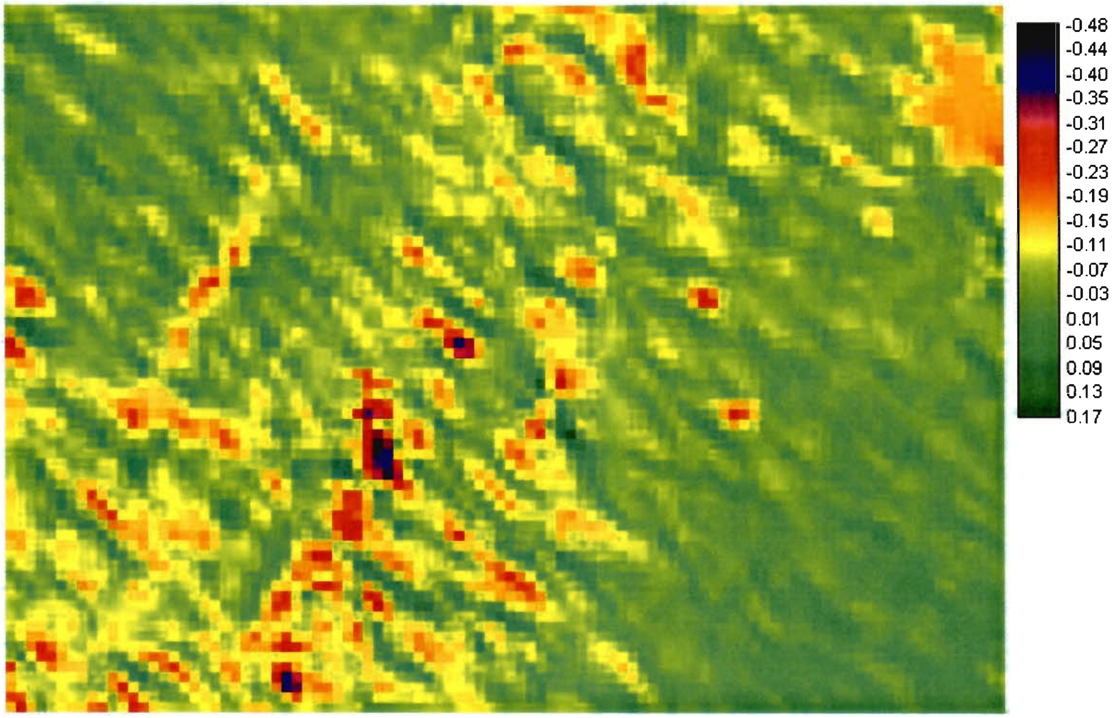


Figure 4.4: Difference in wind speeds between neutral and unstable atmospheres over Sunapee region in m/s.

Successive runs over both test areas of all four stability parameters showed that an unstable or neutral profile seemed to fit our expectations best. While predicted wind speeds were generally higher over the NCDC sites and lower over the mountaintop stations than the measured speeds for all the profiles, the mountaintop sites were never too far off from the measured values, while other surface stations tended to increase to unacceptable levels. When the final runs were completed using both profiles, it was determined that the neutral atmosphere model produced more accurate wind speeds. The details behind these conclusions will be discussed next.

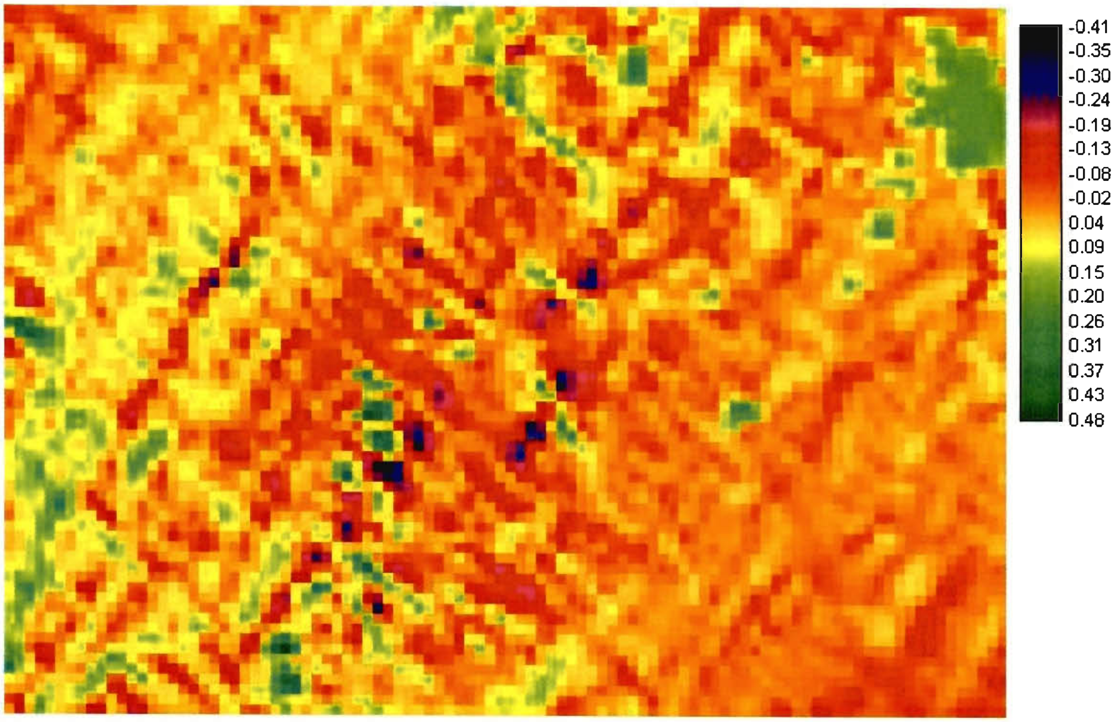


Figure 4.5: Difference in wind speeds between neutral and slightly stable atmospheres over Sunapee region in m/s.

For each atmospheric model the results were very close to one another, which made choosing a vertical profile much easier. For an unstable atmosphere, most of the region is within a very small difference from the neutral prediction (in Figure 4.4, these areas of small differences appear green). The same condition exists for slightly stable and stable atmospheres, only the color red applies to zero values in Figures 4.5 and 4.6. The maximum difference in any of these maps is 0.49 meters per second, a difference of at most 10% from the values obtained for a neutral atmosphere. It is safe to say that running WindMap for a neutral atmosphere will not result in values too far off from what any other atmosphere model would predict.

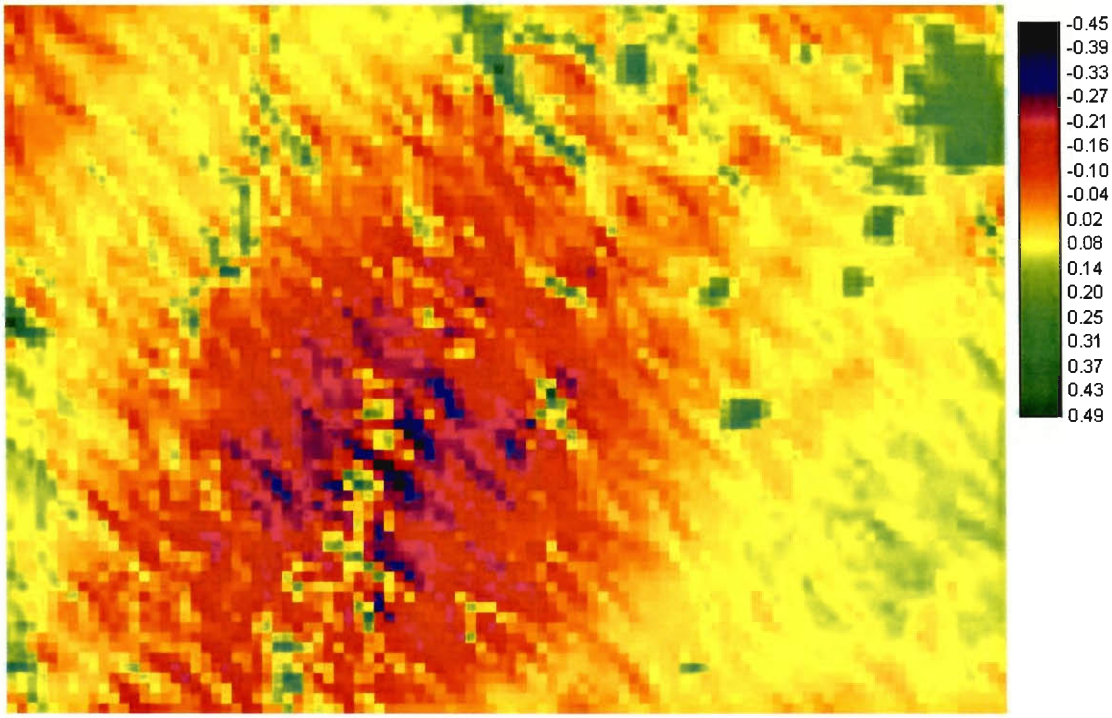


Figure 4.6: Difference in wind speeds between neutral and stable atmospheres over Sunapee region in m/s.

4.1.3 Choosing a Stability Ratio

The stability ratio, as explained earlier, describes how easily air moves in the horizontal direction compared to the vertical direction. In a neutral atmosphere, air can move horizontally as easily as it can move vertically, and the stability ratio is 1. Lower stability ratios correspond to atmospheres in which air moves horizontally easier.

Therefore, as air moves over increased elevations, it becomes compressed and wind speeds increase. As elevation decreases, the air expands, and velocities decrease. This is why wind speeds tend to be higher in mountainous regions, and lower in valleys. Misrepresenting the stability ratio in the WindMap model can result in predictions that are far from reality in these regions.

There are several ways to obtain the stability ratio for running WindMap. The stability ratio can be entered manually by the user, but that was not an option because any values entered would be guesses. It is also possible to have the stability ratio linked to the vertical profile. In the case of a neutral atmosphere, the stability ratio is equal to 1. Finally, under the Initialization menu, it is possible to have WindMap optimize the stability ratio automatically as it runs. This option causes WindMap to take longer with its calculations. In Table 4.1, the percent errors for calculated wind speeds can be seen for all atmospheric options. This table displays the results for four separate combinations of parameters. The two parameters altered were the "Match surface stations" parameter and the "Optimize Stability Ratio" parameter in the Initialization menu. The last two entries in the table compare the results gained when the stability ratio is optimized and when it is linked to the vertical profile, while the surface data is not matched. There proves to be very little difference in results between the two options at all sites, except for Whitefield and Berlin, which already display large errors. Due to the large area covered by this analysis, we will link the stability ratio to the atmospheric conditions in order to save time. Linking the stability ratio to a neutral atmosphere results in a stability ratio equal to 1.

Table 4.1: Comparison of wind speeds at observation stations for various parameters

Station	Match surface?	Optimize Stability?	Measured	Unstable		Neutral		Slightly Stable		Stable	
Sunape	X		8.921	8.626	-3.306804	8.695	-2.533348	8.829	-1.031275	9.003	0.919179
Concord	X		3.929	3.967	0.967167	3.992	1.603461	4.039	2.799695	4.083	3.919572
Lebanon	X		2.822	2.969	5.209072	2.981	5.634302	3.003	6.413891	3.041	7.760454
Laconia	X		2.801	2.901	3.570154	2.921	4.284184	2.958	5.605141	2.99	6.74759
Berlin Mt.	X		4.75	4.308	-9.305263	4.324	-8.968421	4.354	-8.336842	4.398	-7.410526
Walker	X		4.644	4.633	-0.236865	4.659	0.322997	4.706	1.335056	4.777	2.86391
Whitefield	X		2.364	3.301	39.63621	3.323	40.56684	3.363	42.25888	3.416	44.50085
Berlin	X		2.27	3.151	38.81057	3.168	39.55947	3.2	40.96916	3.247	43.03965
Fryeburg	X		4.025	4.197	4.273292	4.241	5.36646	4.318	7.279503	4.419	9.78882
Mt. Washington	X		13.228	11.399	-13.82673	11.46	-13.36559	11.587	-12.4055	11.736	-11.2791
Sunape	X	X	8.921	8.626	-3.306804	8.695	-2.533348	8.829	-1.031275	9.003	0.919179
Concord	X	X	3.929	3.967	0.967167	3.992	1.603461	4.039	2.799695	4.083	3.919572
Lebanon	X	X	2.822	2.969	5.209072	2.981	5.634302	3.003	6.413891	3.041	7.760454
Laconia	X	X	2.801	2.9	3.534452	2.921	4.284184	2.958	5.605141	2.99	6.74759
Berlin Mt.	X	X	4.75	4.308	-9.305263	4.325	-8.947368	4.354	-8.336842	4.398	-7.410526
Walker	X	X	4.644	4.633	-0.236865	4.659	0.322997	4.706	1.335056	4.776	2.842377
Whitefield	X	X	2.364	3.301	39.63621	3.323	40.56684	3.363	42.25888	3.416	44.50085
Berlin	X	X	2.27	3.151	38.81057	3.168	39.55947	3.2	40.96916	3.246	42.99559
Fryeburg	X	X	4.025	4.197	4.273292	4.241	5.36646	4.318	7.279503	4.419	9.78882
Mt. Washington	X	X	13.228	11.398	-13.83429	11.549	-12.69277	11.587	-12.4055	11.737	-11.27155
Sunape		X	8.921	9.673	8.429548	9.732	9.090909	9.845	10.35758	10.01	12.20715
Concord		X	3.929	3.882	-1.196233	3.919	-0.254518	3.994	1.654365	4.05	3.079664
Lebanon		X	2.822	3.074	8.929837	3.11	10.20553	3.196	13.25301	3.282	16.3005
Laconia		X	2.801	3.115	11.21028	3.158	12.74545	3.253	16.13709	3.328	18.81471
Berlin Mt.		X	4.75	4.727	-0.484211	4.826	1.6	5.008	5.431579	*	
Walker		X	4.644	4.958	6.761413	5.062	9.000861	5.296	14.03962	*	
Whitefield		X	2.364	3.445	45.72758	3.501	48.09645	3.629	53.511	*	
Berlin		X	2.27	3.084	35.85903	3.105	36.78414	3.182	40.17621	*	
Fryeburg		X	4.025	4.177	3.776398	4.23	5.093168	4.33	7.57764	*	
Mt. Washington		X	13.228	9.778	-26.08104	9.799	-25.92229	10.084	-23.76777	*	
Sunape			8.921	10.012	12.22957	10.099	13.2048	11.279	26.43201	12.922	44.84923
Concord			3.929	3.87	-1.501654	3.905	-0.610842	3.913	-0.407228	3.826	-2.621532
Lebanon			2.822	3.087	9.390503	3.125	10.73707	3.222	14.17434	3.245	14.98937
Laconia			2.801	3.103	10.78186	3.145	12.28133	3.212	14.67333	3.252	16.10139
Berlin Mt.			4.75	4.637	-2.378947	4.681	-1.452632	5.06	6.526316	5.385	13.36842
Walker			4.644	4.841	4.242033	4.9	5.512489	5.18	11.54177	5.397	16.21447
Whitefield			2.364	3.771	59.51777	3.849	62.81726	3.94	66.66667	3.905	65.18613
Berlin			2.27	3.245	42.95154	3.29	44.93392	3.287	44.80176	3.123	37.57709
Fryeburg			4.025	4.236	5.242236	4.292	6.63354	4.401	9.341615	4.513	12.12422
Mt. Washington			13.228	11.845	-10.4551	11.878	-10.20562	11.614	-12.20139	10.528	-20.41125

4.1.4 Initialization of the Data

Before producing the final maps, the wind field must be initialized from the surface stations. Because we will be utilizing the "Match Surface Data" option, it is important to make sure that not all the sites are used to initialize the data. By choosing the proper sites, the proper wind field can be calculated, while allowing for error checking at sites that were not used for initialization.

It can be difficult to tell whether a site should be included in initialization or not. After first conducting trial runs with all the New Hampshire sites used for initialization, it was discovered that there were three areas near Mt. Washington that appeared "dead". Compared to the regions immediately surrounding them, the predicted winds seemed relatively low. This can be due to terrain features, but these three spots were all located around surface stations. It seemed very possible that these stations did not accurately reflect the conditions in the general regions they were located, and so in subsequent runs they were not used for initialization. This resulted in predicted wind speeds that were obviously much higher than reality, so the "dead" sites were included in the final analysis.

Another important part of initializing the data involved weighing the wind speeds at each station. Left alone, when calculating the wind speed at a specific point, WindMap will take into consideration the observed winds from a station all the way across the state. By using $1/r^2$ weighting (in the Initialization menu), stations closer to a point will count more towards the predicted wind speeds. Furthermore, a distance of 6500 meters was used for this weighting system. This causes points that have more than one station within 6500 meters to reflect an average of the two (or more) stations. The effects of this weighting system can be seen in the maps. After the weighting system is applied, circles can be clearly seen around some points. If a larger minimum distance is used, these circles begin to disappear because more stations are being factored into WindMap's calculations. Comparing Figures 4.3 and 4.7, it can be seen that without a weighting system, the map that results resembles the DEM in many ways. Because the elevation map should not be the only factor determining wind speeds, this kind of result is not encouraging. Weighing the data results in a smoother distribution of the wind speeds.

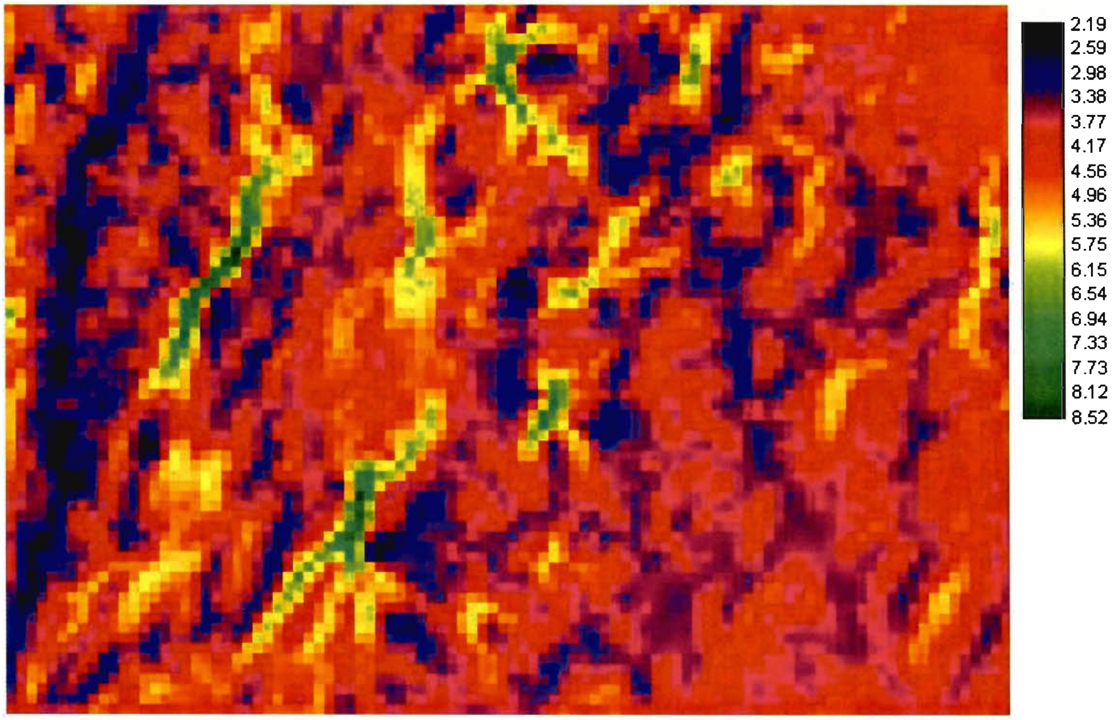


Fig. 4.7: Predicted wind speeds over the Sunapee region without weighting, in m/s.

4.1.5 Optimized Maps

After all of the initialization factors were fixed, WindMap was run over the entire state of New Hampshire rather than the small regions used to test the model. The final model was run for a neutral atmosphere, and a corresponding stability ratio of 1. All New Hampshire observation stations were used to initialize the map. There are areas of high wind speeds interspersed throughout New Hampshire, but high wind speeds are primarily focused in the Mt. Washington and Sunapee regions, as can be seen in Figure 4.8, the final map. Mt. Washington is the area located in the upper right, while Sunapee is the region to the lower left.

Calculated wind speeds in New Hampshire were fairly accurate. In Table 4.2, results from the WindMap log file can be seen, and shows the predicted and observed speeds at each station, along with the root mean square (RMS) error. Because no sites other than those in New Hampshire were used to initialize the data, some of the stations in Vermont show poor predictions, such as Rutland State, Lebanon, Springfield, and Sanford all have percent differences of more than 50%. The predicted speeds in New Hampshire, however, which include station numbers 1-9 and 17-20, are mostly within 10% of the measured values. The RMS values are somewhat high, but this is accounted for by the variation in speeds over the Vermont sites.

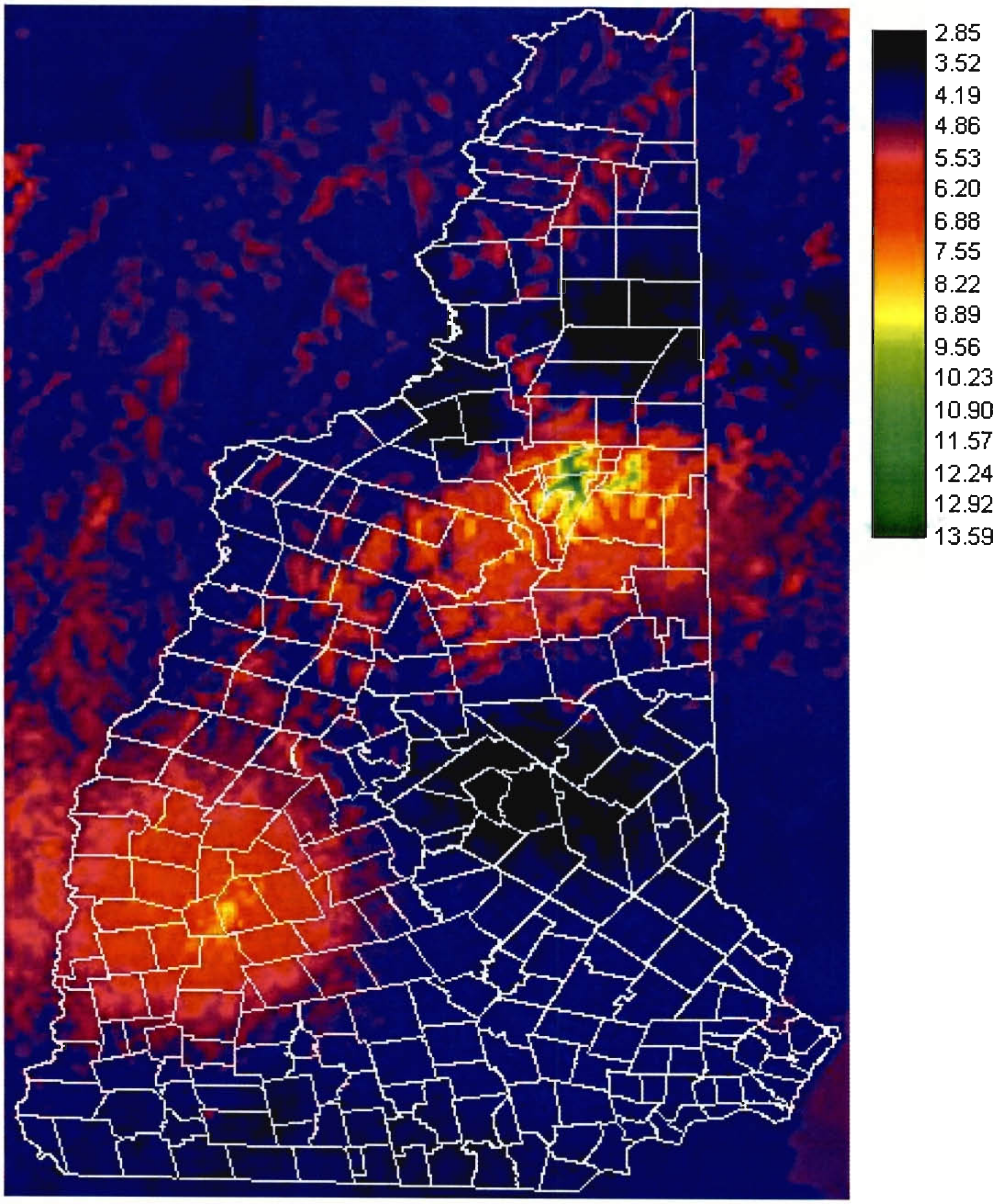


Figure 4.8: Final Wind Speeds in m/s

These wind speeds were calculated at 40 meters, which is the height at which all the wind speeds at the surface stations were measured, thus allowing us to make comparisons between predicted and observed wind speeds easily. Wind turbines typically operate at a height of around 70 meters, however, so wind speeds will be higher there. This map gives a very good idea of the relative speeds involved, however, and is easily incorporated into our weighting system by calculating the minimum wind speed required at 40 meters to run a wind turbine at 70 meters. This will be discussed further in section 4.2, but it involves the same process that was used to estimate the wind speeds of the NCDC sites at 40 meters in section 3.

Table 4.2: WindMap Log File with percent differences added

Station Number	Station Name	Measured Speed	Predicted Speed	Percent Difference
1	Berlin Mt.	4.75	4.195	-11.7
2	Colebrook	4.945	4.953	0.2
3	Sunape	8.921	8.776	-1.6
4	Walker	4.644	4.639	-0.1
5	Manchester	4.453	4.338	-2.6
6	Concord	3.929	3.989	1.5
7	Whitefield	2.364	3.248	37.4
8	Jaffrey	3.488	3.622	3.8
9	Berlin	2.27	3.092	36.2
10	Lebanon	2.822	5.104	80.9
11	Springfield	2.104	5.113	143.0
12	Morrisville	2.993	4.13	38.0
13	Burne/Montpelier	3.705	4.594	24.0
14	Fryeburg	4.025	4.715	17.1
15	Rutland	1.848	4.902	165.3
16	Sanford	2.631	4.03	53.2
17	Laconia	2.801	2.994	6.9
18	Mt. Wasington	13.228	11.334	-14.3
19	Pease AFB	4.374	4.446	1.6
20	Nashua/Boire Field	3.623	3.752	3.6

RMS Error (m/sec) 1.76E+00
Mean Bias (m/sec) 1.31E+00

4.2 Weighting System Results

After a wind speed map was calculated and all accessibility factors were ready to be analyzed, the next step was to take a look at each individual accessibility weighting factor. In this section we explain how accessibility to roads, surface roughness, accessibility to power lines, and wind speeds affect wind farm development in New Hampshire. We first discuss each factor individually and then combine them into one GIS map that displays regions with the most plausible sites for wind farm siting in New Hampshire.

4.2.1 Roads and Trails Accessibility Analysis

In the state of New Hampshire there are very few areas where the distance to the nearest road or trail is of a great value from the cost perspective. Even though there are a few spots in the state that have low road densities, they are seldom and generally unsuitable due to the presence of large lakes. Therefore, many regions of New Hampshire are well suited for wind farm development without construction of additional roads. Roads and trails contribute 10% to the weighting system and the maximum distance to the nearest road inside New Hampshire is about 10.19 kilometers. In Figure 4.9 it can be seen that for each point on the map a corresponding distance of 100 meters is added.

As can be observed from the road accessibility map, most distances greater than 2 kilometers from the nearest road are mostly lakes of the size of Lake Winnipesaukee or areas in the extreme Northern or central part of New Hampshire. Even in the middle of Lake Winnipesaukee, the point value is zero only for a small portion of the water, corresponding to the greatest distance to the nearest road inside the entire state to be about 10 kilometers.

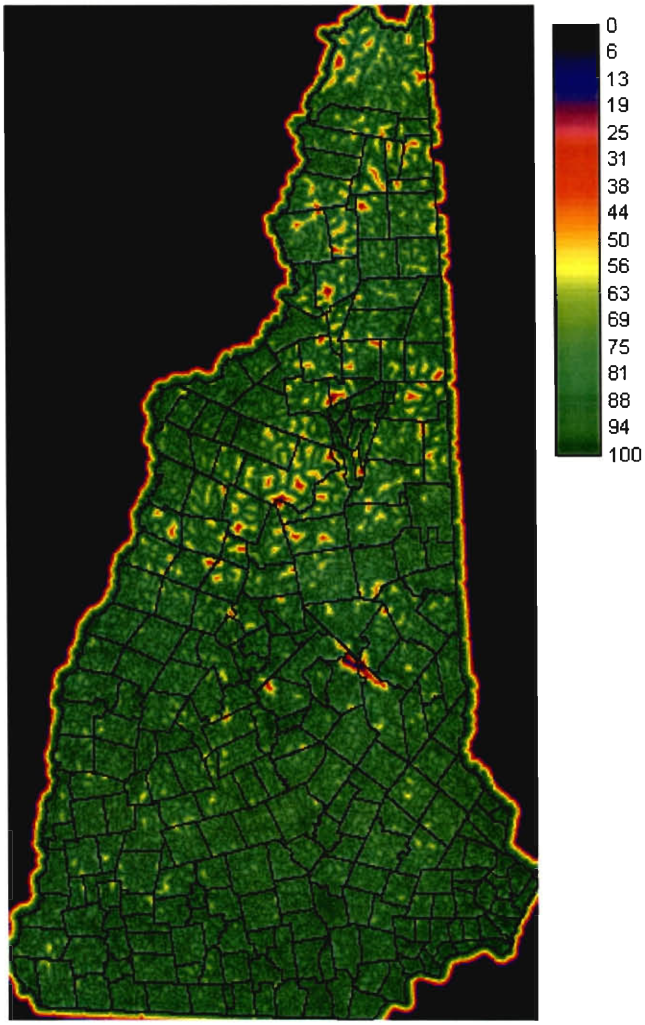


Figure 4.9: Weighted Map of Roads and Trails

There are a few spots in the central part of the state near the mountainous regions where roads can be a significant factor in terms of accessibility. In these areas the average distance to roads is between 4 and 7 kilometers. These areas might be of special interest due to the fact that wind speeds over the tops of mountainous terrain are greater than over relatively flat landscapes; at the same time roads close to the mountaintops are seldom, as can be seen from the image. However, the largest regions with low road densities are represented by the biggest lakes in the state and therefore can be dismissed as having a negligible impact on wind farm development.

In general, the best areas to build wind farms solely based on the road accessibility factor are located in the Southern part of the state. New Hampshire also has a few scattered areas in the Northwest region where road densities are greater than average and the potential for developing wind farms exists there as well. The central part of the state is not well suited for wind farm development from a road accessibility perspective, however, since there are relatively few roads running through that region.

4.2.2 Power Transmission Lines Accessibility Analysis

The next issue that was addressed was the accessibility map due to power transmission lines. Power lines need to be close to potential wind farm sites in order for the development and construction of a new wind farm to be within a reasonable price. The greatest number of power transmission lines is present in the southeast part of New Hampshire, while northern and mid-eastern areas of the state are not adequately supplied with power lines, making these places poor candidates for wind farm development from the power accessibility perspective. Power lines contributed 25% to the entire weighting system, which makes 1 point on the map equivalent to 240 meters.

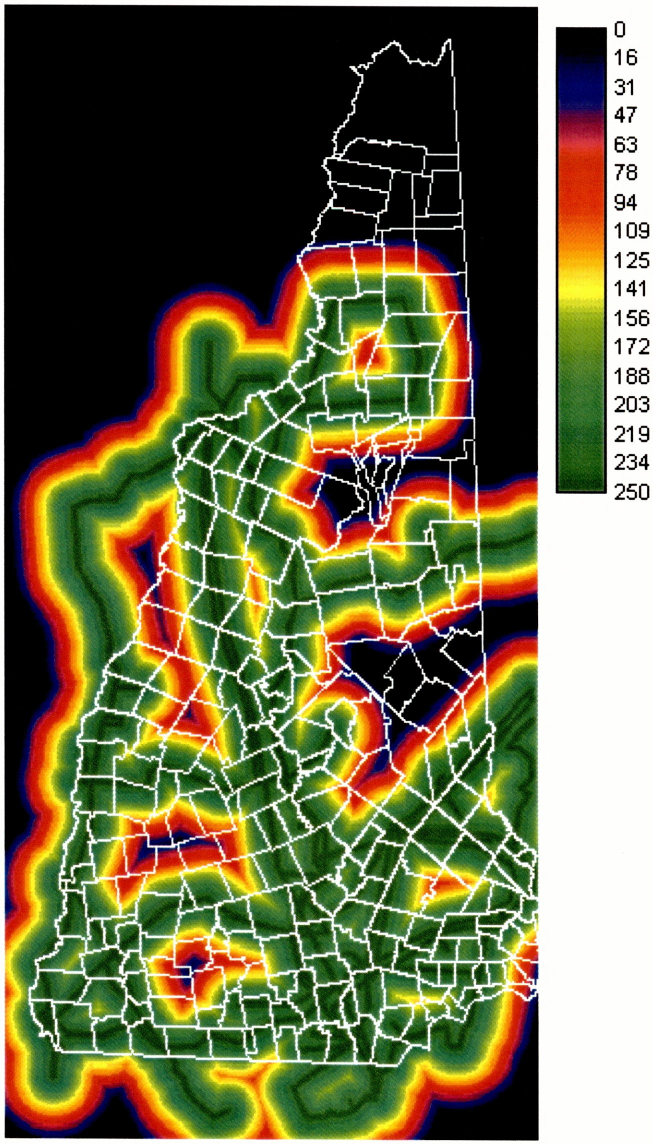


Figure 4.10: Weighted Map of Power Transmission Lines

There are three major regions of the state which have poor accessibility to power transmission lines. These areas are located along the Eastern border of New Hampshire, starting from the central and stretching to northern parts of the state. In the southern-most gap there are about 5-6 counties that do not have power lines anywhere within a 60 kilometers radius. In the middle there are about 2-3 counties without power lines and 10

Northern-most counties also do not have any 69 kV or higher power transmission lines within the same 60-kilometer radius.

The best regions from a power transmission lines perspective are located in the western part of the state and in the southeast quadrant of New Hampshire. However, most of the land around major cities in the south is already developed and therefore does not show any great prospect for wind farm development. On the other hand, mid-western regions possess a lot of undeveloped land and make up the largest area of the state with already existing power lines. In these areas there are usually power lines present within at least a 25 kilometer radius, which makes them excellent candidates.

Therefore, the best regions for potential wind farm sites from the power transmission lines accessibility angle in New Hampshire are located in the mid-western part of the state as well as in the south. The next GIS map that was produced for the accessibility analysis was surface roughness.

4.2.3 Surface Roughness Accessibility Analysis

The last accessibility factor in the weighting system was surface roughness. It consists of a roughness map, which was received from Michael Brower. This map shows the surface roughness ranging from water to grassy and low vegetation fields to buildings in the cities to high-density forests, and can be seen in Figure 4.11.

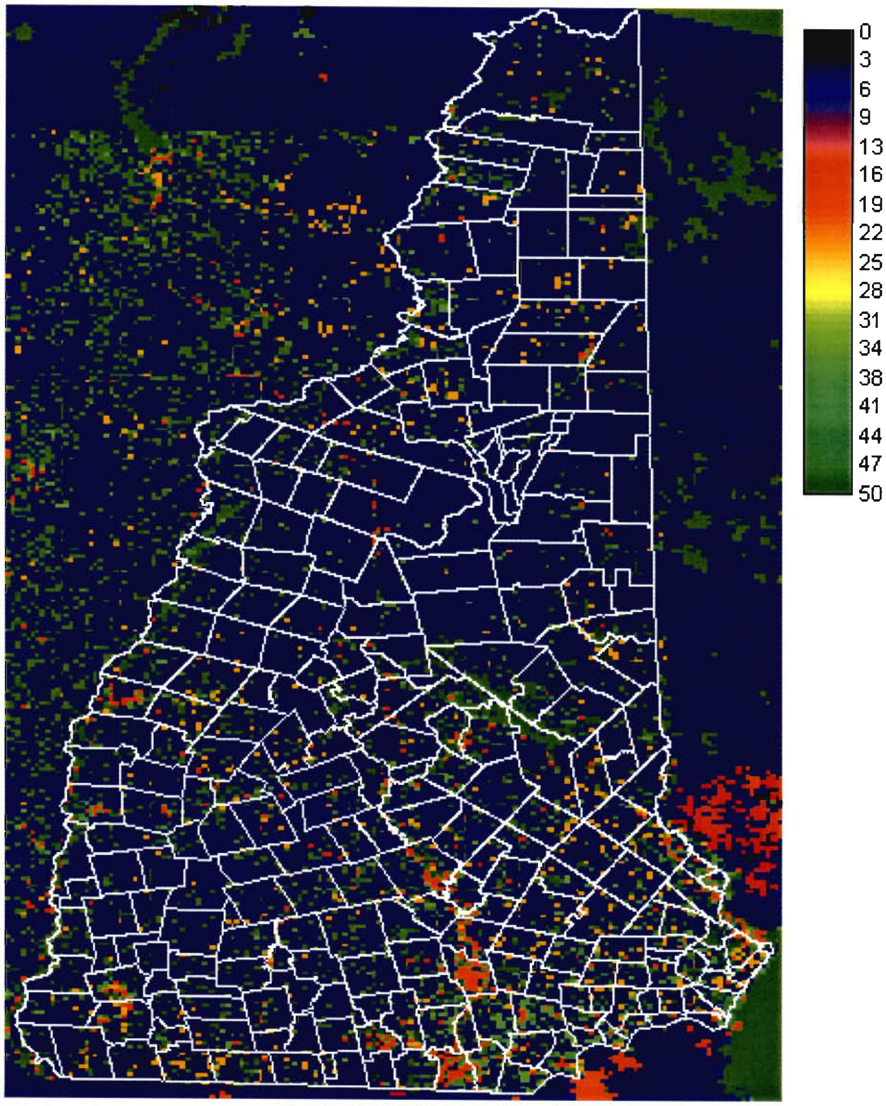


Figure 4.11: Weighted Map of Surface Roughness

In this map it is easier to evaluate and analyze surface roughness on the 0-50 point scale. A 0 value represents the roughest terrain while 50 points shows areas close to the roughness of water.

It is easy to see that most of New Hampshire is covered with thick forests. The only places where there are clear fields are in the suburban areas of large cities. Even small towns represent some land that has already been cleared. However, this land is probably already being used for purposes for which it was earlier cleared. So, even though it seems that most plausible sites could be considered in the southeast region of the state, in reality the best places for wind farm development would be found in northern and south-central New Hampshire.

These northern sections of the state have relatively colder climate with lower vegetation, random bare mountaintops and rare, but naturally clear fields. For example the best areas would be somewhere around Mt. Washington or near the city of Lebanon. There are also some Southern parts of New Hampshire, between Keene and Nashua, as well as regions Northwest of Concord where there is a lot of cleared land that could present good candidate regions for wind farm development.

From the perspective of surface roughness and its impact on accessibility to potential sites the best suited regions for wind farm development are located throughout central and northern New Hampshire. Although most of the southeastern part of the state might seem promising for possible sites, much of its cleared land is already in use for other purposes. Now that each accessibility parameter's results have been discussed individually, a combined map of all three factors must be analyzed.

4.2.4 Combined Accessibility Results and Analysis

After analyzing all accessibility factors individually the next logical step is to overview roads, power transmission lines and surface roughness as one map. The total number of points in the final accessibility map is the combination of all three previous images and therefore is equal to 400. According to final accessibility map, the most plausible sites for wind farm development are located in the southern part of New Hampshire as well as in mid-western part of the state.

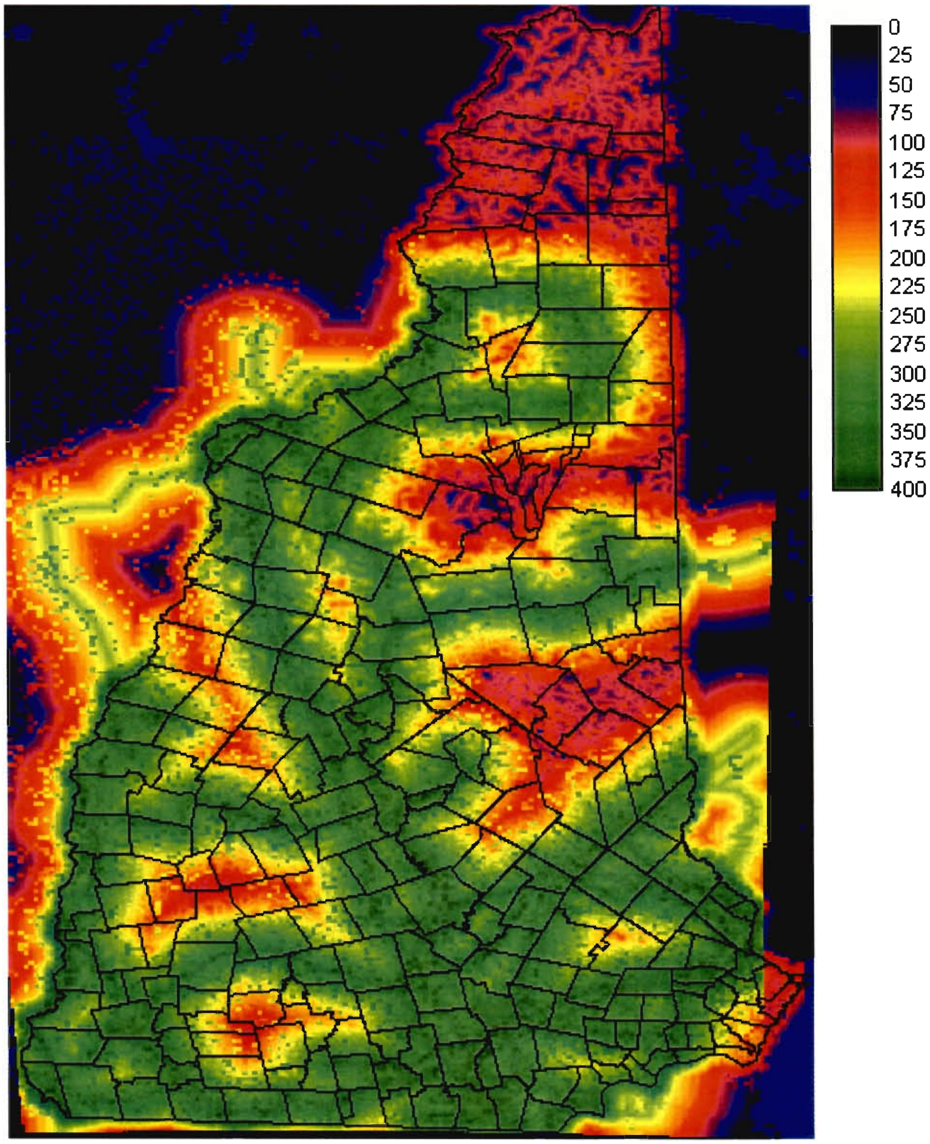


Figure 4.12: Final Accessibility Map

It can be observed that the best regions of New Hampshire to develop wind farms based solely on accessibility factors are located in the southern part of the state where accessibility values reach into high 300s. The mid-western part of New Hampshire also seems promising because there are a lot of power lines, dense road systems, and plenty of cleared land. This is also a region that has a lot of undeveloped land around the cleared terrain, so there is no pressing need for space.

The southeastern part of the state also has a lot of potential for wind farm development based on accessibility. Major city development in that region makes it difficult to propose any new large projects like wind farms even though accessibility values in that area approach 400. On the other hand southwestern areas have smooth terrain and a lot of power lines to transmit produced energy.

Other areas that have a lot of potential for wind farm development are regions around Mt. Washington, especially on the western side of the ridge. Those areas again have direct and close power lines and contain low surface roughness terrain. They are also located in the remote areas, so zoning may not be a big issue.

According to the accessibility map, the most suitable regions for wind farm development in New Hampshire are in the western part of the state as well as around Mt. Washington. The southeastern part of the state also has very high values for accessibility, but population density and major city development in that region must also be taken into account.

4.2.5 Combined Weighting System Results and Analysis

After accessibility has been discussed in detail, the last image that was produced was a combined map of all the weighting factors. The best sites for wind farm development inside the state are located near Mt. Sunapee and Mt. Washington. This map has a 0-1,000-point scale, where 60% is based on wind map, 25% on power lines accessibility, 10% roads and last 5% is surface roughness and is shown in Figure 4.13.

Because wind turbines need a certain range of wind speeds from which they are able to produce useful energy, another map needs to be looked at closely. This image shows the candidate areas in New Hampshire where wind speeds are greater than 5.50 meters per second and is displayed in Figure 4.14.

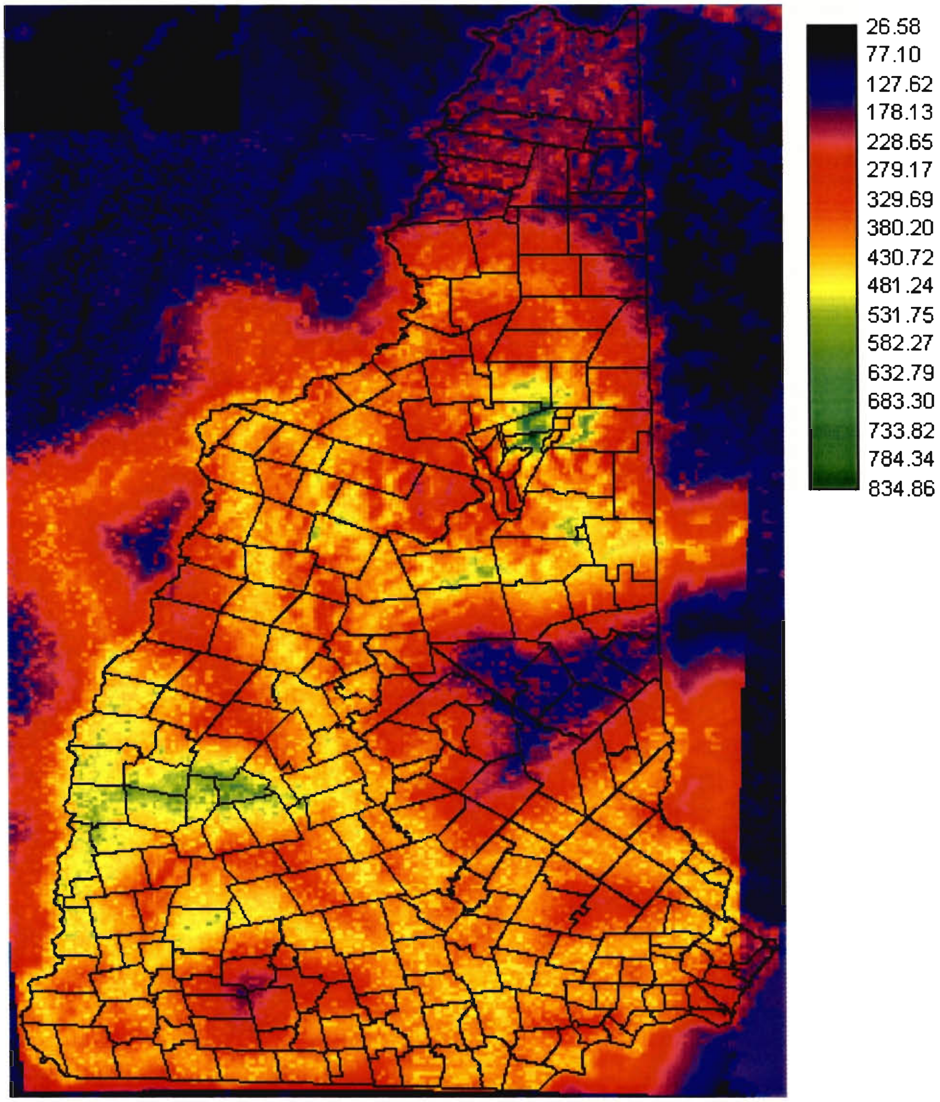


Figure 4.13: Combined Map Using the Full Range of Wind Speeds

The map with all wind speeds taken into account only shows values between 26.58 and 834.86. The minimum value of 26.58 should be disregarded, because areas outside of the state are represented by that value. The maximum number of 1,000 is nonexistent due to the fact that there are no sites in New Hampshire that have low surface roughness, power lines within 240 meters, roads within 100 meters, and have the highest predicted wind speed for the state of New Hampshire. The only region that comes close to that value is the top of Mt. Washington, where the greatest wind speeds are produced. This means that wind speeds are the overriding factor in site locations. The next largest factor is power lines, which surround Mt. Washington from all sides. The fact that power lines contribute 25% to the weighting system is clearly shown on the map. Power lines are still observable even after wind speeds are included.

The only error that is created by combining GIS weighting factors is visible in the southeastern part of New Hampshire and is due to missing information on power transmission lines. Because the size of that missing region is small compared to the entire state, results can be predicted and analyzed easily even without this region.

According to our weighting system and its results above, the most plausible sites for wind farm development are located near Mt. Washington, areas surrounded by the small towns of Conway, Rumney, and Benton (which is south of Mt. Washington), and regions around Lake Sunapee that are southeast of Lebanon. These areas are located in the central and most mountainous regions of New Hampshire and have a great potential for wind farm development based on a survey of wind speeds of all ranges.

In parts of the state that have winds of less than 5.50 meters per second wind turbines cannot produce power regardless of accessibility. If regions with wind speeds of less than 5.50 meters per second are discarded as impractical for wind energy production, the area that is surrounded by the small towns mentioned previously is no longer represented as a plausible region as can be observed in Figure 4.14. The only two areas that are left to represent sites with sufficient values for wind farm development are near Mt. Sunapee and Mt. Washington. Regions around these mountains reach into 500s around Mt. Sunapee and around Mt. Washington, all the way to 835.

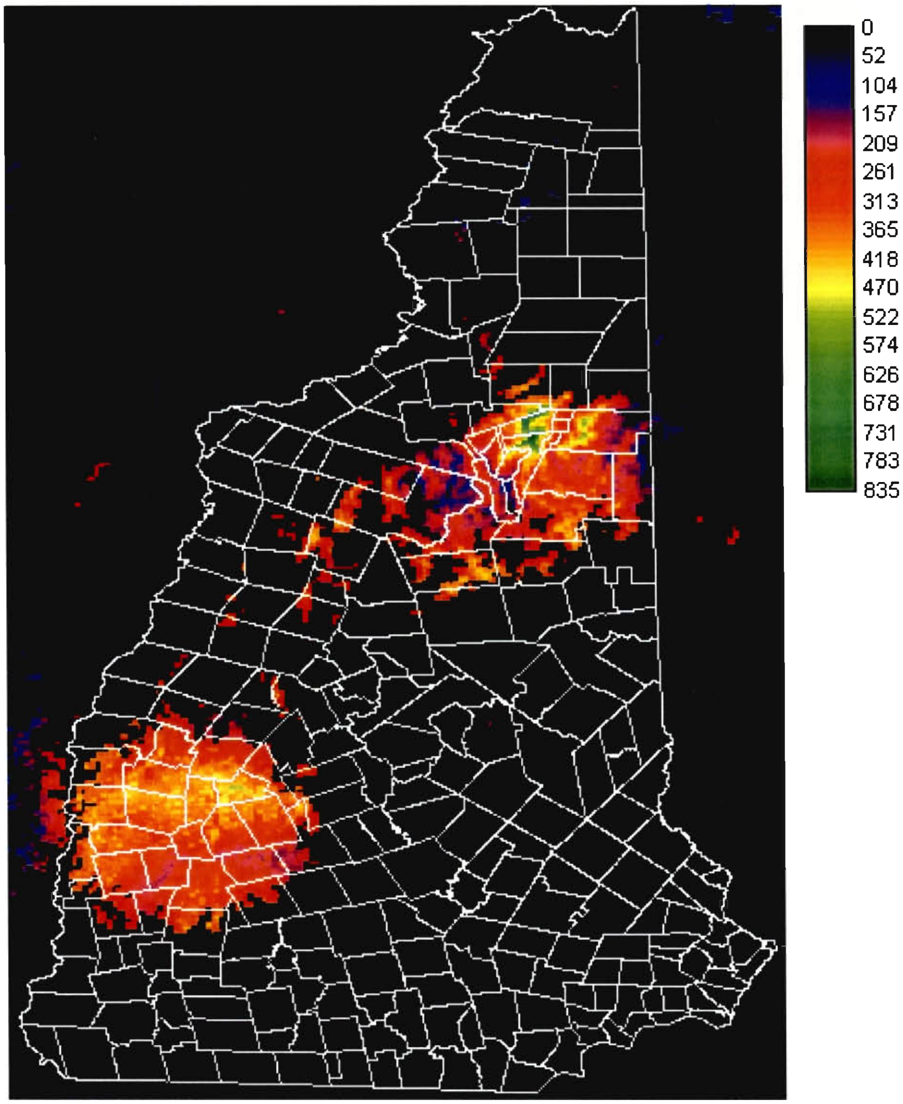


Figure 4.14: Combined Map Truncated for Wind Speeds Lower Than 5.50 m/s.

Mt. Sunapee has power lines running through its windiest regions and has excellent road accessibility as can be observed from the final accessibility image located in Figure 4.12. Mt. Washington also has transmission lines developed around its ridge and good surface roughness that can be observed in Figure 4.11. However, what makes this area an extremely attractive region for wind farm siting is its high wind speeds. According to these results, both of these mountains represent excellent candidate sites for wind farms. However, there are also regions southwest of Mt. Washington with good accessibility that posses wind speeds which can be used to produce wind energy.

On the other hand, according to both maps, there are three main areas in the state where wind farm development is not practical. The worst areas for wind farm development are in the northern part of the state and in the southeast corner of New Hampshire. In the northern section of the state wind speeds are low and accessibility is poor. There are no power transmission lines and a lot of rough terrain. While the southeastern third of New Hampshire has excellent accessibility values, its wind speeds do not allow for profitable wind farm development. However, wind farms do not require enormous areas of land to produce reasonable amounts of energy. Therefore, based on the final map of candidate sites, regions with minimum required wind speeds are broad enough to create a reasonable number of choices for possible wind farm sites.

In general, as can be observed from the weighting system, New Hampshire has very good potential for producing energy from wind. There are a couple of areas that can house profitable wind farms and produce enough energy to comply with existing and proposed renewable energy regulations. The best areas for producing wind energy are located near Mt. Sunapee and south of Mt. Washington. At the same time, poor regions for wind farm sites are present in the extreme northern part of New Hampshire and southeastern third of the state. But setting up a power plant takes more than just cost considerations. Other social factors that are not included in this weighting system have to be recognized. These factors do not have any set guidelines for where most environmentally and aesthetically sound sites could be developed, due to the fact that they are often subject to rapidly changing beliefs of special interest groups and are therefore difficult to put into a quantitative scale. Therefore the next step in our analysis contains recommendations for the process of setting up wind farms as well as minimizing concerns of environmental interest groups.

4.3 Incorporation of Environmental and Economic Restrictions

The main objective of the interviews was to determine what issues various interest groups were interested in as well as their criteria for approving a potential site in relation to these issues. Similarly developers were asked what issues have been most important in the siting of their projects to see how interest groups have impacted the siting of wind farms and related projects. The recurring theme in all the interviews was that specific guidelines and requirements for sites cannot be made and that the siting factors being discussed must be analyzed on a site by site basis. Interviews were conducted with AWS Scientific, a firm that deals mostly with data collection and organization, with Princeton Power, with the Audubon Society, and with the Sierra Club.

4.3.1 Economic Restrictions in Wind Farm Siting

During interviews with AWS Scientific and Princeton Power the economic issues in wind farm siting were discussed. Wind speeds are the overriding consideration. Other factors such as accessibility to roads and power lines as well as clearing costs have an economic impact on a site. If wind speeds are high enough sites with poor accessibility and high clearing costs can still be profitable. On the other hand, if wind speeds fall below a certain level then they cannot be profitable regardless of other factors. These interviews suggest that the factors weighted in section 4.2 all contribute to the cost of a wind farm in such a way that the weighting system used is both helpful and appropriate to wind farm siting.

The cost of clearing land for wind farms is small compared to other costs, but it does indeed affect building costs. Mike Markus spoke with us concerning his coordination of the mountaintop data project in New Hampshire. He was involved in the siting of observation towers as well as the collection of data from the towers. Each tower required a cleared area of about 150 feet in diameter. In order to produce the most accurate and the most useful readings the towers had to be positioned on hilltops and mountaintops, preferably at higher elevations. AWS Scientific did not want to pay to have mountaintops cleared so that a tower could be erected for a study that would last less than two years. Wind turbines cost much more than the clearing of land around them so the amount of foliage at a potential site is not a large economic factor. It is a factor, however, and it seems that a 5% weight was reasonable.

Wind speeds are the overriding factor in the suitability of an area for wind farms. Wind speeds determine the energy output of a site and can therefore affect the costs allowed at a site. John Fitch spoke regarding his experiences with Princeton Power, a company in Massachusetts that has sited some wind farms. They look for wind speeds of at least 15 miles per hour (6.7 meters per second). Below this would not be profitable. In section 4.2 a critical speed of 5.5 meters per second was used because the wind map was created at 40 meters and it was assumed that turbines would be built at about 70 meters. The power rule was used to convert between one height and another. Fitch also said that an increase in wind speed above these minimums would increase power output significantly, potentially making less accessible sites more viable. Because small differences in wind speeds make large differences in power output, wind speeds are by far the overriding factor in wind farm siting.

Accessibility to roads is an issue that changes the building costs of a wind farm significantly. The biggest problem is that generally a crane is used to install the turbine blades onto the base of the turbine. The crane must be as tall as the base, generally between 60 and 70 meters. These cranes can often navigate poor roads as well as cleared grasslands and forests. If roads can be constructed directly to a site then the cost to build that road is an issue. In the case of New Hampshire, the construction of roads to candidate sites would be a problem as the windy areas are in protected mountain ranges. The issue of the crane could be avoided if a helicopter was used to mount the turbine blades, but costs would rise significantly in that case. There is no real limit to the distance to roadways. Rather, larger distances simply mean larger costs. If wind speeds are strong enough, they can justify poor accessibility.

Similarly, accessibility to transmission power lines can affect the costs associated with building a wind farm as well as the amount of power it can supply to the power grid, but there is no set distance at which a site is no longer viable provided wind speeds are high enough. As power is transmitted from a wind turbine to the power grid, resistance in the power lines causes a loss of power. In order to minimize this loss, power lines can be constructed of more expensive materials or can be made thicker to lower resistance. This added expense makes areas with poor accessibility to power lines less attractive, but does not rule them out as wind farm candidates. Due to the scarcity of power transmission lines and the importance of efficient transmission, power line accessibility is a larger factor than road accessibility, as was reflected by the weighting system.

4.3.2 Environmental Restrictions in Wind Farm Siting

When environmental factors were considered, they could not be weighted as the economic factors were. If construction of a site would interfere heavily with the migration of birds, the site will not be constructed regardless of other factors. The environmental factors are much more limiting in that regard. Additionally, the environmental factors cannot be easily quantified or evaluated over large areas. They must be considered and studied at each potential site.

The Audubon Society deals primarily but not exclusively with the protection of birds and their natural habitat. Julian Zelazny, a member of the New Hampshire branch, spoke with us about the Audubon Society's concern for bird life and other environmental issues. While supporting the concept of renewable energy as opposed to fossil fuels, this cannot be blindly done without respect for wildlife and their natural habitat. The Audubon Society was willing to "be pragmatic about it" and accept the fact that at least a small amount of environmental disturbance was unavoidable. Mr. Zelazny said that the two primary concerns were whether a site would be built in an area with a high population of birds and whether it would be built in an area with a lot of bird migration. As a general rule birds tend to prefer areas with higher winds and high elevation gradients. This is not a solid and steadfast rule, of course, but generally speaking the best areas to build wind farms also have high winds and high elevation gradients. Realistically a site by site analysis is required for these issues with observations concerning the movement of birds through a potential site and the nesting of birds in the vicinity of a potential site. While other issues such as aesthetic disturbance and damage to other wildlife were not unimportant to the Audubon Society, they do not have any set policy or much experience in dealing with these issues. As such they suggested speaking with other groups concerning these issues.

The Sierra Club has more dealings with the protection of forestland, wildlife, and natural beauty. Representatives from the New Hampshire branch were reluctant to speak about policy on these issues and suggested that the organization's headquarters in Washington, D.C. would have more information on the subject. The interview was conducted with Ann Mesnikoff. The Sierra Club has no set policy on what would constitute an unacceptable disturbance of aesthetics, natural habitat, or wildlife. Any stance the Sierra Club would have on a potential site would be determined by the state branches rather than the leaders of the organization in Washington. Since this policy can more or less be set at each individual site, concerns for each site have to me made on a site by site basis. Developers would be encouraged to ask about particular sites and whether any objections could be raised towards them. Often studies on the surrounding wildlife are done to get an idea of the impacts a site might have. The results of these studies often directly cause a wind farm to be supported or discouraged.

5. Conclusions and Recommendations

The goal of this project was to devise a system that could be used to find the areas best suited for the construction of wind farms and then implement that system over the state of New Hampshire. A system was developed that use a combination of GIS software and interviews to point out possible wind farm sites. When applied to the state of New Hampshire, the system predicted that the areas around Mount Sunapee and Mount Washington would be prime areas for wind farms. Siting a farm in either of these areas would be very difficult, however. Mount Washington especially is a tourist attraction and is in protected forestland. Although wind speeds are significantly lower in Conway, Rumney, and Benton, good accessibility as well as wind speeds above 5.5 meters per second make these areas prime suspects as well. Careful studies of wildlife and further wind speed monitoring should be completed, and turbines must be carefully placed in order to minimize noise pollution and aesthetic disturbance.

A large number of factors determine the suitability of an area for a wind farm. Some of these factors (such as accessibility, wind speed, and land use) determine the costs and revenues associated with a wind farm. While poor accessibility or thick forests, for example, may drive the costs up, other factors (such as high wind speeds) may yield high energy production and validate high construction costs. Similarly, a site with low wind speeds and therefore little energy output may be acceptable if costs are low. Because the strengths of some factors can balance out the weaknesses of others, it is advantageous to weight these factors together using one system. The weighting system used for this investigation consisted of 60% wind speeds, 25% power line accessibility, 10% road accessibility, and 5% land use. These percentages were used because wind speed is the most limiting factor due to its impact on power output. Land use is a relatively minor factor as it is only a representation of the clearing costs at a site. The distance to existing transmission power lines is a crucial factor as it determines both the length of power lines that must be built and the efficiency at which power is sent to the power grid. Road accessibility is a somewhat minor factor due to the large number and density of roads in our areas of study.

The suitability map obtained for New Hampshire using this weighting system is presented in section 4.2.6. As noted above, the system makes use of WindMap and Idrisi to do a GIS analysis of the state of New Hampshire with regards to wind speed, accessibility, and land use. The final map suggests rather conclusively that the areas around Mount Washington and Mount Sunapee are most suitable for the placement of wind farms. This result does not rule out other areas in New Hampshire for future wind farm siting nor does it conclude that these areas are suitable for wind farm construction and operation. Rather, the study highlights the plausibility of successful wind farm siting in these areas given this set of factors. Assuming that a project within these areas is approved it will likely be logistically viable and have a high energy output at low cost.

In the state of New Hampshire, the major source of variation in this system is the wind speeds. Wind speeds throughout much of the state are too low to have a suitable energy output, but reach extremely high values at specific points. The large variation in wind speeds is a result of elevation changes and surface roughness. In New Hampshire accessibility is not much of a problem. There is a lack of transmission lines in the northern third of the state, but winds in that area are too low for wind farms there to be profitable anyway. There are plenty of roads; the largest distances to roads were over bodies of water, and these areas would obviously not be considered.

If this system were used to identify candidate wind farm sites in another area, different issues may be highlighted. In many Midwestern states, for example, winds would be high enough, and more uniform over the terrain that they would have less impact on suitability than the accessibility issues. The Midwest generally does not have steep elevation gradients, unlike the mountainous region of New England. If this system were to be used in an area with lower population density, with a smaller number of suitable roadways and power lines then more of the variation within the final maps would come from accessibility issues.

Other criteria must also be met at candidate sites or else a site would be considered unacceptable regardless of other factors. Factors such as noise pollution, interference with wildlife, and aesthetic disturbance could all stop a site from being built. If, for example, a candidate area was easily accessible and had high winds but was an area with large endangered bird populations that would be disturbed by wind farm construction and operation, the farm could not be built. Most likely if projects were proposed in the Sunapee and Mount Washington areas there would be objections on the grounds that both areas are within protected forestland and are considered scenic. Construction of a wind farm there would constitute a disturbance of this aesthetic value as well as the wildlife that helps maintain this value. Due to the relatively low population densities in the mountainous regions of New Hampshire turbine noise will probably not be a problem but some investigation would be required. Generalizations concerning these issues are hard to make and an in-depth study of them in proposed areas is recommended, as any analysis must be made on a site by site basis.

Our model is a general approach towards finding suitable sites for wind farm development, and can easily be modified to take into account new factors. An analysis of all the factors that can affect a site's suitability for wind farm development would be a monumental task. The results would vary little from a study done of only a few key factors, and the identification of these factors could add to the efficiency of the system. For instance, there are maps that can be specially ordered from GRANIT that detail the existence of public and privately owned forestland. Additionally, the proximity of a location to population centers could be considered. Some sites could be taken out of consideration permanently if they are in areas where development is prohibited. Even considering that there are factors this model does not currently take into account, it serves as an excellent basis for determining the best possible sites to build wind farms.

References:

Gipe, Paul. Wind Power for Home and Business: Renewable Energy for the 1990s and Beyond. White River Junction, Vermont: Chelsea Green Publication Co., 1993. p.131, 140, 120, 121, 123, 136, 139, 143, 146.

<http://www.awea.org/policy/rpsmechfed.html> "The Mechanics of a Renewables Portfolio Standard Applied at the Federal Level". September, 1997.

<http://www.nrel.gov/docs/fy00osti/27705.pdf> "The Changing Market For..". April, 2000. p.16, 17.

<http://www.awea.org/policy/rpsmechfed.html> "The Mechanics of a Renewables Portfolio Standard Applied at the Federal Level". September, 1997.

<http://www.awea.org/wpny/ny_legis.html> "Wind Power New York, State Energy & Wind Power Generation". 2000.

<http://www-solar.mck.ncsu.edu/finance/NH01F.htm> "New Hampshire - Local Option Property Tax Exemption for Renewable". 1976.

<http://www-solar.mck.ncsu.edu/regulatory/NH03R.htm> "New Hampshire - Electric Utility Restructuring". 1997.

<http://www.solar.mck.ncsu.edu/incentF.cfm?Incentive_Code=NH02F&Back=xstate> "New Hampshire - Renewable Energy Technology Grants Program".

Swift-Hook, D.T. Wind Energy and the Environment. London, United Kingdom: Peter Peregrinus Ltd. 1989. 4.

Gipe, Paul. Wind Power for Home and Business: Renewable Energy for the 1990s and Beyond. White River Junction, Vermont: Chelsea Green Publication Co., 1993. p.94, 254, 264.

"New Off-shore Plans Launched in UK", EWEA Magazine Vol. XVII, No.1 - Oct.1998. http://www.ewea.org/oct2.htm

Mac Daniel. "Turbine Turnabout Improved Technology, Lower Costs Spur Move Towards Wind Power." The Boston Globe, Monday, June 19, 2000.

Blake Nicholson. "Energy from Wind Cuts Costs for Nuns." The Seattle Times, Monday, August 16, 1999.

National Wind Coordinating Committee. "Wind Energy Costs." Washington, D.C., January 1997.

Steve Painter. "Why Our Energy Costs the Earth." Green Left Weekly, February 24, 1992.

National Wind Coordinating Committee. “Understanding Consumer Demand for Green Power.” Washington, D.C., June 2000.

American Wind Energy Association. “Comparative Costs of Wind Energy and other Fuels.” Washington, D.C., April 2000.

United States Department of Energy. "Wind Energy Information Guide." Washington, D.C., April 1996.

Soren Krohn. "Guided Tour on Wind Energy." Danish Wind Turbine Manufacturers Association, August 6, 2000. http://www.windpower.dk/tour/

United States Department of Energy. "Wind Energy Information Guide." Washington, D.C., April 1996.

Anderson, Richard, Michael Morrison, Karin Sinclair, and Dale Strickland. "Studying Wind Energy/Bird Interactions: A Guidance Document." National Wind Coordinating Committee, 1999.

American Wind Energy Association. “Wind Energy: the Fuel of the Future is Ready Today.” Washington, D.C., 1999.

Environmental Protection Agency. “Environmental Effects of Acid Rain.” April 1999. http://www.epa.gov/acidrain/effects/envben.html

David L. Chandler. “The Devil in the Details: Global Warming Could Bring a Host of Local Problems from Floods to Droughts to (Gasp) Vanishing Maples.” The Boston Globe, June 20, 2000.

Environmental Protection Agency. “Global Warming Impacts.” July 2000. http://www.epa.gov/globalwarming/impacts/index.html

Cousteau, Jean-Michel. “Powering the Future”. Skin Diver. Jan. 2000: 34.

Madsen, Birger T. “Energy’s Wind of Change”. UNESCO Courier. Mar. 2000: 9.
Wewetzer, Hartmut. “Germany: Tilting at Windmills”. UNESCO Courier. Mar. 2000: 11.

Speaker, Scott C. “Tax Credit Gives Boost to Windpower”. Natural Gas Week. Dec. 13, 1999: 10.

Chamberlain, Gary. “Wind Farm Turbines Harvest Energy for Iowa Utilities”. Design News. August 2, 1999: 20.

"The State of U.S. Renewable Power". Mother Earth News. Feb. 1999: 16.

"Wind Energy Resource Atlas of the United States." The Renewable Resource Data Center (RreDC). . 1986 <http://rredc.nrel.gov/wind/pubs/atlas/chp3.html#region>

Wind Energy Projects: Green Mountain Power Corporation 6-MW Wind Plant, Searsburg, Vermont . http://www.eren.doe.gov/wind/green.html

"Wind Energy Information Guide": National Renewable Energy Laboratory. April 1996. Washington, DC

Eldridge, Frank R. Wind Machines. n.p.:MITRE Corporation, 1975.