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WIND ENERGY ASSESSMENT OF MASSACHUSETTS USING GIS

An Interactive Qualifying Project Report

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by

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Abstract

This project is a pilot study for a full Massachusetts wind energy evaluation which uses IDRISI, a Geographic Information System (GIS) program, to create wind energy potential maps for Massachusetts. Also involved is an economic evaluation which will be continued by more students in the future using the project team's report and a similar methodology. The results obtained indicate that all areas having a Class 4 or above designation should be explored as possible windfarm sites and that this project has further potential for other groups in the future.

Executive Summary

The United States, the most industrialized nation in the world, is at the center of the global energy problem. Fossil fuels, the most widely utilized source of energy in all industry and residential applications, produce numerous pollutants and damage the delicate ecosystems in which we exist.

Renewable energy is one of the more promising solutions to this problem with fossil fuels. This IQP, which was done for the Union of Concerned Scientists, investigates, using GIS, one type of renewable energy feasible for Massachusetts, windpower, and produces preliminary windmaps of Massachusetts and lays the ground for further assessment by future groups.

The project team used a method of wind energy assessment developed by the Union of Concerned Scientists with the basic premise as follows; the main source of windpower information, the Wind Resource Database, is of too low a resolution to have any real usefulness to anyone attempting to find a potential windfarm location. The method uses a mathematical correction based on elevation and land cover data to refine the Wind Resource Database and thus produce a new windmap that more accurately reflects the influence of local terrain on windclass.

While most of what the project team attempted was successful, some approximations were made and are fully explained in Chapter III. The final products of this project are a corrected windpower density map for Massachusetts and a map showing the cost of electricity that would be produced by a windfarm at that location.

The project team concludes that numerous sites in the central, northern, and eastern parts of Massachusetts are of Class 4 or higher and, as such, would be potentially

feasible windfarm sites. Also, the project team feels it worthwhile for another group to continue this work in pursuit of a more accurate result.

I. Introduction

Worldwide energy consumption habits show no regard for the environment or anticipation of the future, and the United States is at the heart of the problem. Americans, lulled into complacency by the pseudo-stability of the present energy situation, have all too quickly forgotten the oil embargo of 1973. They heedlessly consume cheap, readily available energy in the form of natural gas, crude oil, and coal. They are responsible for 25 percent of the energy consumption worldwide, but account for only 5 percent of its population [1]. As is obvious from these figures, Americans play a substantial role in worldwide energy consumption. Therefore, changing American habits can have a significant impact on the global environment.

There are numerous, potentially dangerous elements in the current U.S. energy situation. Burning fossil fuels creates pollution and is responsible for problems such as smog, acid rain, and contamination of water bodies. All fossil fuels are finite and the present estimate is conventional crude oil reserves will last another 70 to 120 years [2]. The United States consumes much more energy than it produces, and the heavy energy importing that results from this energy deficit puts the United States in a vulnerable global position. If something is not done about America's energy consumption, it may well find itself in another energy crisis or war to protect its energy interests.

Obviously, energy is an issue of paramount importance in the modern world. People, the societies they comprise, and the infrastructures that support both depend upon energy for daily survival. One is hard-pressed to think of a modern implement that does not require energy to function. Because of this extreme reliance on energy, we must start looking at the future consequences of the present energy situation and mend our heedless

and gluttonous consumption of fossil fuels. Consequently, people are beginning to look to renewable energies as a viable means to power our societies.

This IQP will investigate one of the types of alternative, renewable energy feasible in Massachusetts: windpower. The project team is working for the Union of Concerned Scientists in an effort to gather the information and resources necessary to build a Geographic Information System (GIS) for designing wind energy maps focusing on selected areas of Massachusetts. Wind energy maps, which show the density of power available in the wind are an important tool for anyone attempting to find suitable windfarm sites, as well as being useful for economic calculations to estimate the cost of electricity that would be produced by a windfarm at a specific site. After the GIS is assembled, future groups can use it to extend the windmaps to other areas or for further analysis. Another type of renewable energy feasible for Massachusetts is biomass, which will be discussed in the Background Chapter. Unfortunately, an evaluation of biomass is beyond the scope of this project.

The main goal of this IQP is to amass the necessary resources to construct a wind energy GIS for Massachusetts. The project team will also carry out a limited analysis of the wind energy potential of Massachusetts, employing the constructed GIS. The results of the project team's analysis (and of future analyses carried out by other IQP teams) will be particularly useful to any person, corporation, or utility company that wishes to find potential windfarm sites. Very little information is currently available on this topic, and the main data available (Wind Resource Database) is of too low a resolution to aid in choosing real windfarm sites. Thus the analysis we are beginning will refine the Wind Resource Database so that potential windfarm sites are visible on a windclass map.

The remainder of the report is structured as follows. Chapter II, Background, has seven subdivisions and outlines the state of energy affairs in the United States, discusses GIS, the main tool in this project, and considers previous work on related subjects. Chapter III, Procedure, details the project team's information search methods, what data the project team employed, and the method of wind energy assessment employed in this IQP. Chapter IV, Economic Analysis of Results, discusses the methodology for calculating the cost of electricity produced by wind. The project team's calculated cost per kilowatt hour of electricity for each windclass is also included. Chapter V, Conclusions and Recommendations, presents the conclusions drawn from the results, and the project team's recommendations for further study on this project.

References

- (1) Howes, R., Fainberg, A., *The Energy Sourcebook* (New York, NY: American Institute of Physics, 1991), p. 6
- (2) Howes, R., Fainberg, A., *The Energy Sourcebook* (New York, NY: American Institute of Physics, 1991), p. 43

II. Background

The United States produces nearly all its energy by consuming fossil fuels. Fossil fuels are used even in the production of electricity, which produces no pollution when consumed. Despite this benign end-use nature, electricity consumption still has adverse environmental effects because of the production method. So the production of electricity, which is where fossil fuel dependence lies, is an excellent candidate for reform, especially considering the enormous amount of electricity consumed in this country. This IQP addresses the reform of electricity production, and so a discussion of the issues surrounding electricity production is important, as it lays the foundation for analysis. The Background Chapter carries out this discussion, and has seven main sections: an overview of the current U.S. energy situation, electricity generation, consequences of U.S. energy consumption, renewable energy, evaluation of renewable energy potential, GIS, and a discussion of previous work.

A. Overview of the Current U.S. Energy Situation

Energy has become an integral component of daily life, and as such it plays a primary role in the economy and foreign policy decisions of the United States. In this section, we will discuss the marked U.S. dependence on fossil fuels, the U.S. energy trade deficit, and the economics of petroleum use in the United States.

Presently the United States relies heavily on three fossil fuels for energy: coal, natural gas, and petroleum, which were responsible for 56.3 quadrillion Btu's (herein known as "quads") of energy generated in 1997 out of a total 72.4 quads generated [1]. Therefore, 77.76 percent of the U.S. energy needs came from these three fossil fuels. Coal

supplies 22 percent of the fuel used for all types of energy production in the United States, natural gas comprises approximately 19 percent and crude oil supplies about 13 percent [1].

The United States currently consumes more energy than it can produce. For example, in 1997, the United States consumed 94 quads of energy, 21.6 quads more than it produced. This “energy deficit” began in the early 1970’s and has necessitated heavy energy importing. In 1997, the United States imported 25 quads of energy.

The price of petroleum, the main energy import in the United States, can be volatile and heavily influences domestic consumption. The actual amount of petroleum the United States imports depends upon consumption, which depends upon the global price of petroleum. This pattern has shown itself historically time and again. For example, in 1986 the price of crude oil fell sharply and has not fluctuated significantly. As a result, U.S. petroleum consumption has been steadily increasing since then and is presently approaching the all time yearly record for amount of petroleum consumed. In contrast, the 1973 oil embargo imposed by OPEC (the Organization of Petroleum Exporting Countries) caused global prices of petroleum to rise sharply. Consumption followed the pattern and decreased rapidly. Transportation is responsible for over half of the total petroleum use in the United States. Petroleum is also used in electricity production, but to a limited extent.

B. Electricity Generation and Sources of Electric Power

The main topic of this IQP is electricity generation from windpower and Biomass. Therefore the principal concern is with energy consumed in generating electricity. This

section will discuss the main fuels used in electricity generation and the sectors that consume electrical energy.

The United States has turned to coal as its primary energy source. In 1997, coal accounted for 52 percent of electricity production in the United States [2]. Originally, utilities used oil to generate electricity, but as oil became more expensive, electric utilities began to switch to coal as their primary fuel for generation. In 1973, the electric utilities generated 8.66 quads of energy from coal and 3.52 quads from oil. By 1989, these numbers had switched to 15.95 quads generated by coal and only 1.68 quads generated by oil. These were relative changes of 84 percent and negative 52 percent for coal and oil, respectively [3]. In 1997, oil accounted for 95.5 of the total 3532.5 billion kilowatt-hours of electricity generated (three percent) and coal accounted for 1853.1 billion kilowatt-hours of the total (52 percent) [4].

Natural gas accounted for 14 percent of the electricity generated in 1997. Its use in electricity generation has declined, going from 341 TWh produced in 1973 to 264 TWh in 1989. Since 1995, total natural gas consumption in the United States has slowly risen from 21.58 Trillion Cubic Feet (TCF) to 21.99 TCF, while in the Electrical Utility sector, natural gas consumption has fallen from 3.20 TCF in 1995 to 2.96 TCF in 1997 [5]. The reason for this drop is that, since the 1970's, natural gas prices have risen more than oil and coal prices [6]. Despite this drop, natural gas, like petroleum, is in trade deficit right now.

Nuclear power plants were responsible for 18 percent of the total electricity generation in the United States in 1997, but emphasis on building new nuclear production plants is all but gone. In fact, of the 259 total nuclear power plants ordered for

construction between 1953 and 1977, 124 have been canceled, 24 have been shut down, and only 110 are in operation or being constructed [7].

Hydroelectric power and other renewable energy resources made up the remaining 14 percent of the total electricity generation in 1997. Oddly, hydroelectric generation was responsible for about one third of the electricity produced in the United States in 1949. In 1949 however, the total production of electricity was only around 0.5 trillion-kilowatt hours. Now it is well in excess of 2 trillion-kilowatt hours. Thus the actual number of trillion kilowatt-hours produced from hydroelectric power has increased slightly since 1949, but the relative percentage has decreased markedly.

There are three main sectors that consume electricity: the commercial and residential sector, the industrial sector, and the transportation sector. For the commercial and residential sector and the industrial sector, the amount of energy lost in converting other forms of energy to electricity is actually much larger than the amount of electrical energy consumed. Quantitatively, "... for every three units of energy that are converted to create electricity, only about one unit actually reaches the end user" [8]. This loss occurs in generation; transmission losses are much smaller. Thus electricity is by far the largest form of energy consumed in either of these two sectors, and coal is the primary stock fuel for generating this huge amount of energy [9].

C. Consequences of U.S. Energy Consumption

The fossil fuels discussed here have numerous problems associated with their use, as does nuclear power. These problems can be separated into four main categories: finite quantities, environmental damage, effects on human health, and economic deficit.

Fossil fuels, by nature, are a finite resource. These substances are generated over millions of years, through chemical processes taking place deep within the earth. This means that an exhausted fossil fuel cannot be expediently regenerated with present technology. Current estimates of the remaining crude oil reserves or resources worldwide are around 1400 billion barrels of oil (bbo) [10]. If the worldwide consumption rate of crude oil is about 21 bbo per year, the world will run out of oil in approximately 70 years, assuming that consumption remains a constant 21 bbo per year. If, on the other hand, consumption grows at the same rate as the GNP, crude oil resources will be exhausted much more quickly. Estimated natural gas reserves are 8×10^{15} ft³. Assuming constant worldwide consumption at the present rate, these reserves will last about 140 years. Remaining coal resources are estimated between 10 and 12 trillion tons. Again, assuming a constant rate of consumption, this coal reserve will last for thousands of years [11].

All fossil fuels, when used by combustion, produce CO₂ and some or all of the other greenhouse gases. The greenhouse gases are CO₂, O₃, CH₄, N₂O, and some chlorofluorocarbons. In high atmospheric concentrations, greenhouse gases may cause extreme (with reference to changes that would occur in the absence of man) climactic changes on earth, including increased average global temperature, some melting of the polar ice caps, and altered rainfall patterns. In 1988, the concentration of CO₂ in the atmosphere was 350 PPM (parts per million). This represents an increase of approximately 75 PPM over the estimated levels at the time of the last ice age (approximately 10,000 years ago). In 1996, CO₂ emissions were around 5.5 billion metric tons. About 5.39 billion metric tons of this resulted from "... petroleum consumed by the

transportation sector, coal burned by electric utilities, and natural gas used by industry, homes, and businesses” [12].

Besides greenhouse gases, fossil fuels also produce other pollutants. Some examples of these pollutants are sulfuric acid, lead, ash, and soot. Acid rain is one result of these pollutants, caused by emissions from fossil fuel plants that lower the pH of natural rain. Coal contributes the most to the acid rain problem, with oil coming in second, and natural gas being the lowest contributor. Approximately 25 percent of the acid rain-producing emissions come from automobiles [13]. This acid rain enters rivers, lakes, and streams and can disrupt or even destroy the ecosystem within the body of water. This acid rain also can enter the ground and contaminate the soil and groundwater.

The adverse effects of fossil fuel use on the health of the humans whose societies they power are rather ambiguous. “Studies suggest that sulfur dioxide emissions from Midwest power plants alone may result in \$25 billion a year in health-related costs.” [14]. If one considered the output from all power plants nationwide and the entire U.S. population, the figure would probably double, and it goes widely unaccounted for in cost analysis and comparison between the culprit fossil fuels and benign renewable energy sources.

In addition to the aforementioned problems, a fourth problem exists. The United States must import energy stock fuels heavily because, as mentioned, it consumes more energy than it can produce. Reliance on imports puts the U.S. at the mercy of price fluctuations, political instability in OPEC, and the availability of resources in other countries. To understand why this is undesirable, consider the 1973 OPEC oil embargo

and the inflation and economic strife that it caused. Consider also the Gulf War and the human lives wasted in combat over oil.

Nuclear generation has its share of problems as well. While nuclear power plants do not emit greenhouse gases, they do expel warm water into lakes and rivers. Nuclear plants are usually located on a body of water because the plant needs a source of water as coolant. The water passes through the plant, taking heat from the reactor, and re-enters the body of water from whence it came, at a higher temperature. This disrupts local ecosystems and has adverse effects on organisms that are temperature sensitive. Nuclear plants also produce spent nuclear fuel and control rods, which are highly radioactive and as yet, no permanent disposal solution for the fuel or control rods has been found. Also, an accident at a nuclear generator is potentially much more dangerous than one at a comparable size fossil fuel generation plant. Of course, nuclear generation facilities have an excellent track record here and abroad, but it is impossible to produce a foolproof facility [15]. Finally, nuclear power plants increase the background radiation in the surrounding area. The effects of this are unclear, and different plants produce different levels of radiation.

D. Renewable Energy

Renewable energy is very loosely defined as any energy that is inexhaustible or replenished easily. This type of energy source obviously has numerous advantages over fossil fuels. In this section, we will identify the most common types of renewable energy, discuss their benefits and drawbacks, and consider to what extent these renewables will penetrate the modern energy market.

Currently, five prominent renewable energy sources dominate the renewable market; they are wind energy, biomass, geothermal energy, solar energy, and hydroelectric power. Wind energy, quite simply, is energy derived from the wind. Usually Wind Energy Conversion Systems (WECS) convert the kinetic energy of the air into electric potential energy. The term “biomass” encompasses a cornucopia of materials, including (but not limited to) wood, wood waste, peat, wood liquors, wood sludge, agricultural waste, straw, tires, fish oils, waste alcohol, municipal solid waste (MSW), and landfill gases. The chemical potential energy of biomass materials is converted to thermal energy by combustion in plants similar to fossil fuel power plants. Geothermal energy is the thermal energy stored within the Earth, which can be utilized for numerous applications. Solar energy is energy from the sun. This electromagnetic radiation can be converted into electric potential energy by photovoltaics and can also be used to heat a heat reservoir. Hydroelectric power is derived from moving water. The kinetic energy of the water is converted to electric potential energy.

Wind power is one of the most promising renewable energies today. Wind, being a naturally occurring phenomenon in nature, is completely harmless to the environment. Windpower is widely distributed and an inexhaustible resource. Utility scale windfarms have much shorter construction times than fossil fuel plants. They also have the advantage of modularity. Modularity refers to having a plant consisting of numerous parts that can be added or taken away as demand for power dictates; this is a definite impossibility for fossil fuel plants. Wind power is very competitive with fossil fuels for generation of electricity. Current windpower technology can generate electricity for 3.6 to 6.1 cents per kilowatt-hour [16].

Wind does have drawbacks however. The current method of wind generation utilizes windfarms, which occupy large amounts of land and obstruct scenic views. Also, wind has high startup costs per kilowatt-hour capacity compared to gas combined cycle and gas combustion turbine generators. "... the initial cost of a 50 MW wind farm constructed in the Midwest with this machine (the US Windpower's 33M-VS model) would be about \$43 million, or \$860 per kilowatt, not including transmission interconnection, substation, land, and permitting fees" [17]. Avian deaths are another problem with windfarms, as birds sometimes fly into the blades of the windmill and are seriously injured or killed.

Biomass fueled generation of electricity also has numerous advantages over fossil fuel generation. Basically, all biomass materials are burned and energy is derived from this process in the form of heat or steam for turning turbines. Unlike fossil fuels, burning wood does not release sulfur into the air as wood contains no sulfur. Another advantage of burning wood over fossil fuels is that, while wood releases CO₂ into the air, the amount of CO₂ released by burning wood is approximately the same as the amount of CO₂ taken in by these plants and trees during growth. Hence, there is no net CO₂ generation to contribute to the greenhouse effect, whereas with fossil fuels there is a net generation of CO₂ gases contributing to greenhouse warming. Another more obvious advantage of wood fuel is that wood fuel is replenishable, whereas fossil fuels are not.

Biomass generation does have some undesirable aspects. If trees were removed in mass quantities without any replanting or management there could be major erosion problems and ecosystems would also be greatly effected. Also, logging practices are sometimes noisy and bothersome; characteristics that are likely to be bothersome to

anyone living near the logging operation. Siting problems in general can be a negative with any biomass fuel. One problem associated specifically with MSW is that unprocessed MSW contains highly caustic materials like batteries, metals, styrofoam, etc. When combusted, these materials release many harmful chemicals into the atmosphere. Refuse Derived Fuel (RDF) eliminates some of the emissions, but still produces an appreciable amount of pollution.

Geothermal energy is another environmentally harmless energy source. Using the heat stored in the Earth is completely safe for the environment. And, this could theoretically be the best known renewable resource because of the vast amounts of heat stored in the Earth. Unfortunately, not much is known about geothermal energy and substantial digging into the Earth's crust is needed to access the areas at very high temperatures because they are typically very far below the surface. Also, geothermal wells are essentially finite. After some period of time, the heat will be exhausted and the well will no longer be useful [18].

Of all the types of energy generation, solar is the most benign to the environment. Once a solar system is installed, it has low to no operating costs and the distinct advantage of modularity: panels can be added or taken away as demand for power dictates. Solar heating is versatile; it can heat buildings, water for human use, and generate electricity through a heat engine [19]. Finally, solar power is inexhaustible.

Unfortunately, solar generation of electricity is too expensive to be competitive with other sources of electricity, and it comprises a tiny share of the total generation of electricity. U.S. production of solar photovoltaic devices in 1988 was about 12 peak MW, which translates into approximately 0.002 percent of our electric capacity [20]. In 1996,

only .075 quads of energy consumed were generated from solar power, compared to 3.942 quads from hydroelectric. Only windpower had a smaller percentage of the total share [21].

Hydroelectric power has been a solid, dependable source of electricity since the 1940's, utilizing the kinetic energy of water to create electrical potential energy. Unlike nuclear power plants, a hydroelectric plant has no adverse effects on the water it uses, and it produces no byproducts or emissions. The lifetime of a hydroelectric plant is typically longer than a fossil fuel plant, sometimes as much as two to three times longer. The efficiency of the hydroelectric generation process is about twice the efficiency of a thermal process, and the technology of hydroelectric generation is well established and field tested [22]. Dams and the reservoirs they create can even become popular tourist attractions.

Hydroelectric plants do have drawbacks, such as high startup cost and the large amounts of land buried underwater when a reservoir is created. There is always a risk of dam failure, which has catastrophic implications for anything, including land, wildlife, and communities, downstream from the dam. Finally, hydropower is not modular as are some of the other renewable energies [23].

As stated earlier, fossil fuels comprise the lion's share of electricity and overall energy generation in the United States. But renewables do play a small part in the present energy game. In 1997, renewable energy constituted 8 percent of the total energy, and 14 percent of the electricity generated in the United States. Renewable energy production has steadily increased since 1949, going from 1.43 quads produced in 1949 to 6.93 quads produced in 1997 [24]. Recently, electric utilities have begun to utilize renewable

energies for their electricity production. There has been some expanded use of renewable energy and decreased reliance on fossil fuels in the New England area. While these steps are small, they are moving in the right direction. New England Power Co. announced in 1993 that it intended to purchase 36 MW (megawatts) of generating capacity from seven renewable energy plants in seven years. If New England Power Co. does purchase this amount of capacity, it will reduce its polluting air emissions by 20 percent by the end of the plan. The renewable energies that New England Power will be utilizing are Maine wind turbines and solid waste combustion, landfill methane combustion in Massachusetts and New Hampshire, municipal solid waste combustion in Maine, and waste heat in Rhode Island. Currently the New England Power Company has 580 MW in renewable energy coming from hydroelectric sources.

In 1997, an "Electricity Deregulation Pilot Program" was initiated in Massachusetts by the Massachusetts Electric Company. This pioneering program allows customers that want a choice to choose their power supplier. Considering only the residential customers, 66 percent chose based solely on the price of the electricity and 31 percent of the customers chose an environmentally friendly "green" provider. These green providers were considered green because they either generated power by renewable means, offered energy conservation, or a combination of the two. The remaining 3 percent is inconsequential. All of the participating customers will save money due to the competition induced, and more electricity is coming from environmentally sound sources than before the test program.

The D.O.E stated in the report "Estimates of U.S. Biomass Energy Consumption 1992" that biomass accounted for approximately 2,785 trillion Btu's of total energy

generated in the United States, which was three percent of the United States' total energy consumption. 81 percent of this 2,785 trillion Btu's came from wood fuel, 16 percent from waste, and 3 percent from ethanol. Geographically, 49 percent of the total biomass-fueled energy was generated in the South, 21 percent in the West, 15 percent in the Northeast, and 15 percent in the Midwest. Specifically, the Northeast used more solid waste as biomass fuel than any other region of the country, but used very little ethanol as biomass fuel and fell approximately in the middle for using wood as a biomass fuel. The D.O.E. predicts that by 2010 U.S. biomass resources could contribute 4,770 trillion Btu's of energy per year.

As mentioned, hydropower generates the most energy of any renewable source. Hydropower is responsible for 55 percent of all renewable energy produced in the United States [25].

By comparison, geothermal has five percent and solar energy has one percent of the total energy generated from renewable sources. As such, neither solar nor geothermal has a great deal of market penetration and are suited for limited applications.

E. Evaluation of Renewable Energy Potential

Evaluating renewable energy potential takes previous work to consider and build upon, information to employ in the evaluation, a tool to aid the evaluation, and a general procedure for evaluation. We discuss all four components in this section.

When carrying out a scientific study, one must consider what similar work has been done in the past. As such, the project team has compiled a list of previous reports, IQPs, and other published material that relates to this project.

- “Powering the Midwest” Published by the Union of Concerned Scientists.
This report assesses the wind energy potential of the Midwest for generating electricity and presents cost comparisons between various renewable energies and fossil fuels. The assessment is GIS based. Published in 1993.
- “Windpower in New England: Modeling and Analysis of Non-Dispatchable Renewable Energy Technologies” by Judith B. Cardell and Stephen R. Connors. This report presents a methodology for analyzing renewable energy technologies. Published in 1997.
- “Alternative Energy Generation.” This IQP was a prefeasibility study on using hydroelectric or wind power to supplement the Sunday River area with the intent of stimulating other business interest in researching the area. This IQP assessed wind potential. Published in 1995.
- “New England Wind Resource Assessment.” An unpublished report by the UCS. This report estimated three different geographic wind potentials for New England (ridge crest, coastal, and offshore). While this report was never published, it still provides valuable insight as to the process of evaluating wind potential.

Next one must consider data. The project team's data sources for wind are as follows:

- National Climactic Data Center – this government agency provides numerous types of meteorological data, including hourly wind data, etc.
- Typical Meteorological Years – this set of data put out by the NREL has wind data for every day of a “Typical” year for various locations across the country. Published in 1995.
- “Wind Energy Resource Atlas.” – product of the Pacific Northwest Labs. This publication has a great deal of information on “wind,” ranging from the Wind Resource Database (a wind energy map for the entire United States) to appendices that detail the calculations encountered when considering wind energy. Published in 1986.

F. Geographic Information Systems

A Geographic Information System (GIS) is the best tool available today for evaluating the renewable energy potential of a location, regardless of which type of renewable is considered. The most common renewable energies today have limitations that make them feasible for only certain areas of the country, and as such, careful analysis must be done to discern whether a location is feasible for conversion to renewable energy production. This is where GIS is so helpful. GIS is defined as a “system that contains spatially referenced data that can be analyzed and converted to information for a specific set of purposes, or application... The key features of a GIS is the analysis of data to produce new information.” [26]. What does this mean? GIS can take data that has some spatial dependence and use it to make decisions, generate scenarios, and create new data.

Some concrete examples of a GIS's capability are creating a map with the locations of resources on it; creating maps of cities with landmarks denoted; assessing the biomass resources within a specified radius of a power plant; decaying public infrastructure; landuse studies; evaluating and developing timber, coal, mineral, and oil reserves; and selecting optimum sites for locating waste treatment plants. It is also especially well suited to the task of renewable energy assessment. Whether the objective is to assess a site for its wind capacity or find out which electricity plants would be most easily and efficiently converted to biomass combustion, GIS is the optimum tool.

GIS are rooted in the 1950's in automated mapping: the use of punch cards to produce accurate maps. Automated mapping represented a vast improvement over trying to hand-produce them, which spawned an expanded use of computer maps. The Canadian government was the first entity to put a large system with information referenced geographically into use. Many universities also contributed to the advancement of the use of spatial relationships and geography in data representation during these early days of GIS.

The earliest GIS systems were raster based rather than the now popular vector based systems. In the raster format, one finds graphics stored as values in uniform grid cells, or pixels. Vector based systems have images represented in a Cartesian coordinate system. Depending upon the application the GIS is being used for, one format is usually suited to the task better than the other, but current technology allows for conversion of data between formats. Some of the raster based software today is IDRISI (developed by Clark University Graduate School of Geography) and Windmap (developed by Mike

Brower specifically for wind applications). Vector based software includes ArcInfo and ArcView (both developed by Environmental Systems Research Institute or ESRI).

In general, GIS data bases divide into two types of data: graphic and non-graphic. Graphic data is basically the maps that the information is going to be placed on, described digitally. Non-graphic data is the information that will be placed on the map, such as crop type, current land use, temperature, etc. It is useful to think of these sets of data as layers that fit on top of one another to produce a complete map. For example, one can have the first layer as the map itself (graphic data), another layer above it as soil composition at a certain depth (non-graphic), another layer as soil composition at a different depth, etc. Almost any information can be stored as non-graphic data, so long as it is spatially referenced.

More specifically, GIS has greatly expedited the analysis process for renewable energy. No matter which type of renewable energy is being considered, GIS is an invaluable tool. Consider biomass. As mentioned, soil composition, current land use, location of electricity plants, location of roads, location of power lines, location of crop residues, etc. can be entered into a GIS. The GIS can then combine all this information and use it to decide whether a certain plant has the resources surrounding it to be converted to biomass. Conversely, one could also choose a specific plant and use GIS to assess the biomass resources available within a specified radius of the plant (usually 50 miles is considered the maximum economically feasible limit for transport of biomass fuels, due to their low energy density). GIS is applicable to almost any type of renewable energy problem conceivable.

G. Extension of Previous Work

We obviously do not want this IQP to be simply a rehashing of another, previously published report or another IQP. Consequently, it's important to consider how this project is going to be different from other publications and reports in the past. In this case, there are four reports we have that directly relate to the subject at hand.

“New England Wind Resource Assessment.” This unpublished UCS project assessed the wind energy potential in New England. This study did not employ GIS or GIS generated maps as tools for evaluating the wind resource. We hope to assemble a GIS and generate GIS wind maps to stimulate continuation of the project in the future.

“Powering the Midwest.” This UCS report assesses the wind energy and biomass potential in the Midwest, and establishes the algorithm for doing so. The report does utilize GIS, but obviously it had nothing to do with New England or Massachusetts. This report will utilize the same techniques used in “PTM,” but applied to the Massachusetts area.

The “Wind Energy Resource Atlas” has wind maps for large sections of the country (i.e. the Northeast), but no state-specific maps. We hope to narrow down the focus and generate more accurate maps of a smaller geographic area.

The report “Windpower in New England: Modeling and Analysis of Non-Dispatchable Renewable Energy Technologies” did not involve GIS or maps. It presented a method of assessing wind energy potential. We hope to employ some of the techniques and models presented in this report and go beyond it by again, producing GIS based maps of the Massachusetts wind potential.

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III. Procedure and Results

Any project of this nature requires a large body of data, containing background data, information to be used in analysis, and information about the method of analysis. A careful description of this information is imperative for anyone to actually understand the report. Chapter II described the background data of this project. The first section of this Chapter, Resources Used, details what information the project team utilized. The actual implementation of the analysis is addressed in the second section of this Chapter, Project Method.

A. Resources Used

The starting point for any project is a review of the available literature on all of the topics that the project addresses. This report is certainly no exception. We began with a search of the Gordon Library, WPI. This includes previous IQP's and MQP's. We also went to the FirstSearch Database System, the UnCover Periodical Article Database, and the Engineering Information Village in an attempt to find recent publications on wind energy. The World Wide Web proved to be an invaluable asset in the background research for this project. It was there that we obtained the Pacific Northwest National Laboratory's "Wind Energy Resource Atlas of the United States" and the Department of Energy's "Annual Energy Review 1997," amongst other articles, publications, and data. During the actual execution of the project, we contacted Gary Votour at Clark Labs Technical Support as well as the MapInfo Technical Support department numerous times. We also enlisted the help of Dr. Michael Brower, a professional in the field of renewable energy assessment and founder of the company Browerco, many times. We are forever in

his debt. Other GIS resources that we utilized were the comp.infosystems.gis and comp.soft-sys.gis.esri newsgroups, as well as the IDRISI discussion group maintained by Clark Labs.

The project team employed the following digital data: Digital Elevation Models (DEMS), Land Use \ Land Cover (LULC) files, and the Wind Resource Database, which came from the United States Geological Survey (USGS), the Environmental Protection Agency (EPA), and the Pacific Northwest National Laboratory (PNNL) respectively.

B. Project Method

This IQP uses a method of wind energy assessment established by the Union of Concerned Scientist in their publication “Powering the Midwest.” The underlying principle is to take the Wind Resource Database from the *Wind Energy Resource Atlas*, which does not have adequate resolution to be useful for windsite selection, and refine it using elevation and land use/land cover data that has much finer spatial resolution. The method has two steps, and the project team took numerous steps in preparing the data for use. In this section, a general overview of the method is given, then all steps to prepare for analysis and the actual analysis are detailed.

1. Theory Behind the Method

The starting point of the assessment is the “Wind Resource Database,” a digital version of the U.S. Annual Average Windpower map in the *Wind Energy Resource Atlas*. This windmap (Fig. 3.1) has the windclass ranking of the contiguous United States. The ranking is based on the average windspeed and/or windpower density of a location, and

windspeed/windpower increases with class number. These maps were originally assembled by PNNL in 1979 and 1980, using windspeed data from ship observations, Forest Service Data, and other sources. The contour map for southern New England (Fig. 3.2) is the actual published product.

Figure 3.1

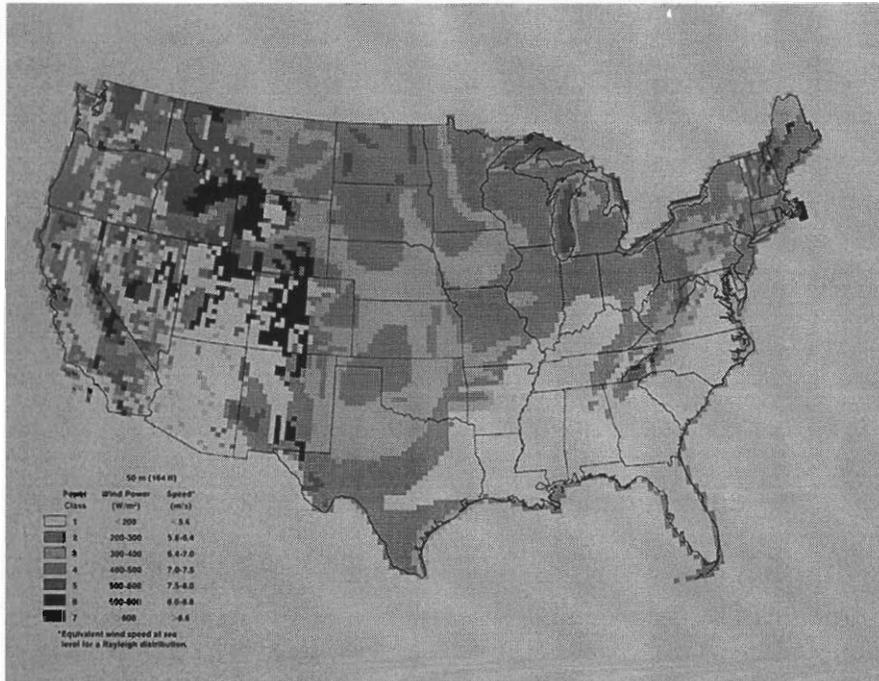
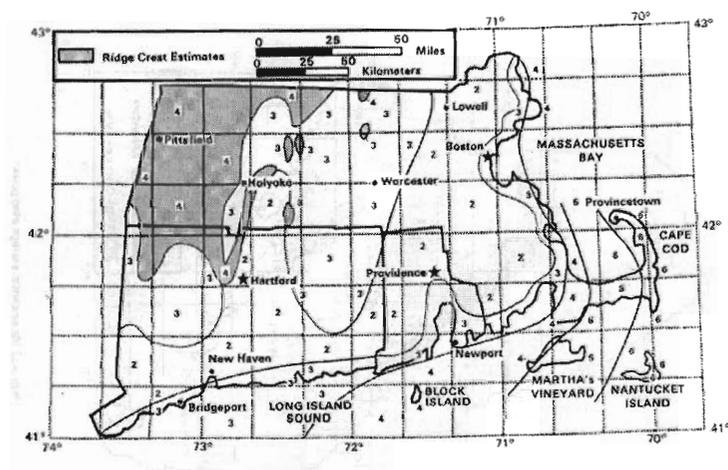


Figure 3.2



The digitized map has an angular resolution of $1/3^\circ$ longitude by $1/4^\circ$ latitude, which corresponds to a cell approximately 37 X 28 km. Obviously this scale is much too large to be useful for finding promising windsites, which are much smaller. Therefore this data must be refined to account for fluctuations in land cover and topography that occur on a small scale.

The first step in refining the data is to normalize the Wind Resource Database. Normalization involves two steps, the first being "...reducing by one the wind class of those areas in the map clearly associated with elevated or hilly terrain" [1]. This is done so that the newly downgraded areas can be re-evaluated with the elevation data, which is on a much smaller scale and thus will show sites, such as hills and ridges, with a higher windclass than the surrounding area. The general premise of windspeed and height is that the higher the elevation, the faster the wind is moving on average. As such, hilltops, crests, ridges, etc. can artificially "push" the windclass of a large surrounding area up one or two (in rare cases) classes. For example, on page 34, Figure 3.4 shows the percent of land area estimated to be Class 4 or higher. Looking at Massachusetts, one can see that 1 to 20 percent of the land area of western Massachusetts is estimated to be Class 4 or higher. But on the Wind Resource Database (Fig. 3.1), this entire area is shown as Class 4. Thus a small amount of land pushed up the windclass of a large surrounding area, and the windclass of this surrounding area must be dropped so that the actual hilltops, ridges, crests, etc. can be brought out using the higher resolution DEMs.

To actually deduce what is "hilly," the project team went to the Wind Energy Resource Atlas following advice from Dr. Brower. Looking at Fig. 3.1, it is evident that

mainland Massachusetts is divided into three large windclass regions: the western part of the state is Class 4, the Central part of the State is Class 3, and the Eastern part of the state is Class 2.

Now, the Wind Energy Resource Atlas also contains maps showing the percent of land area estimated to be in a specific windclass for a certain region. For example, the map in Figure 3.3 shows the percent of land area estimated to be Class 3 or higher.

Figure 3.3

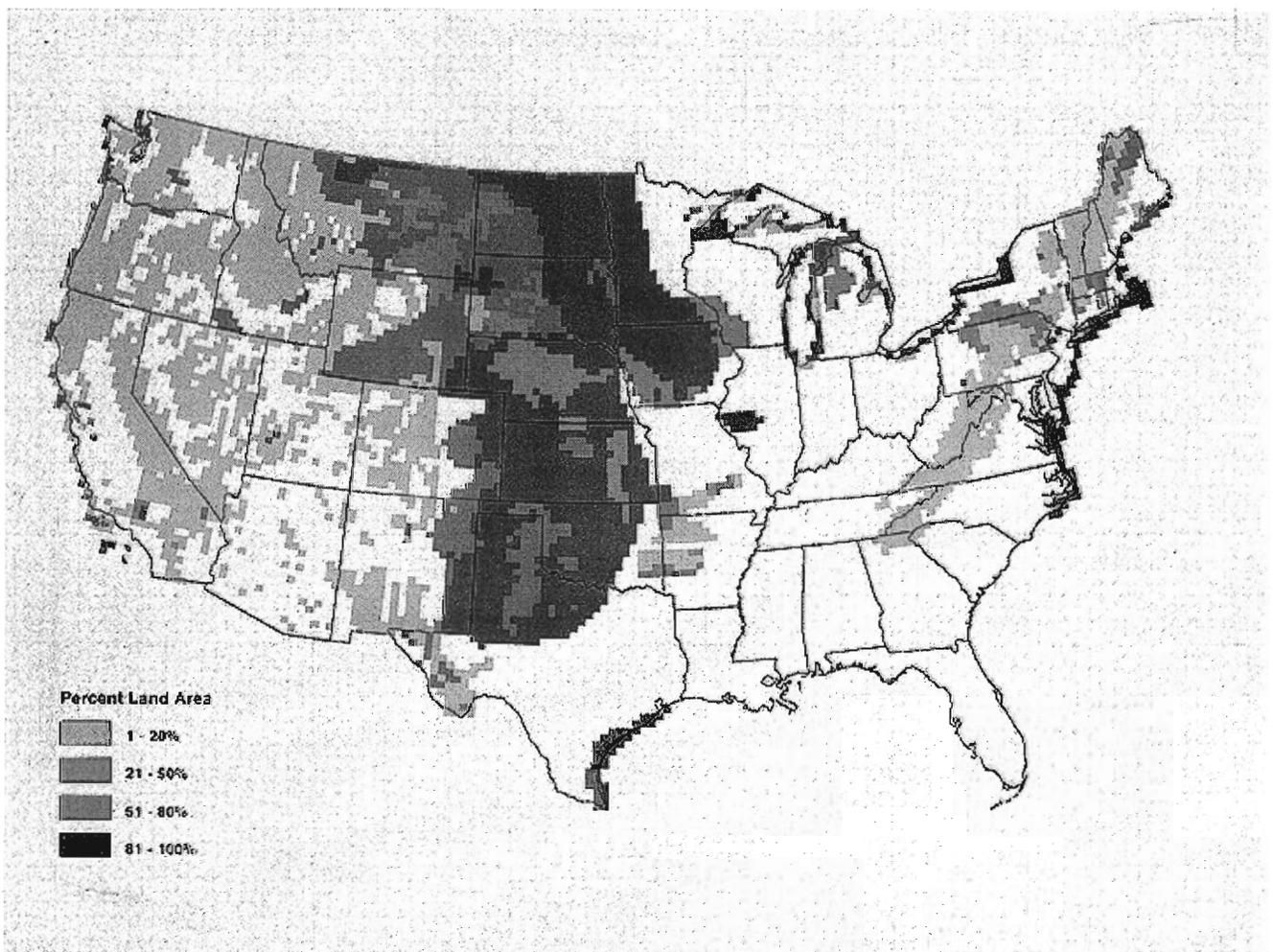
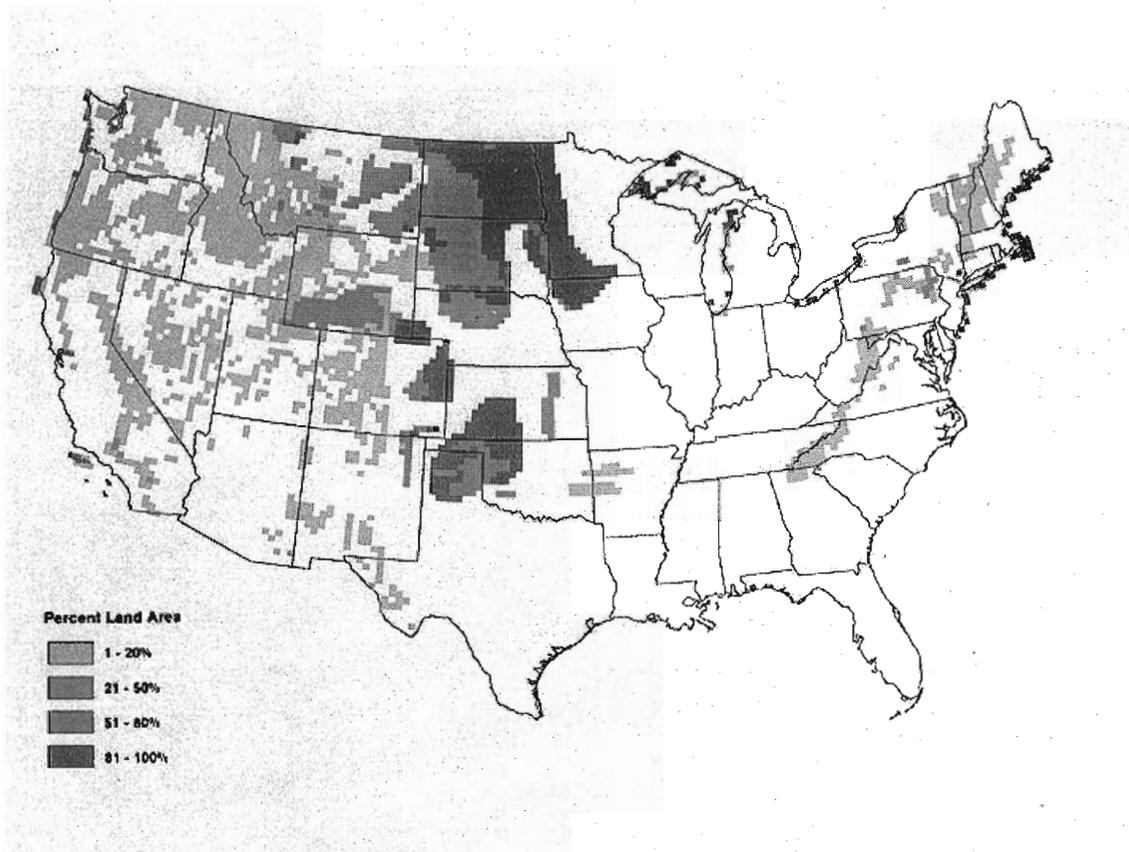


Figure 3.3 shows that 21-50 percent of Central Massachusetts is Class 3. Next, consider Fig. 3.4, which shows the percent of land area estimated to be Class 4 or higher.

Figure 3.4



This map shows that none of Central Massachusetts is Class 4. Therefore, all of the 21-50 percent of Central Massachusetts that is Class 3 or higher (the dark green area in Central Massachusetts) actually contains no Class 4 areas, just Class 3. Now, less than half of the actual land of Central Massachusetts is responsible for the Class 3 designation of the entire area. Therefore, this wind class rating is associated with the hilly terrain, and it must be dropped to Class 2. Similarly, for Western Massachusetts, with Class 4 designation, the above map shows that only 1-20 percent of the land area in Western Massachusetts is actually Class 4. Thus Western Massachusetts must be dropped to Class 3. The end result of this analysis is that all original Class 4 areas in Massachusetts are dropped to Class 3 and all original Class 3 areas are dropped to Class 2.

The next normalization step is to account for land cover. This entails reducing all Class 4 and Class 3 sites to Class 2 in any forest region and reducing Class 4 areas to Class 3 where mixed woodland and cropland occurs [1]. This step dropped all remaining Class 4 and Class 3 areas to Class 2 because of an assumption made in the analysis, described later.

Once this normalization is complete, the next step is to account for the how the local terrain affects wind class. To do so one needs to employ the following formula:

$$\frac{P}{P_{ave}} = \frac{\ln\left(\frac{H_h + E}{z_o}\right)}{\ln\left(\frac{H_h}{z_o}\right)} \quad (1)$$

where P is the corrected power density (having units of Watts/m²) of the wind, P_{ave} is the average power density of the wind given on the normalized Wind Resource Database, H_h is the hub height of the wind turbine (50 meters), E is the exposure, and z_o is the roughness length, which numerically characterizes surface roughness. The roughness length can have the following values:

$z_o = 0.03\text{m}$ for cropland

0.10m for mixed woodland and cropland

0.80m for forest [2]

This formula shows how the exposure, hub height, land cover, average power density, and the correct power density are related, and can be utilized to adjust the Wind Resource Database so that it shows windclass on the same scale as the DEMs. On this scale, hills, crests, and ridges are distinguishable from the surrounding area, whereas in the Wind Resource Database, they are not.

The exposure is determined by whether a location is higher or lower than its surroundings. It is found by calculating the average elevation of all the cells within a 12 km radius of a given cell and then subtracting that average from the actual elevation of said cell. If a point has positive exposure, this indicates the point is exposed compared to its surroundings and negative exposure indicates that the point is sheltered by its surroundings. The above formula is not valid for areas with negative exposure; as such, a different formula must be used for these areas;

$$\frac{P}{P_{ave}} = \frac{\ln\left(\frac{H_h}{z_o}\right)}{\ln\left(\frac{H_h + E}{z_o}\right)} \quad (2)$$

The symbols here mean the same as above, except that in this formula “E” is the absolute value of the exposure (as this formula applies only to areas with negative exposure).

In extremely limited cases, this power correction algorithm will produce jumps of three or more wind classes for a region. Such a large jump is most likely incorrect, hence the maximum adjustment allowed is two wind classes, or 155 percent of the original power density [2]. Performing this calculation on the entire Massachusetts area of the Wind Resource Database yields a much more accurate windmap.

2. Obtaining the Data and Resources

With the basic theoretical process in place, the entire operation can be described in detail. The first step was to collect all of the necessary resources. The Union of Concerned Scientists loaned the project team IDRISI for Windows, v1.0, the main GIS software. The project team installed IDRISI on Eleuthera, a 300 MHz PC with 32 MB

RAM and a 3 GB hard drive, located in Olin Hall, Room 125. A large amount of work was done using IDRISI v1.0, but the project team opted to upgrade to IDRISI v2.010 midway through the second term of the project. The upgrade came with several new features, such as the user-defined filter and sixty days of Technical Support help. IDRISI v2.010 was installed on both Eleuthera and Abaco, which has identical specifications to Eleuthera and is also in Olin Hall, Room 125. The remainder of the work done was performed on IDRISI v2.010. The project team also utilized MapInfo v3.05, which was obtained from Dr. Paul Mathisen of the Civil Engineering Department here at WPI. MapInfo was needed to deal with the LULC files. The project team needed to obtain an extension to MapInfo called "Arclink." This Mapbasic Program was written specifically for importing and exporting between MapInfo and ArcInfo formats. The project team also had to modify the ArcLink program because it lacked certain necessary projection files (see Appendix A.1).

The final piece of computer software the project team utilized was the Iomega Zip Drive purchased by the Physics Department to back up the extremely large files utilized in this project.

Next, the project team obtained the necessary files for the analysis. The Digital Elevation Model files were the first to be obtained. These files show the elevation of the land, using a raster image format, and they can be found at the United States Geological Survey Geodata webpage, <http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html>. The project team chose to use the 1:250,000 Scale Digital Elevation Models because the geographic scope of this project is much smaller than that of "Powering the Midwest," which used data with 1 km X 1 km spatial resolution. Also, the DEM file format is

supported by IDRISI, while the Spatial Data Transfer Standard (SDTS) format is not. The 1:250,000 scale DEMs are raster images with each cell having dimensions of 3 X 3 seconds. This corresponds roughly to a 100 X 100 m square. The total area covered by each DEM is one-half of a quadrangle; a quadrangle is a rectangle 2° longitude by 1° latitude that is bordered by integer lines of latitude and longitude. The project team chose to “FTP via State.” This allows the user to select the state he or she wishes, and all DEMs that contain a piece of that state are shown. For Massachusetts, there are eight DEMs: Albany east, Albany west, Boston east, Boston west, Providence east, Providence west, Chatham west, and Hartford east. Downloading was a simple matter. It is interesting to note that only three of the DEMs (Albany east, Boston east, and Boston west) were usable in IDRISI v1.0. Version 2.0, however, was able to open all eight of the files with no trouble.

The next files the project team obtained were the Land Use Land Cover (LULC) files from the EPA. These files can be found at the EPA ftp site, <ftp://www.epa.gov/pub/EPAGIRAS/egiras/>. The four files that were downloaded were `lal42072.e00.gz`, `lbo42070.e00.gz`, `lha41072.e00.gz`, and `lpr41070.e00.gz`, corresponding to Albany, Boston, Hartford, and Providence quadrangles. The project team used WinZip to uncompress these files. Since these files are in .gz format the user has to take special care to make sure the “TAR File Smart CR/LF Conversion” option is turned off. These files were originally created by the USGS in the early 1970’s. The files span entire quadrangles, unlike the half-quadrangle DEMs. The EPA recently updated these LULC files using ArcInfo, another GIS program. As such, the project team needed MapInfo and

the ArcLink extension to open the LULC files and also to export them in MIF (MapInfo Interchange Format) format, which IDRISI supports. Also, the files are in vector form because ArcInfo is a vector-based GIS program. This requires further manipulation in IDRISI, to be described later.

The final file the project team needed was the “Wind Resource Database,” the starting point of the entire analysis. Tracking this file down was rather difficult. An image of the file is on the National Wind Technology Center (NWTC) website, <http://www.nrel.gov/wind/usmaps.html>, but this is just a picture. After making numerous calls to the NWTC and the Pacific Northwest National Laboratories, the project team found George Scott of the Wind Resource Assessment Group at the National Renewable Energy Laboratory, who e-mailed the “Wind Resource Database” file to the project team. As mentioned, this file is a gridded file with 174 columns and 100 rows, with each cell representing a $1/3^\circ$ longitude by $1/4^\circ$ latitude area. Each cell contains one numerical value, which is the average annual windclass of the area represented by the cell. The upper-left cell of the file is at 125° W and 49.5° N, and the lower-right cell of the file is at 67° W and 24.5° N. The upper-left cell of the Massachusetts area is at 74° W and 43° N, and the lower-right cell of the Massachusetts area is at 70° W and 41° N.

3. Preparing the Data for Analysis

Once the project team had the files in hand, the next logical step was to open them and carry out the necessary manipulations to make them usable. For the DEMs, the project team utilized IDRISI’s import/export utility. GIS files exist in a plethora of

formats, ranging from standard government formats such as DEM and CTG, to BMP image files and DXF vector files. The import/export utility is the module in IDRISI that translates all of these different formats into IDRISI image or vector files and exports IDRISI files into the various formats. The project team used the import/export utility to translate the DEM files into IDRISI image files. As the import/export utility is translating the DEM file, it also creates the necessary documentation file that has the essential data, such as projection, minimum and maximum coordinates, etc. about the image file. Once all eight DEMs had been imported, the project team employed the concat module in IDRISI to create one image of the entire Massachusetts area from the individual DEMs (see Appendix A.2 for importation and concatenation details). The concat module is a general utility for pasting images together. This module can use the spatial information contained in the image documentation files to deduce how the images are to be concatenated. When the concatenation process is done, IDRISI displays the concatenated image, shown below in Figure 3.5.

Figure 3.5

The next step in preparing the data is to prepare the LULC files. The project team could not, despite its best efforts, make the LULC files functional. So, in the actual calculation, a constant z_0 value of .8 was assumed. The following is a description of the process used in trying to make the LULC files useable.

The first step is Arlink in MapInfo. Arlink is a utility comparable to IDRISI's import/export utility, except that Arlink was created strictly for translating between ArcInfo and MapInfo. All of the LULC files were run through Arlink, which makes them useable in MapInfo (see Appendix A.3 for description of how to use Arlink).

Once the files are useable in MapInfo, they must be exported in MapInfo Interchange Format (MIF), which IDRISI can import (see Appendix A.4, Section One for description of how to export in MapInfo). With the files exported in MIF format, the next step is to import the files, again employing IDRISI's import/export utility. The utility translates the files from MIF format to IDRISI vector file format. When the utility finishes translation, the file will be displayed and the user can see that the vector image is actually rotated approximately ten degrees counterclockwise (see Appendix A.4, Section Two for a description of how to use the import/export module for LULC files). To correct this, the project team employed the project module in IDRISI. This module changes the projection of images. For example, if an image is in Universal Transverse Mercator projection, the project module can convert it to a latlong projection. The project team used the project module to change the LULC files from Albers Conical Equal-Area to latlong and, in the reprojection process, the vector images were rotated back to the normal position (see Appendix A.5 for a description of the project module).

The next step is to rasterize these corrected LULC files. Rasterize means convert them from a vector format to a raster format. The first step in rasterization is to create an image (or raster) file to “update”. This image file must have the same dimensions, projection, etc. as the vector file because the information in the vector file will be written directly onto the image file. IDRISI’s initial module is designed to create new image files. Creating a new image file is a simple procedure and, once accomplished, rasterization of the LULC vector files can be undertaken. This can be accomplished using IDRISI’s polyras module, which is designed to convert polygon vector files to raster image files. Polyras does this by considering a point in the vector file and looking at the cell in the blank image file most nearly centered at that same point and copying the information corresponding to the point in the vector file to the z-value of the cell in the raster file. Polyras goes through this process for each point in the vector file, and the once blank image file is now the raster equivalent of the LULC vector file (See Appendix A.6 for a description of the rasterization process).

The rasterization makes one characteristic of the LULC files very obvious: each LULC file has a border of null information around the actual quadrangle. This black border around the image is completely useless, as it contains all “zero” information. This border must be removed from each LULC file. To do so, the project team employed the window module in IDRISI. This module can focus in on a specified part of an image file. The project team simply windowed in on the rasterized LULC images until all of the black border had been removed from each side (see Appendix A.7 for a description of how to use the window module).

Once the borders had been trimmed off of all three LULC files, the next step would be to concatenate them. Again, the concat module in IDRISI accomplishes this (see Appendix A.8 for instructions on how to concatenate LULC files).

The next step is to convert the LULC information from the format it is in (Anderson landuse codes) to z_0 values for the power correction calculation. This can be accomplished using IDRISI's reclass module. This module is designed to take the z-value of one location in an image and, according to user specification, assign a new z-value to that location. The reclass module creates a new image with all the specified changes rather than overwriting the original image. Unfortunately, the reclass module can only assign integer values, so when reclassing the LULC files, one would have to assign all areas that should have a z_0 value of .03 an actual value of 3, all areas that should have z_0 of .1 an actual value of 10, and all areas that should have a z_0 of .8 an actual value of 80. Then, the image that the reclass module produces would be multiplied by .01, using the image calculator, to obtain the correct z_0 values (see Appendix A.9 for a description of the Anderson landuse codes, the reclass module, and the correspondence between Anderson values and z_0 values).

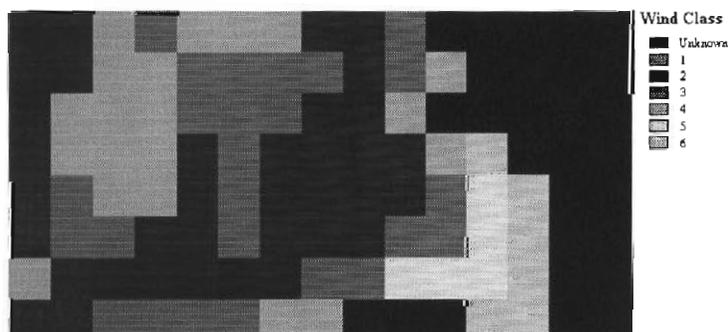
The LULC files were imported into MapInfo, exported out of MapInfo in .mif format, imported into IDRISI in vector format, and reprojected into latlong geographical referencing with success according to the procedure described above. The problem came when changing the files from vector to raster format, which is the requisite format for IDRISI. The project team could not make the proper z-value carry through the translation from the vector file to the raster file. The problem may have come from the double importation from ArcInfo export format (.e00) to MapInfo format (.mif) to IDRISI format

(.img) as opposed to a direct ArcInfo to IDRISI format change. The simplest way to correctly go from ArcInfo to IDRISI format requires a usable version of ArcInfo. The UNGEN command can be run on the ArcInfo export file using ArcInfo, which makes the files importable by IDRISI. The project team did not have an available copy of ArcInfo to use. The project team was then forced to use alternative means which did not work.

The Wind Resource Database was the last file to be entered into IDRISI. To accomplish this, the project team had to take the received file, which was in spreadsheet format, and convert it to an IDRISI image file format, which is simply one column of numbers. Also, every image file has a corresponding documentation file, as mentioned earlier. The project team created the documentation file for the Wind Resource Database file using the spatial parameters received from George Scott (see Appendix A.10 for a description of how to create an IDRISI image file and documentation file).

The next step was to select the area of the Wind Resource Database that corresponds to the Massachusetts area. The window module, described earlier (see Appendix A.11 for a description of the windowing process for the Wind Resource Database), accomplished this. Figure 3.6 shows the final, digitized Wind Resource Database for the Massachusetts area.

Figure 3.6



Looking at Fig. 3.6, one can easily forget that it represents Massachusetts. The map appears as such because it was derived directly from the Wind Resource Database (Fig. 3.1). This map shows the entire contiguous United States. When looking at such a large geographic area, this resolution appears normal. When a small piece of the map is considered however, the resolution of the cells is not sufficient so that one may distinguish a state's outline.

4. Carrying Out the Analysis

Before discussing how to do the actual calculations, it is necessary to describe the approximations made during calculation. First, the project team was not able to make the LULC files functional, as explained in the previous section. So a constant z_0 value of .8 was assumed. This is a reasonable approximation, because quite simply, most of Massachusetts is forest. Also, almost any area that would, by common sense, be a potentially good windsite is in undeveloped, forested territory. Further, the power correction formula is not heavily dependent upon z_0 . For example, assuming an exposure of 50m and $z_0 = .8$, the right hand side of the power correction equation is 1.1676. If we change z_0 to .1, the right hand side is 1.1115. Changing z_0 to .03 changes the right hand side to 1.0934. This is not a strong dependence.

Second, windclasses are ranges of wind velocity and the corresponding power density. For example, any site that has average windspeeds between 5.6 and 6.4 m/s is classified as a Class 2 windsite. The corresponding power range for these velocities is 200 to 300 W/m². IDRISI image files can have only one windpower density value associated with each cell, and thus a range cannot be used. The project team used the median of the endpoints of each windpower range as the windpower density on the

normalized Wind Resource Database. For example, the project team substituted the value 250 W/m² for all Class 2 windsites, 350 W/m² for all Class 3 windsites, etc.

Calculating the exposure is the first step in this analysis. The project team could have accomplished this on its own using the user-defined filter in IDRISI, but this module had a bug, rendering it useless for the size of calculation necessary. As such, the project team had to send the file to Clark Labs, where it was run through the user-defined filter of the unreleased IDRISI v3.0. Clark Labs sent back the calculated average image, shown in Figure 3.7 and the project team subtracted this from the original Massachusetts Area DEM, yielding the exposure, shown in Figure 3.8 (see appendix A.12 for a complete description of calculation of exposure).

Figure 3.7

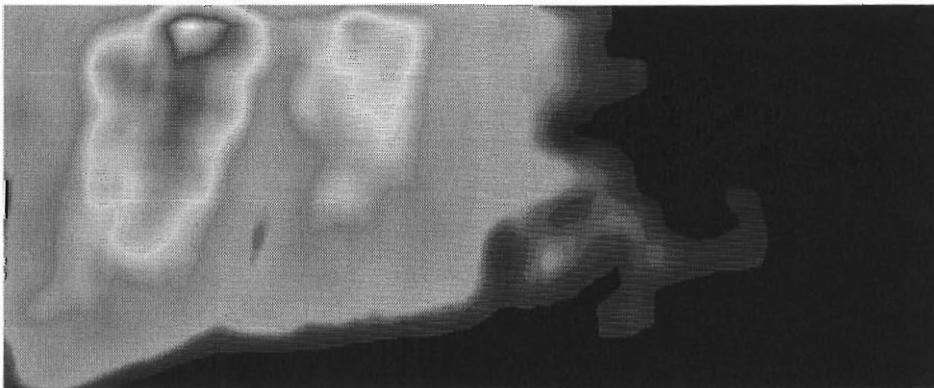
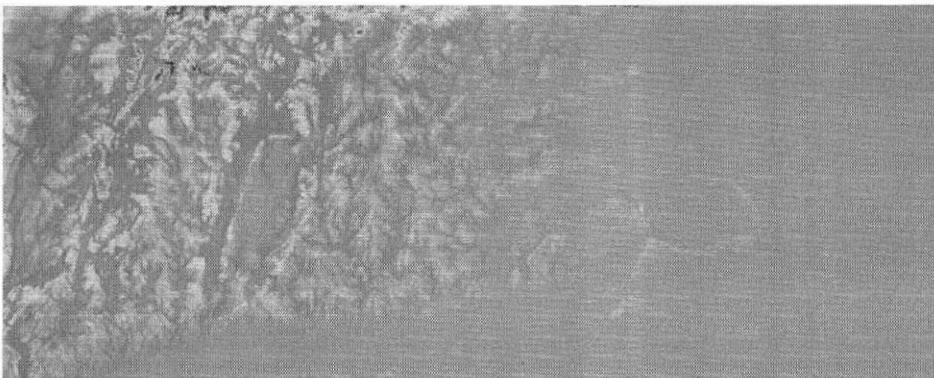


Figure 3.8



The next step in the analysis is to isolate the areas of positive exposure from the areas of negative exposure, as these areas have different power correction formulas. Once the areas of positive and negative exposure have been separated, it is possible to calculate the right hand side of equations (1) and (2). See Appendix A.13 for a complete description of how to isolate areas of positive and negative exposure and how to perform the calculation mentioned above.

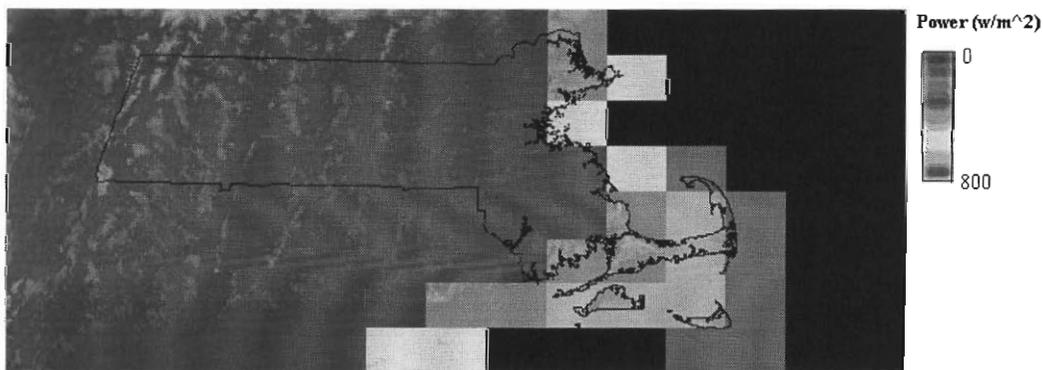
With this calculation accomplished, P_{ave} was needed next. It was obtained by taking the Massachusetts area of the normalized Wind Resource Database and using the reclass module on it to set all of the windclass numbers (i.e. 1-7) to their corresponding windpower density values. The project team used the median of the endpoints of each range of windpower densities. The reclass is in the following table. The resulting image was simply called “AA.”

Table 3.1

<u>Windclass</u>	<u>Windpower Density on Map ($\frac{watts}{m^2}$)</u>
1	150
2	250
3	350
4	450
5	550
6	700
7	800

Having “AA” allows the project team to obtain the corrected power densities for both areas of positive and negative exposure. Obtaining the full Massachusetts area windmap from here is a simple matter, and the last remaining step is to check whether any areas had undergone a jump of more than 155 percent of their original value. This did not occur. See Appendix A.14 to learn how to obtain the corrected power densities for the areas of positive and negative exposure, how to construct the full Massachusetts area windpower density map, and how to accomplish the 155 percent check. The Massachusetts area windmap is shown in Figure 3.9. Again, keep in mind the explanation given for the Wind Resource Database's "blocky" appearance. It still applies here.

Figure 3.9



To put windpower densities back into windclasses, the project team employed the RECLASS module (see Appendix A.15 to learn how to reclass windpower into windclass). Figure 3.10 is the windclass map for the Massachusetts area.

Figure 3.10



References

- (1) Brower, M., Tennis, M., Denzler, E., Kaplan, M., *Powering The Midwest*, (Cambridge, Massachusetts: Union of Concerned Scientists, 1993), p. 18
- (2) Brower, M., Tennis, M., Denzler, E., Kaplan, M., *Powering The Midwest*, (Cambridge, Massachusetts: Union of Concerned Scientists, 1993), p. 20

IV. Economic Analysis of Results

Having completed the above described procedures it is now useful to look into the economics of windpower. Using the wind class maps obtained in chapter III, and an associated cost for each wind class, an economic map of Massachusetts can be produced. This chapter will include an economic analysis of different wind classes in Massachusetts. The economics of wind power in Massachusetts will be compared with current methods of US Windpower electricity generation. Using the output power results obtained from IDRISI, and applying this to the US Windpower USW 33M-VS wind turbine a cost per kWh is obtained and compared to current electricity generation prices. The methods of analysis will be discussed here and the project team's conclusions will be presented in Chapter V.

General Theory

The economics of a wind farm depend on two main factors: expenses and revenue. Included in expenses is initial cost and maintenance costs. The revenue is generated by selling electricity at a rate per kWh. To find out how much electricity is produced in kWh the annual average output is calculated. It is important to keep in mind while doing economic calculations that an amount of money in hand today is not worth the same amount of money in the future. Money in hand today can be invested in stocks, bonds, etc. and interest will be earned off of it. To account for "time value of money" there are different economic entities such as net present value, internal rate of return, modified internal rate of return, etc. which are explained below. The final economic step explained

is the annual cost in dollars per kWh to see how much it will cost to generate electricity through a wind farm, depending on wind class.

Annual Average Output

The annual average output, the starting point for the economic evaluation, is the amount of electricity produced in kWh for a wind turbine in one year. The annual average output for a wind turbine is calculated using the following equation.

$$O = P \times CF \times A \times 8760 \frac{\text{hours}}{\text{year}} \times \frac{1\text{kW}}{1000\text{W}}$$

O = Annual Average Output.

P = Maximum Wind Power Density ($\frac{\text{watts}}{\text{m}^2}$).

CF = Capacity Factor.

A = Area swept by the rotor blades (m^2).

The annual average output will vary significantly depending on the wind class of the area in which a turbine is located. The annual average output, along with other calculations, can be seen for each wind class for the US Windpower 33M-VS model wind turbine in appendix A.16.

Table 4.1

<u>Wind Class</u>	<u>Annual Average Output (kWh)</u>
2	417702
3	786704
4	1237372
5	1743111
6	2548920

Initial Cost

The initial cost for a single wind turbine is found using a unit cost per kW for the US Windpower USW 33M-VS wind turbine. The unit cost per kW is \$942/kW which takes into account the price of the wind turbine, substation, transmission, service center, land, and indirect/permitting costs [1]. The US Windpower USW 33M-VS wind turbine is rated at 400 kW yielding the following initial cost [2].

$$IC = UP \times PR = 942 \frac{\$}{kW} \times 400kW = \$376,800$$

IC = Initial Cost.

UP = Unit Price.

PR = Power Rating.

Annual Revenue

The annual revenue is the annual amount of money that comes back from an investment. It is found for any year by multiplying the annual average output of electricity by the average generation costs of that electricity, assumed to be \$ 0.0369 in 1996 interpolated off of Table A.1 from the article *Competitive Electricity Prices: An Update* [3]. This figure of \$0.0369 specifically represents the average cost of generation for the industrial sector in the northeastern United States. Each year the price of electricity will change due to inflation and this is taken into account in the equation found below. The electricity inflation rate was found by subtracting the electricity deflation rate in real dollars (one percent) [4] from the regular inflation rate (three percent) [5]. The electricity deflation rate is explained in the Annual Energy Outlook on page 52. On page 52 it states the average price of electricity in real dollars "...is projected to decline by 1.0

percent a year as a result of competition among electricity suppliers.” Doing the simple calculation described above gives an overall electricity inflation rate of two percent.

$$AR = O(PC(1 + EI)^n)$$

AR = Annual Revenue.

O = Annual Average Output

PC = Price Charged in 1996 Dollars

EI = Electricity Inflation Rate

Maintenance Costs

The maintenance cost is the cost associated with the upkeep and maintenance of a wind turbine. The maintenance is calculated by multiplying a unit cost found to be \$0.008 per kWh in Powering the Midwest [6] by the annual average output. Again, inflation is taken into account in the following equation with an assumed inflation rate of 3 percent [4].

$$MC = O\left(\frac{\$0.008}{kWh}\right)(1 + IF)^n$$

MC = Maintenance cost.

O = Annual average output.

IF = Inflation Rate

n = Number of years.

Cost of Capital

The cost of capital in a life cycle cost study “is both the interest rate that must be paid in order to acquire funds (including equity) and the rate that could have been earned if these funds were invested externally” [7]. The cost of capital is dependent on the following:

$$k = k_D(1 - T)\left(\frac{D}{D + S}\right) + k_{SP}\left(\frac{S}{D + S}\right)$$

k = cost of capital

k_D = interest rate paid on the firm's debt

T = the firm's marginal tax rate-federal and state combined

D = the market value of the firm's debt

S = the market value of the firm's stock

k_{SP} = the return required on the stockholder's equity invested in the project

$$k_{SP} = R_F + \beta_p\left(1 + \frac{D}{S}(1 - T)\right)(k_M - R_F)$$

R_F = the risk free rate (20 year T bond rate)

$(k_M - R_F)$ = the expected risk premium on the market

β_p = the project's beta coefficient if it were financed entirely with equity

The project team's advisor Dr. Douglas Woods suggested the following values: T-Bond rate of five, beta of one, D/S AT of 0.6, market risk premium of eight, and debt cost of eight, yielding a k value of 11.3 to be used in further calculations.

Net Present Value

The net present value (NPV) is calculated in order to determine if an investment is going to be profitable. The net present value is most important because of the 'time value of money'. The time value of money takes into account that a certain amount of money today will not be worth the same as that same amount in the future. The said amount in the future is worth less because if it were available now it could be invested in stocks, bonds, etc. and money could be made off of it. Therefore the future sum is equivalent to a smaller amount in hand right now. Finding the net present value requires finding the present value of each future cash flow by multiplying the net cash flow from each year by the Present Value Interest Factor (PVIF).

$$PVIF_{k,n} = \frac{1}{(1+k)^n}$$

k = The annual compound rate of interest or cost of capital to the investor.

n = The year.

This gives future cash flows in terms of present values. These figures are summed over an assumed 20-year life span for a wind turbine and finally the initial investment figure is subtracted from the cash flow to get the net present value. If this number is positive then the investment is deemed a good one. For this project different values of NPV, depending on wind class, were calculated and presented below, the details are found in the project team's economic calculations in Appendix A.17 [8].

Table 4.2

<u>Wind Class</u>	<u>Net Present Value</u>
2	\$-269,847.49
3	\$-175,364.79
4	\$-59,971.19
5	\$69,522.88
6	\$275,850.09

Internal Rate of Return

The Internal Rate of Return (IRR) is defined as the rate of interest which equates the present discounted value of the future net cash flows to an investment's initial cost or the investment's NPV to zero. The IRR is another way to determine if an investment will be profitable or not. If solving the equation below (through trial and error) yields an r value greater than the cost of capital, k, then the investment is profitable.

$$I = \frac{F_1}{(1+r)} + \frac{F_2}{(1+r)^2} + \dots + \frac{F_n}{(1+r)^n}$$

I = initial investment.

F_n = future cash flows.

Although IRR and NPV both tell if an investment is going to be profitable some people prefer IRR because it is only a function of the profitability of money invested where as the NPV is a function of the amount of money invested as well as profitability. For this project different values of IRR (depending on wind class) can be seen below, details located in the project team's economic calculations in appendices A.17 [9].

Table 4.3

<u>Wind Class</u>	<u>Internal Rate of Return</u>
2	Undefined (DIV/0)
3	3.60
4	8.90
5	13.90
6	20.99

Modified Internal Rate of Return

The modified internal rate of return (MIRR) is an excellent measure of an investment's rate of return. MIRR is an excellent measure because it assumes that future cash flows are reinvested at the cost of capital, k , rather than whatever the rate of return works out to be as is the case with IRR. Any large deviations between k and r will cause inaccurate IRR calculations. Any large deviations between k and r will not effect MIRR calculations. The MIRR calculation is essentially the same as the IRR calculation with k

substituted for r . The MIRR is calculated by finding the value for r^* which satisfies the following equation;

$$r^* = \left(\frac{[F_1(1+k)^{n-1} + F_2(1+k)^{n-2} + \dots + F_n]}{I} \right)^{\frac{1}{n}} - 1$$

IRR and MIRR can be thought of in the following context. IRR and MIRR are the annual compound interest rate which would be needed on the loan of equivalent sum of money to earn as much money as will be made from the chosen investment. For this project different values of MIRR, depending on wind class, can be seen in the project team's economic calculations in appendix A.17 [10].

Table 4.4

<u>Wind Class</u>	<u>Modified Internal Rate of Return</u>
2	4.51
3	7.87
4	10.34
5	12.25
6	14.40

Annual Worth

The annual cash worth is “the uniform annual cash flow whose total present value over the life of the investment is equal to the net present value” [11]. Annual worth can be thought of as the excess return of money taking into account the time value of money. For this project different values of annual worth, depending on wind class, can be seen in

the project team's economic calculations in appendix A.17. The equation for annual worth reduces to the following [11].

$$AW = \frac{NPV}{PVIFA_{k,n}}$$

AW = Annual worth.

NPV = Net present value.

$$PVIFA_{k,n} = \frac{1 - (1 + k)^{-n}}{k}$$

Annual Cost

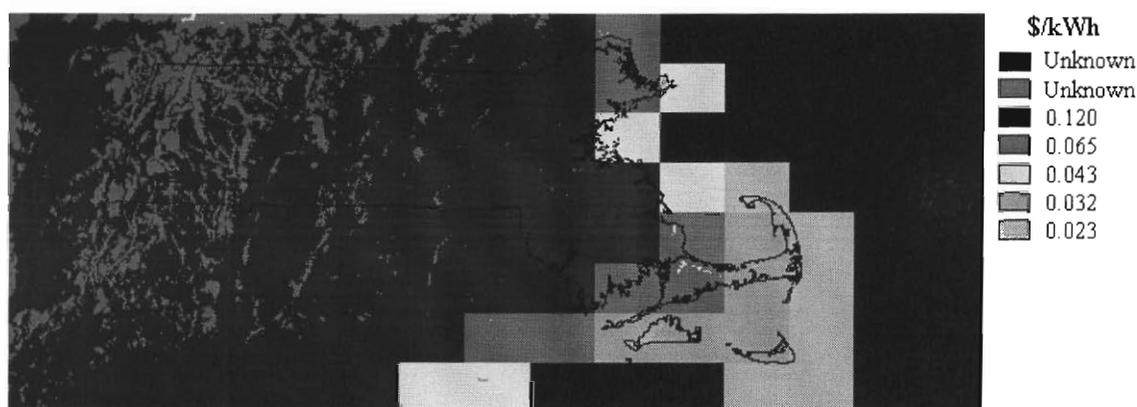
To find a final figure for the cost of electricity the average annual revenue of the wind turbine must be subtracted from the annual worth of the wind turbine to get total annual cost, and this quantity must be divided by the annual average output of the wind turbine to get average annual cost per kWh. This calculation gives cost in dollars per kWh and can be converted to cents per kWh by simply dividing by 100. An economic map of Massachusetts can be seen below in figure 4.1 approximating the cost of wind energy per kWh in cents depending on location. For different locations there are different wind classes and economic figures were calculated for wind classes two through six. Figure 4.1 was obtained by reclassing figure 3.10 into cents per kWh using table 4.5, also shown below.

Table 4.5

<u>Windclass</u>	<u>Economic cost in \$ per kWh</u>
1	-----
2	\$0.120
3	\$0.065

4	\$0.043
5	\$0.032
6	\$0.023

Figure 4.1



References

- (1) Brower, M., Tennis, M., Denzler, E., Kaplan, M., *Powering The Midwest*, (Cambridge, Massachusetts: Union of Concerned Scientists, 1993), p. 25
- (2) Brower, M., Tennis, M., Denzler, E., Kaplan, M., *Powering The Midwest*, (Cambridge, Massachusetts: Union of Concerned Scientists, 1993), p. 15
- (3) Beamon, J. Alan, *Competitive Electricity Prices: An Update*, <http://www.eia.doe.gov/oiaf/issues98/cep.html#rcep>
- (4) Energy Information Administration (1998) *Annual Energy Outlook 1998*, Washington, DC: Energy Information Administration, p. 52
- (5) Energy Information Administration (1998) *Annual Energy Outlook 1998*, Washington, DC: Energy Information Administration, Table A.20
- (6) Brower, M., Tennis, M., Denzler, E., Kaplan, M., *Powering The Midwest*, (Cambridge, Massachusetts: Union of Concerned Scientists, 1993), p. 26
- (7) Woods, Douglas W., 1998 *ISD Module: Quantitative Methods in Economics*, Interdisciplinary Studies Division, p. 19
- (8) Woods, Douglas W., 1998 *ISD Module: Quantitative Methods in Economics*, Interdisciplinary Studies Division, p. 7-8
- (9) Woods, Douglas W., 1998 *ISD Module: Quantitative Methods in Economics*, Interdisciplinary Studies Division, p. 9-10
- (10) Woods, Douglas W., 1998 *ISD Module: Quantitative Methods in Economics*, Interdisciplinary Studies Division, p. 12
- (11) Woods, Douglas W., 1998 *ISD Module: Quantitative Methods in Economics*, Interdisciplinary Studies Division, p. 9

V. Conclusions and Recommendations

Presently the United States is facing major energy problems in terms of declining reserves of fossil fuels, fluctuating prices of fossil fuels, and environmental destruction caused by fossil fuels. Alternative "clean" energy, specifically windpower, is a viable substitution for fossil fuels and should be greatly considered. In this report the project team has created wind energy potential maps of Massachusetts, along with economic wind energy maps of Massachusetts. Here the project team will summarize its findings, draw conclusions, and make recommendations for further study. This chapter will be divided up into two sections: conclusions and recommendations.

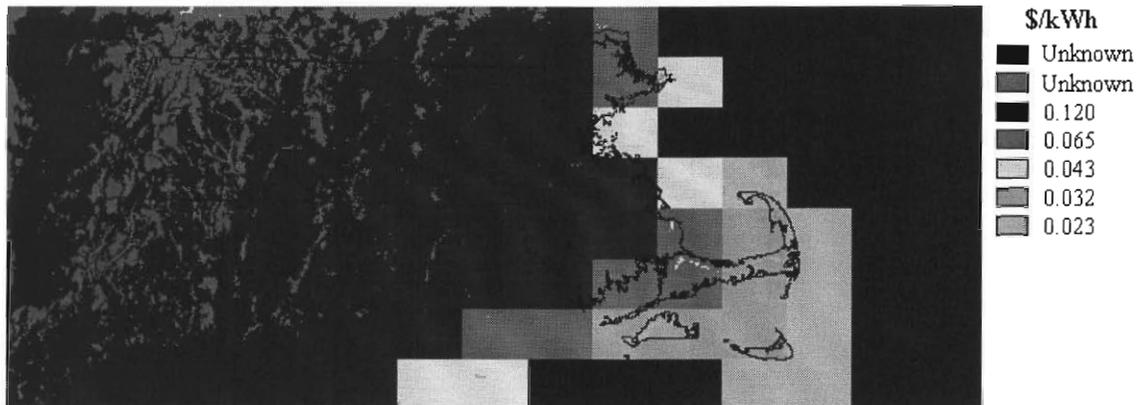
Conclusions

The primary results of the project team's wind power analysis of Massachusetts are the wind-power density and economic maps shown in figure 3.10 and figure 4.1 respectively, and the economic analysis of each wind class, the latter yielding the following cost in cents per kWh for each wind class seen in table 4.5. First we will discuss figures 3.10 and 4.1.

Figure 3.10



Figure 4.1



As can be seen in figure 3.10 and figure 4.1 a large quantity of Massachusetts lies between wind classes two and four. This includes most of Massachusetts except for the eastern border. Excluding the eastern border the majority of wind class is class two, followed by class three, with specks of class four. Among these three wind classes, the class four wind areas are the most important because they have the highest wind power density and hence yield a lower cost.

On the original Batelle Pacific Wind Maps there are areas of Massachusetts identified as areas containing class four winds but no real significance can be drawn from this. Areas identified as class four winds in this project can more safely be deemed suitable for wind site testing because of finer resolution maps, which help in correcting for elevation. On the original Batelle Pacific Wind Maps, seen in figure 3.6, each grid area covers a large amount of land area and hence has a poor resolution. On the map seen in figure 3.6 a large amount of land area corresponding to approximately an angular resolution of $1/3^\circ$ longitude by $1/4^\circ$ latitude (37 X 28 km) takes up each grid cell. Within this $1/3^\circ$ longitude by $1/4^\circ$ latitude grid cell there is no differentiation of wind class. Within each grid cell there can be large fluctuations between wind class, largely

depending on elevation, and these are taken into account in this project. Therefore, within these grids the project team can specifically say what different areas probably correspond to a class four wind and what areas do not. Therefore all of class four areas in Massachusetts, excluding the Eastern Boarder can safely be assumed to be actual class four wind sites and it is concluded that they could prove to be promising wind farm sites.

In the large section of Massachusetts excluding the eastern border some limitations have to be taken into account although they are not significant drawbacks. Because of the problems discussed in chapter three (section 3 & 4), the LULC (land use land cover) files were not utilized in the project team's analysis and a constant 'forest' land cover was chosen for Massachusetts. The primary options for land cover are forest, cropland, and mixed woodland/forest. A large percentage of Massachusetts is forest and therefore this assumption can be taken as a reasonable one. Another problem that needs to be taken into account is the following: in part of the procedure from Powering the Midwest, the land elevation is averaged over a 12 km radius circle (see Appendix A.12). The project team used the geometry of a 21.27 km X 21.27 km square because only a square averaging routine was available to the project team. Using this size square results in an area approximately the same as a 12 km radius circle. The error allotted in this type of assumption can be thought of in the following way: Imagine that you're standing in the Grand Canyon and the terrain around you has a constant elevation of 300 meters in the shape of a 21.27 km x 21.27 km square. However, just outside that square, the elevation drops immediately to zero km. The average height using the circle averaging method will be somewhere between 0 and 300 meters (closer to the 300 end) but with the project team's square averaging method, you'll find the average to be exactly 300 meters. There

are not many known areas in Massachusetts that exhibit this type of sharp elevation change. It is assumed that Massachusetts's elevation changes are fairly continuous. The project team therefore feels that its square averaging method will give results close to the circular averaging method for Massachusetts.

The Eastern border of Massachusetts, where the winds are stronger than the rest of the state are where the project team's conclusions are more ambiguous, because of the LULC files. The Project team's maps contain 'blocky' areas that can be seen on the Eastern border of Massachusetts (figure 3.10 & 4.1). The LULC files have a fine resolution of 1/1200 of a degree of latitude and longitude and would have helped in smoothing these blocky areas. These blocky areas resemble their original Batelle Pacific counterpart areas but have slightly more detail because of the finer resolution of the Digital Elevation Models. Within each block you can see where there are different levels of wind power and therefore you can use this to differentiate between more promising wind sites within the chosen block. The ambiguity arises mainly when looking at block borders. There are sharp differences in wind power on some adjacent blocks and the question is how to decide which half of the block is correct if you are say, standing with one foot on each block. No clear answer can be given for this. Depending on circumstances, such as land cover and elevation, educated guesses would have to be made for different areas of Massachusetts.

The eastern border of Massachusetts occupies a small land area percentage of Massachusetts, and also the popular tourist location 'the Cape'. Therefore there is a good chance that wind farms may never be located on the eastern border of Massachusetts because of simple land area probability, and environmental concerns, respectively. The

issues expressed above concerning the area of Massachusetts excluding the Eastern Border (unutilized LULC files and circle/square averaging method), also apply to the eastern border of Massachusetts. Barring the above it would have to be said that the Eastern border of Massachusetts looks like the most promising area for possible wind farms with wind classes ranging mainly from three to six. Because of inherent environmental problems it may be harder to implement wind farms on the eastern border of Massachusetts although this study is outside of the scope of this report.

Overall any class four or higher wind areas seen on the above maps should be explored further to see if possible wind farms could be built there, if economically feasible. Further testing would include intensive wind speed monitoring and evaluation. In the Annual Energy Review 1997, Table 8.13, the retail price of electricity sold by electric utilities to the industrial sector for 1996 in real dollars is \$0.042 per kWh [1]. The project team's economic analysis calculated class four winds to cost slightly above this figure, \$0.043 per kWh, for the industrial sector in 1996 real dollars. Class five and class six winds yielded even lower costs for the industrial sector in 1996 real dollars, \$0.032 per kWh and \$0.023 per kWh, respectively. Improvements are constantly being made to wind turbines, which further reduce the cost of wind energy. The effect of the rapid change in wind energy technology on energy prices is illustrated by the UCS report from just four years ago that concluded that wind turbines could produce electricity for around five cents per kWh. [2]. With class four, five, and six winds costing approximately the same or lower than current methods of electricity production, coupled with the many problems of fossil fuel electricity generation, the project team feels strongly that wind power should be explored further in Massachusetts.

It is finally concluded that another project team should continue our project team's work, incorporating our project team's recommendations. Also our project team's maps should be utilized as starting points for wind siting evaluations in Massachusetts.

Recommendations

The main recommendation for a new and updated project would be to fix the few problems that the project team ran into during our project. The first problem the project team encountered was that the LULC files could not correctly rasterize in IDRISI. The second problem was that a circular area averaging routine was not found in IDRISI. General recommendations follow after the project team's project recommendations.

The first recommendation would be to try and obtain a copy of ArcInfo so as to be able to correctly import the LULC files into IDRISI. Using the UNGEN command in ArcInfo, this can be accomplished. If another method was found that could import the .e00 format LULC files into IDRISI, this would be acceptable. The route taken to get the files into IDRISI does not matter if the end product is the same. The LULC files would then be implemented into the project team's procedure as described in the procedure chapter.

The second recommendation would be to fix the averaging method used to average the elevations over a 12 kilometer radius circle. Outlined in the project team's procedure is a method of averaging using squares which is similar to circular averaging. It is not known to the project team how to do a circular averaging routine on IDRISI. Perhaps a team with considerably more programming experience could find a method. There is a new version of IDRISI coming out, version 3, that may contain a circular

averaging routine. Any intuitive methods may be thought of for circular averaging on IDRISI, using the different modules, although there were no apparent methods for this that the project team could figure out in the time allotted for the project.

As far as more general recommendations, it is first recommended that new project team's take some sort of course on IDRISI, ArcInfo, MapInfo or whatever software they choose to use. Although the project team did not take any type of training or courses, and still learned IDRISI independently of this, it would have helped greatly and saved a lot of time to have taken some sort of training. If courses or training are not available it is recommended to fully go through the tutorial included with IDRISI.

For determining economic analysis it is recommended that one use a GIS program (as opposed to just spreadsheets) in order to include a variable in the economic analysis that takes into account the distance of transmission lines from proposed wind farms. This distance can turn out to be a large amount of the initial costs if the distance is far enough and new transmission lines have to be installed. This was outside of the scope of this project because of allotted time.

If all of these recommendations were completed, an even better picture of wind energy in Massachusetts can be obtained.

References

- (1) Energy Information Administration (1998) *Annual Energy Review 1997*, (Washington, DC: Energy Information Administration, 1998), p. 233
- (2) Cole, N., Skerrett, P.J., (1995) *Renewables Are Ready: People Creating Renewable Energy Solutions*, White River Junction, Vermont: Chelsea Green Publishing Company, p. 1

Appendix A.1

The project team had to modify the ArcLink program because it lacked the necessary Albers Equal Area Conical projection files for the Land Use Land Cover Files.

The following text was entered via wordpad in Windows95 to the Mapinfow.prj file located in the C:\Mapinfo directory.

"--- North American Coordinate Systems ---"

"Albers Equal-Area Conic (North America)", 9, 62, 7, -96, 23, 20, 60, 0, 0

"Albers Equal-Area Conic (Continental US)", 9, 62, 7, -96, 23, 29.5, 45.5, 0, 0

"Albers Equal-Area Conic (Alaska)", 9, 63, 7, -154, 50, 55, 65, 0, 0

"Albers Equal-Area Conic (Hawaii)", 9, 62, 7, -157, 3, 8, 18, 0, 0

"Equidistant Conic (North America)", 6, 62, 7, -96, 23, 20, 60, 0, 0

"Equidistant Conic (Continental US)", 6, 62, 7, -96, 23, 29.5, 45.5, 0, 0

"Lambert Conformal Conic (North America)", 3, 62, 7, -96, 23, 20, 60, 0, 0

"Lambert Conformal Conic (Continental US)", 3, 62, 7, -96, 23, 33, 45, 0, 0

This text was added to the very end of the Mapinfow.prj file with one line of blank space between the text that was already there and this new text to be added. With the modified Mapinfow.prj file the project team could proceed on to use MapInfo as needed.

Appendix A.2

For the DEMs, the project team utilized the import/export utility in IDRISI (File → import/export). Within this utility is a module named DEMIDRIS, which is specifically for importing U.S. government DEM files. In the import/export utility window, one chooses import → Government/Agency Data Formats → DEMIDRIS. This opens a window for file input where the input file is specified, as well as the name of the output file. To start the importing, simply click “OK.” Once IDRISI finishes importing the file, it will launch the image file so the user may see immediate results. This process was used on all eight DEMs. Next, the DEMs had to be put together so as to form one image of the entire area of Massachusetts. This was accomplished using IDRISI’s “CONCAT” module. The user chooses Reformat → CONCAT. The CONCAT module gives two placement options: manual placement by row and column and automatic placement using file reference coordinates. In the case of the DEMs, the latter option could be used because the files contained self-consistent spatial referencing. With this option selected, the user must then choose from two concatenation types: the first image is opaquely covered by the other images and the first image transparently covers the other images. The project team chose the former image because the DEM’s perimeter latitude and longitude lines are repeated in each DEM causing an overlapping of one column/row of data in each direction. With these options set, the project team specified which images to concatenate. Clicking on the “OK” button starts the concatenation process.

Appendix A.3

The first step in opening the LULC files is Arclink. The project team imported the LULC files into MapInfo using the aforementioned modifications to Arclink. In MapInfo, the user chooses file → run mapbasic program. Here, the user specifies Arclink (which has a “.mbx” extension) and clicks “OK.” The program is run, and another pulldown menu titled “Arclink” appears on the menu bar. Next, the user chooses Arclink → “ArcInfo → MapInfo.” This opens a window in which the user specifies the working directory and the file to be imported. Once a file is selected (the file must be in the ArcInfo export format, which has an “.e00” extension), the option “Save and Set Output” becomes active, and the user clicks on this. This brings up another window in which to specify the output file name, the file type (the project team used MapInfo Native format), the method of Allocation of Tabular Data (the project team used Allocate to One), and the method of Complex Polygon Partitioning (convert to split polylines was used). The Projection File is the final option available, and this is where the code added by the project team is utilized. The correct projection is **category** : North American Coordinate Systems; **category members**: Albers Equal-Area Conic (North America). Once all of these choices are specified, the user clicks “OK” and is returned to the original window. The program is ready to translate the file, so the user simply clicks “Translate” and the translation process begins. MapInfo/Arclink creates numerous files associated with the single ArcInfo file.

Appendix A.4

Section One

Once the translation process is complete, the user must launch the image (or table in MapInfo terminology). To do so, the user chooses file → open table. With the directory set to whatever working directory was used during the translating process, the user is presented with numerous tables to display. The only table significant to this project's purposes is the one with name ending in "p.tab". This file has all of the Land Use Land Cover information and is a vector image. The user chooses the "p.tab" file and opens it. With the file now open, exportation is possible. This is necessary to make the file importable by IDRISI. Also, the user will note that the image is "rotated" counter-clockwise approximately 15 degrees. This will be fixed in IDRISI. To export, follow the path Table → Export. This brings up the Export window, where the user chooses the file to export, as well as the format. The MapInfo Interchange format is used (".mif" extension), as IDRISI can import this file format. With the format and file specified, the user clicks "OK" and the exportation process begins. Once MapInfo has exported the file, the project team went to IDRISI to import the file.

Section Two

In IDRISI, the import/export utility is opened (File → Import/Export) and the path Import → Software – Specific Formats → MIFIDRIS is taken. This brings up a window in which the user is presented with several options. For the type of conversion, use "MIF to IDRISI" (bringing a MIF file into IDRISI). Specify the file to import, and the name of

the output vector file. For the output reference system, choose “albersus,” which is short for Albers Equal-Area Conic Projection for the United States. This is the projection the files are in, so the output file should be in the same form. The output reference units should be degrees, and the output unit distance should be set to one. Choose all of the different features under “Features to be processed.” With all of these options set, the user clicks “OK” to begin the importation. Once the importation is complete, IDRISI will launch the vector file.

Appendix A.5

To correct the rotation of the LULC files, the project team employed IDRISI's PROJECT module, with path Reformat → Project. This calls up a window with numerous options. The first option is to choose between a raster and vector file. We chose vector file, as the LULC files are vector files. The user should leave the background value set to zero. The resampling type should be set to nearest-neighbor because nearest-neighbor resampling considers the z-value of a cell in the original image and assigns that z-value to the cell in the new image with the same position (or the cell closest to the same position) as the cell in the original image. Bilinear uses an average over several surrounding cells in the original image to deduce the z-value for a cell in the new image. Next the user specifies the input file and its corresponding projection file (albersus). Finally, the output file name is specified and the projection that the user wants the original file to be converted to is chosen. The project team chose latlong. All of the files used were in latlong format or projected to latlong. To start the projecting process, click "OK." When IDRISI finishes projecting the file, it launches the file and the image is no longer rotated.

Appendix A.6

To rasterize the vector file, the user must first create an image file to “update” in the rasterization process. This is accomplished by using the INITIAL module, which has the path Data Entry → INITIAL. To create a new image (raster) file, one needs spatial parameters to give to the new image file. Since rasterizing converts a vector file to an image file, the image file should have the same spatial parameters as the vector file. To find out which characteristics the vector file has, use the IDRISI “Describe” module by following File → Describe. Choose vector file as the file type, and highlight the name of the vector file to be rasterized. The characteristics of the file will be in the right side of the window. With these characteristics, the user can now finish initializing a new image file. In the Initial window, choose to “define spatial parameters individually.” Next, input a name for the image file, select the corresponding output data and file types (should be the same as the vector file being updated), choose an initial value of zero, and input a title if desired (titles aren’t necessary). To continue, click “continue.” This brings up another window in which the user may input the characteristics of the file. For rows and columns, this image file should contain the same number of rows and one less than the number of columns as TWO contiguous DEMs as the image file will be spanning a whole quadrangle while the DEMs span half a quadrangle. The 1:250,000 DEMs have 1201 columns and rows, so the image file should be 1201 X 2401. The one column is lost because during concatenation of the DEMs, the two adjacent edge columns of the DEMs to be concatenated are laid on top of each other (i.e. column 1201 of the DEM on the left is laid over column 1 of the DEM on the right, or vice versa). With the number of rows and

columns entered, the user can proceed to enter the minimum and maximum X and Y coordinates, taken from the vector file to be rasterized. Set the reference system to latlong, the reference units to degrees, and the unit distance to one. Value units are not necessary to input. To begin initialization, click “OK.” Once initialization is complete, IDRISI launches the new image file, which should simply be a black rectangle.

Now, with a “blank” image file, the user may rasterize the vector file. To rasterize, the project team used the POLYRAS module, which has path Reformat → Raster / Vector Conversion → POLYRAS. This brings up the POLYRAS window, which has two text fields. Enter in the name of the input vector file to be rasterized and the name of the image file to be updated, and click “OK.” This starts the rasterization process. Once IDRISI finishes rasterizing, it will launch the new rasterized version of the LULC file.

Appendix A.7

After rasterization, the LULC file has a large section of blank space on each side of the actual image. This is because in the vector file, if a region is not enclosed by a polygon, it has no information. So the borders on the image in vector form are assigned zero z-value when rasterized. These must be trimmed off so that the rasterized LULC files may be concatenated. To do so, the project team used IDRISI's Window module, which has the path Reformat → WINDOW. This shows the WINDOW window, which has numerous options. First, the user should choose "Window only one image." Then, the name of the LULC file to be altered is entered, as well as the desired name of the output image. The project team chose "Row and column positions" for the "Window specified by:" option. There is no header, so header size is set to zero. Finally, the project team entered in an "upper-left column" value slightly greater than zero (the first column) and a "lower-right column" value slightly smaller than the number of the last column in the image and clicked "OK." (Note that rows are not taken off as there is no black border around the top and bottom of the image). This windowed in on the image, but didn't cut off all of the black space. So the window module was used again, with an "upper-left column" value slightly larger than the previous and a "lower-right column" value slightly smaller than the previous. This process was repeated just until the last columns of zero z-value were removed.

Appendix A.8

When all LULC files have been rasterized and had the black borders removed, they may be concatenated using the CONCAT module, previously described. In this instance however, the option “Manual placement by row and column” must be chosen. Choose Albany as the main reference image, give the output file a name, and choose three as the number of paste images. The user then clicks “Continue.” This moves to another window where the placement options are specified. The order that the paste files are input is inconsequential; correct row and column matching with the input file is what’s important. The Boston quadrangle is immediately to the east of the Albany quadrangle, so the “upper-left” corner of Boston must go to the first row and last column of Albany. Similarly, the Hartford quadrangle is immediately south of the Albany quadrangle, so the “upper-left” corner of the Hartford quadrangle must go to the last row and first column of Albany. Finally, the Providence quadrangle is southeast of the Albany quadrangle, so the “upper-left” corner of the Providence quadrangle must go to the last row and last column of Albany. Once the user specifies the information for the first paste file, the right arrow must be clicked to specify the information for the next paste file, and so on. When all three paste files have been specified, the user clicks “OK” to begin the concatenation process. Again, IDRISI will launch the new image once it has finished concatenation.

Appendix A.9

The final step in preparation of the LULC files was reclassification. Land is generally classified according to the Anderson Classification System (http://www.epa.gov/nsdi/projects/giras.htm#Identification_Information), which uses two digit numbers, ranging from one to ninety-two, to represent land use/land cover types. The first digit of the number (the tens place in decimal notation) signifies a broad classification of land, which has numerous divisions. The second digit in the Anderson Classification System represents the specific type of the broad classification represented by the first digit. Following is a list of the land use / land cover type associated with each number.

1	Urban or built-up land
11	Residential
12	Commercial and services
13	Industrial
14	Transportation, communication, utilities
15	Industrial and commercial complexes
16	Mixed urban or built-up land
17	Other urban or built-up land
2	Agricultural land
21	Cropland and pasture
22	Orchards, groves, vineyards, nurseries, and ornamental horticultural
23	Confined feeding operations

24	Other agricultural land
3	Rangeland
31	Herbaceous rangeland
32	Shrub and brush rangeland
33	Mixed rangeland
4	Forest land
41	Deciduous forest land
42	Evergreen forest land
43	Mixed forest land
5	Water
51	Streams and canals
52	Lakes
53	Reservoirs
54	Bays and estuaries
6	Wetland
61	Forested wetland
62	Nonforested wetland
7	Barren land
71	Dry salt flats
72	Beaches
73	Sandy areas not beaches
74	Bare exposed rock
75	Strip mines, quarries, gravel pits

76	Transitional areas
8	Tundra
81	Shrub and brush tundra
82	Herbaceous tundra
83	Bare ground
84	Wet tundra
85	Mixed tundra
9	Perennial snow or ice
91	Perennial snowfields
92	Glaciers

These are the values that actually appear as the z-value on the LULC files. Obviously the LULC files are where the parameter z_0 is deduced from, but the Anderson LULC codes do not conform to the above convention for z_0 . So the project team would use the Reclass module in IDRISI to create a new raster image with z_0 values, deduced from the Anderson Classifications. The reclassification would go as follows;

<u>Anderson Code Range (inclusive)</u>	<u>Equivalent z_0 Value</u>
11 – 17	0
21 – 24	.03
31	.03
32 – 33	.1
41 – 43	.8
51 – 54	0

61	.8
62	.03
71 – 76	.03
81 – 85	not applicable to New England
91 – 92	not applicable to New England

The Reclass module has path Analysis → Database Query → RECLASS. This calls up the RECLASS window. The first option is “Type of file to reclass,” and Image is the requisite type. The next option is “Classification type:”, and the user should choose “User-defined reclass.” Next, input the name of the LULC file for Massachusetts, and the desired name of the output image. Title and value units are unimportant, and may be skipped. Now the user must enter in the Anderson values, and the corresponding z_0 values, multiplied by 100 to make them all integer values. This is done by entering the z_0 value into the field “Assign a new value of:” and the range of Anderson values into the fields “To all values from:” and “To just less than:”. For example, if the user considers the Anderson range 11 – 17, the correct input would be

Assign a new value of: 0

To all values from: 11

To just under: 12

When this first data set is entered, the right arrow on the right side of the window is clicked to advance to an empty data set, where the next Anderson range and corresponding z_0 value is entered. Twelve must be used as the “To just under:” value so

as to include eleven. This is also true of the endpoints of all other intervals. For a range with only one Anderson value (e.g. 31), the proper input would be

Assign a new value of: 3

To all values from: 31

To just under: 32

When all data sets have been entered, the “OK” button starts the reclassification process. IDRISI will launch the new, reclassified file, call it “LULC.” This file must be multiplied by .01 to obtain the correct z_0 values. This can be accomplished using the image calculator, which has path Analysis → Mathematical Operators → Image Calculator. The expression to enter into the image calculator would be

[LULC] * .01

The resulting image would have the correct z_0 classification for Massachusetts.

Appendix A.10

To enter the Wind Resource Database into IDRISI, the project team noted that the general form of an IDRISI image file when opened in a text editor is one column of numbers going down the page on the left hand side. The documentation file that IDRISI creates for every image file has information such as the number of rows and columns the image file is supposed to contain. When IDRISI attempts to open an image file, it looks to the corresponding documentation file for the number of columns the image is supposed to have, call the number “C”. Then IDRISI takes the first C numbers going down the page of the image file and makes the first row of the image out of those C numbers, takes the next C numbers and makes row two of the image, etc. The Wind Resource Database came in a spreadsheet format. The project team opened the file in Word 97 and chose the Replace utility, which has path Edit → Replace. This brings up the “Find and Replace” window. The project team clicked on “More → Special” to show more options, and selected **find what: white space ; replace with: manual line break**. This replaces all tabs, spaces, etc. with a manual line break and hence puts the Wind Resource Database file into the requisite “one column” image file format. With this result saved, the project team then went to the directory that the file was saved in and changed the extension to “.img”, as all IDRISI image files have this extension. Next the project team had to go into IDRISI and use the Document module (path File → Document) to create a documentation file for the Wind Resource Database. The user selects image file and inputs the name that the altered Wind Resource Database file is stored under and clicks “OK.” This calls up the Document window, where there are a number of different characteristics to enter. The

project team entered in all of the known data about the Wind Resource Database file (Pos'n error, Resolution, Value error, value units, flag value and flag definition are unimportant). With the documentation file created, the image file is now ready to be displayed and used.

Appendix A.11

To obtain just the Massachusetts area of the Wind Resource Database, the project team employed the WINDOW module in IDRISI. The website <http://edcwww.cr.usgs.gov/bin/maptest/coords=55.000000+-130.000000+20.000000+-65.000000/scale=250/type=lulc/zoom=4?495,149> shows the latitude and longitude borders of the Albany, Boston, Hartford, and Providence quadrangles, which comprise the Massachusetts area. The rectangle created by these quadrangles has its upper-left corner at the coordinates 43°N and 74°W and its lower-right corner at 41°N and 70°W. Now, knowing the coordinates of the upper-left corner of the Wind Resource Database and the degrees latitude and longitude represented by each column and row, it is a simple matter to calculate the exact rows and columns of the Wind Resource Database that correspond to the Massachusetts area. They are rows 26 through 33 and columns 153 through 164, inclusive. Knowing this, the user may now activate the WINDOW module, described earlier. This calls up the familiar window. Choose option “Window only one image.” Next, the input image and name of the output image are specified. Now the user must choose how to specify the Window. The project team used rows and columns as mentioned, so Row/Column positions is again the correct choice. There is no header, so header size should be set to zero. Finally, the rows and columns must be entered; the upper-left column is 153 and the upper-left row is 26. The lower-right column is 164 and the lower-right row is 33. The user should click “OK” to begin the windowing process. IDRISI will launch the new, windowed image when it has finished. This image is the Massachusetts area of the Wind Resource Database.

Appendix A.12

The first step in carrying out the analysis was to calculate the exposure of the Massachusetts DEM. The project team could have calculated the exposure using the user-defined filter, which has path Analysis → Context Operators → Filter, except for the fact that a bug existed in the user-defined filter code. So the project team was forced to send the Massachusetts DEM to the Clark Labs, where they ran the file through the user-defined filter in the unreleased IDRISI v3.0. Had the project team done user-defined filter, it would have used the following process. First, one must deduce how many cells on the DEM represents 12 km. This is done by noting that each cell in the DEM is 3 X 3 arc seconds (or seconds), which corresponds to 1/1200 of a degree of latitude or longitude. This can be converted into radians by multiplying by $\pi/180$. Then, with the radian measure of the sides of the cell, one simply multiplies by the radius of the earth (6.371×10^6 m) [3] to find the number of meters each side of a cell represents. This turns out to be about 92 meters. Now, the user-defined filter is a matrix, and hence it takes a square area on the DEM and calculates averages over that. But the actual specification for calculating exposure is a 12 km circular radius. So the project team made an approximation that the area of the square covered by the user-defined filter should be the same as the area of a circle with a 12 km radius. This amounts to solving the equation $r^2 = 144 * \pi$ for r , which is approximately equal to 21km. Dividing this by .092 (number of km a cell side represents) gives the dimension that the user-defined filter should have, which is 229. So the user-defined filter will be a 229x229 matrix, with every element a 1. The project team would have used a text editor such as Wordpad to create this large file.

The process is simple; the user has to enter in each element of the matrix and the columns are separated by a space and the rows fall on successive lines of the document. For example, a 2x2 filter would look as such:

1 1

1 1

The file, once created, is saved with a “.fil” extension. Now the filter is ready to be run. The user should follow the aforementioned path, which brings up the filter window. “User-defined (variable size kernel)” is the correct option. Choosing this creates an input field to the right, and this is where the name of the filter file should be entered. Then the name of the file to run the filter on and the name of the output image must be specified. Value units and title are not important and may be left blank. To start the filtering, the user should click “OK.” This will create an image where every cell has a value equal to the sum of all cells within a 12 km “radius” of the cell with the corresponding location in the input image. For example, if the filter is currently working on cell (3000, 2500), where 3000 is the row number and 2500 is the column number of the cell, the filter will sum the z-values of all cells within a 12 km “radius” of cell (3000, 2500), and cell (3000, 2500) in the output image will have a z-value equal to that sum. The filter does this for every cell in the input image. Once the filtering is complete, the project team would use the Image Calculator, path Analysis → Mathematical Operators → Image Calculator, to divide the filter output file by 229^2 to make the z-value the actual average. This path

opens the Image Calculator window, which looks something similar to a scientific calculator. To divide the filtered file by 229^2 , the user must first choose “Mathematical expression.” Then, an output file name must be specified. This output image will be referred to as “average” in the remainder of the section. After this, the user should put the cursor in the “Expression to process” field and click on “Insert Image.” This pops up a window that contains all the image files in the working directory. The user should highlight the name of the filtered file, and click “OK.” This places the name of the file in the “Expression to process” field, with square brackets around the name. These brackets are requisite for an image file. After the end bracket on the image file name, the “/” should be entered, indicating the division operation. After the “/”, the number 52441 should be entered (this is 229^2). The whole expression should look like this:

[Name of filtered file] / 52441

The user then clicks “Process expression” to begin the calculation. Once the filter output file has been divided by 229^2 , IDRISI will launch “average,” which will be the average of the elevation over a 12 km “radius.” Now, to obtain the exposure, the project team subtracts “average” from the original Massachusetts DEM. This is accomplished by employing the Image Calculator again. In this case, the user should specify “mathematical expression” as the operation type, “exposure” as the output file name, and enter the expression

[Name of Massachusetts DEM] – [average]

Into the “Expression to process” field. “OK” starts the calculation. IDRISI will launch the new image, which will be the exposure for Massachusetts.

Appendix A.13

To isolate the areas of positive and negative exposure, the project team used the reclass module twice on the exposure image; once to reclass all positive values to zero and all negative values to negative one (the reason for choosing negative one will be explained shortly) and once to reclass all positive values to one and all negative values to zero. The former image was called “allneg” and the latter was called “allpos.” Next, the project team multiplied the exposure by “allneg” using the image calculator, where the expression entered into the image calculator had the following form:

$$\text{[exposure]} * \text{[allneg]}$$

This produced an image that had all the areas of negative exposure set to their absolute value (multiplying the negative exposures by negative one yields positive exposure numbers) and all areas of positive exposure set to zero. This image was called “negprod.” Next, the exposure was multiplied by “allpos.”

$$\text{[exposure]} * \text{[allpos]}$$

This created an image, called “posprod,” which had all areas of positive exposure as their original value and all areas of negative exposure set to zero.

The next step in the calculation was to actually calculate the right side of the power correction equation for both “posprod” and “negprod.” For posprod,” the expression was as follows;

$$\ln(50 + \text{[posprod]}) / .8 / \ln(50/.8)$$

The resulting image was called “posquo.” For the areas of negative exposure, the expression was like this:

$$\ln(50/.8) / \ln(50 + \text{[posprod]}) / .8$$

The image resulting from this calculation was called “negquo.” Now, in “posquo” and “negquo,” all the areas that were zero in “posprod” and “negprod” were very nearly one (if the value of “posprod” or “negprod” was zero, the above expressions evaluate to one, within computer round-off error). To make these areas zero again, the project team multiplied “posquo” by “allpos,”

$$[\text{posquo}] * [\text{allpos}]$$

and “negquo” by “allneg” and negative one

$$[\text{negquo}] * [\text{allneg}] * -1$$

The resulting images were called “posmult” and “negmult,” respectively.

To recap briefly, “posmult” has as z-values the calculation of the right hand side of equation (1) for areas of positive exposure and zero for areas of negative exposure. Conversely, “negmult” has as z-values the calculation of the right hand side of equation (2) for areas of negative exposure and zero for areas of positive exposure.

Appendix A.14

To obtain the corrected power densities, the project team multiplied “AA” by “posmult” and “negmult,” which yielded the images “pospow” and “negpow,” respectively. The expressions were as follows

$$[AA] * [posmult]$$

$$[AA] * [negmult]$$

“Pospow” and “negpow” have the corrected power densities for the areas of positive exposure and negative exposure, respectively. To obtain the full power map for the Massachusetts area, “pospow” and “negpow” were added together (remember, in “pospow” all areas that had negative exposure are zero and in “negpow” all areas that had positive exposure are zero. As such, adding “negpow” to “pospow” fills in all of the zero values with the correct power density for those areas). The expression was as follows

$$[pospow] + [negpow]$$

The resulting image was named “temppow.”

Next, the project team determined whether or not any areas had undergone a jump of more than 155 percent of their original wind power density value. This was done by taking the original Massachusetts area of the Wind Resource Database, reclassing the windclasses to the corresponding windpower densities, and multiplying this image by 1.55. This image, called “155bat,” shows the maximum correction allowed for the Massachusetts area. To determine if any area had exceeded the maximum allowed adjustment, the project team subtracted “temppow” from “155bat”

$$[155bat] - [temppow]$$

The resulting image, called “differen,” shows the difference between the maximum allowed and actual windpower density adjustments. If “differen” had any negative values, that would mean the area with a negative value was adjusted to greater than 155 percent of its original value. “Differen” had no negative values, and thus no further corrections had to be made. Thus “Temppow” is the final windpower density map for Massachusetts.

Appendix A.15

The project team used the RECLASS module (path Analysis → Database Query → RECLASS) to put the calculated windpower densities for Massachusetts back into windclasses. The reclass ranges are taken from the definition of the seven windclasses.

<u>Windpower Density Range (W/m²)</u>	<u>Corresponding Windclass</u>
0 – 200	1
200 – 300	2
300 – 400	3
400 – 500	4
500 – 600	5
600 – 800	6
800 and above	7

One RECLASS statement would look as follows.

Assign a new value of: 1

To all values from: 0

To just under: 200

The project team entered this for each of the above ranges and clicked “OK.” The resulting image shows windclasses for the Massachusetts area.

Appendix A.16

Wind Class	Power Density	Capacity Factor	Swept Area (Rotor Blades)	Annual Average Output	Cost per kWh
-----	(w/m ²)	(%)	(m ²)	(kWh)	(\$/kWh)
2	250	22.3%	855	417702	\$0.120
3	350	30.0%	855	786704	\$0.065
4	450	36.7%	855	1237372	\$0.043
5	550	42.3%	855	1743111	\$0.032
6	700	48.6%	855	2548920	\$0.023

Appendix A.17

WIND CLASS 2 INVESTMENT CASH FLOW PATTERN

YEAR	INITIAL COST	ANNUAL REVENUE	MAINT. COST	NET SAVINGS
0	\$376,800.00			-\$376,800.00
1		\$15,731.70	\$3,441.87	\$12,289.83
2		\$16,046.33	\$3,545.12	\$12,501.21
3		\$16,367.26	\$3,651.48	\$12,715.78
4		\$16,694.61	\$3,761.02	\$12,933.59
5		\$17,028.50	\$3,873.85	\$13,154.65
6		\$17,369.07	\$3,990.07	\$13,379.00
7		\$17,716.45	\$4,109.77	\$13,606.68
8		\$18,070.78	\$4,233.06	\$13,837.72
9		\$18,432.19	\$4,360.05	\$14,072.14
10		\$18,800.84	\$4,490.85	\$14,309.98
11		\$19,176.85	\$4,625.58	\$14,551.27
12		\$19,560.39	\$4,764.35	\$14,796.04
13		\$19,951.60	\$4,907.28	\$15,044.32
14		\$20,350.63	\$5,054.50	\$15,296.14
15		\$20,757.64	\$5,206.13	\$15,551.51
16		\$21,172.80	\$5,362.31	\$15,810.48
17		\$21,596.25	\$5,523.18	\$16,073.07
18		\$22,028.18	\$5,688.88	\$16,339.30
19		\$22,468.74	\$5,859.55	\$16,609.19
20		\$22,918.12	\$6,035.33	\$16,882.78

COST OF CAPITAL(K) =(COST OF DEBT AT)*.5 + (REQ'D RTN ON STOCK)*.5
 REQ'D RTN ON STOCK =T-BOND RTE+BETA*(1+DEBT/STK AT)*MKT RISK PREM.
 T-BOND RTE =5.0 BETA = 1.0 D/S AT =1*.6 MKT RISK PREM = 8.0
 DEBT CST =8.0 K=(8.0 0*0.6)*.5+(5.0+1.0*(1+0.6)*8.0)*.5= 11.3

PRESENT VALUE OF NET SAVINGS:PV =@NPV(F80/100,F56..F75)= 106952.506

NET PRESENT VALUE OF PROJECT:NP V=PV-INIT COST(F82-B55)= -269847.494

INTERNAL RATE OF RETURN: IRR[@IRR(0.3,F55..F75)*100] = #DIV/0!

MODIFIED IRR: MIRR = [(PV*(1.113)^20/INIT COST)^(1/20)-1]*100
 = [(F82*(1.113)^20/B55)^(1/20)-1]*100
 = 4.507911285

LIFE CYCLE COST OF WIND SYSTEM = PV OF FUEL & MAINT. COST+INIT COST
 =@NPV(F80/100,D56..D75)+@NPV(F80/100,E56..E75)+B55
 = 409466.7568

LIFE CYCLE COST CURRENT ELECTRIC= PV OF ELECTRICITY COST
 = @NPV(F80/100,C56..C75)
 = 139619.2631

NPV WIND = LCC ELECTRICITY - LCC WIND
 = D98 -C94
 = -269847.4937

AVERAGE ANNUAL COST = LIFE CYCLE COST/PVIFA(k,n)
 = C94/(@PV(1,F80/100,20))
 = 52431.25025

AVERAGE ANNUAL REVENUE = LIFE CYCLE COST/PVIFA(k,n)
 = D98/(@PV(1,F80/100,20))
 = 17877.91658

WIND CLASS 3 INVESTMENT CASH FLOW PATTERN

YEAR	INITIAL COST	ANNUAL REVENUE	MAINTENANCE COST	NET SAVINGS
0	\$376,800.00			-\$376,800.00
1		\$29,629.21	\$6,482.44	\$23,146.77
2		\$30,221.79	\$6,676.91	\$23,544.88
3		\$30,826.23	\$6,877.22	\$23,949.01
4		\$31,442.76	\$7,083.54	\$24,359.22
5		\$32,071.61	\$7,296.04	\$24,775.57
6		\$32,713.04	\$7,514.92	\$25,198.12
7		\$33,367.30	\$7,740.37	\$25,626.93
8		\$34,034.65	\$7,972.58	\$26,062.07
9		\$34,715.34	\$8,211.76	\$26,503.58
10		\$35,409.65	\$8,458.11	\$26,951.54
11		\$36,117.84	\$8,711.85	\$27,405.99
12		\$36,840.20	\$8,973.21	\$27,866.99
13		\$37,577.00	\$9,242.41	\$28,334.60
14		\$38,328.54	\$9,519.68	\$28,808.86
15		\$39,095.11	\$9,805.27	\$29,289.84
16		\$39,877.02	\$10,099.43	\$29,777.59
17		\$40,674.56	\$10,402.41	\$30,272.15
18		\$41,488.05	\$10,714.48	\$30,773.57
19		\$42,317.81	\$11,035.92	\$31,281.89
20		\$43,164.16	\$11,366.99	\$31,797.17

COST OF CAPITAL(K) =(COST OF DEBT AT)*.5 + (REQ'D RTN ON STOCK)*.5
 REQ'D RTN ON STOCK =T-BOND RTE+BETA*(1+DEBT/STK AT)*MKT RISK PREM.
 T-BOND RTE =5.0 BETA = 1.0 D/S AT =1*.6 MKT RISK PREM = 8.0
 DEBT CST =8.0 K=(8.0 0*0.6)*.5+(5.0+1.0*(1+0.6)*8.0)*.5= 11.3

PRESENT VALUE OF NET SAVINGS:PV =@NPV(F80/100,F56..F75)= 201435.2136

NET PRESENT VALUE OF PROJECT:NPV =PV-INIT COST(F82-B55)= -175364.7864

INTERNAL RATE OF RET TURN: IRR[@IRR(0.3,F55..F75)*100] = 3.601931691

MODIFIED IRR: MIRR = [(PV*(1.113)^20/INIT COST)^(1/20)-1]*100
 = [(F82*(1.113)^20/B55)^(1/20)-1]*100
 = 7.868934597

LIFE CYCLE COST OF WIND SYSTEM = PV OF FUEL & MAINT. COST+INIT COST
 =@NPV(F80/100,D56..D75)+@NPV(F80/100,E56..E75)+B55
 = \$438,324.83

LIFE CYCLE COST-CURRENT ELECTRIC= PV OF ELECTRICITY COST
 = @NPV(F80/100,C56..C75)
 = \$262,960.05

NPV WIND = LCC ELECTRICITY - LCC WIND
 = D98 -C94
 = (\$175,364.79)

AVERAGE ANNUAL COST = LIFE CYCLE COST/PVIFA(k,n)
 = C94/(@PV(1,F80/100,20))
 = 56126.45874

AVERAGE ANNUAL REVENUE= LIFE CYCLE COST/PVIFA(k,n)
 = D98/(@PV(1,F80/100,20))
 = 33671.4124

WIND CLASS 4 INVESTMENT CASH FLOW PATTERN

YEAR	INITIAL COST	ANNUAL REVENUE	MAINTENANCE COST	NET SAVINGS
0	\$376,800.00			-\$376,800.00
1		\$46,602.52	\$10,195.95	\$36,406.57
2		\$47,534.57	\$10,501.83	\$37,032.74
3		\$48,485.26	\$10,816.88	\$37,668.37
4		\$49,454.96	\$11,141.39	\$38,313.57
5		\$50,444.06	\$11,475.63	\$38,968.43
6		\$51,452.94	\$11,819.90	\$39,633.04
7		\$52,482.00	\$12,174.50	\$40,307.51
8		\$53,531.64	\$12,539.73	\$40,991.91
9		\$54,602.27	\$12,915.92	\$41,686.35
10		\$55,694.32	\$13,303.40	\$42,390.92
11		\$56,808.21	\$13,702.50	\$43,105.70
12		\$57,944.37	\$14,113.58	\$43,830.79
13		\$59,103.26	\$14,536.99	\$44,566.27
14		\$60,285.32	\$14,973.09	\$45,312.23
15		\$61,491.03	\$15,422.29	\$46,068.74
16		\$62,720.85	\$15,884.96	\$46,835.89
17		\$63,975.27	\$16,361.51	\$47,613.76
18		\$65,254.77	\$16,852.35	\$48,402.42
19		\$66,559.87	\$17,357.92	\$49,201.95
20		\$67,891.07	\$17,878.66	\$50,012.41

COST OF CAPITAL(K) =(COST OF DEBT AT)*.5 + (REQ'D RTN ON STOCK)*.5
 REQ'D RTN ON STOCK =T-BOND RTE+BETA*(1+DEBT/STK AT)*MKT RISK PREM.
 T-BOND RTE =5.0 BETA = 1.0 D/S AT =1*.6 MKT RISK PREM = 8.0
 DEBT CST =8.0 K=(8.0 0*0.6)*.5+(5.0+1.0*(1+0.6)*8.0)*.5= 11.3

PRESENT VALUE OF NET SAVINGS:PV =@NPV(F80/100,F56..F75)= 316828.8146

NET PRESENT VALUE OF PROJECT:NPV =PV-INIT COST(F82-B55)= -59971.18541

INTERNAL RATE OF RET TURN: IRR[@IRR(0.3,F55..F75)*100] = 8.904091726

MODIFIED IRR: MIRR = [(PV*(1.113)^20/INIT COST)^(1/20)-1]*100
 = [(F82*(1.113)^20/B55)^(1/20)-1]*100
 = 10.33945976

LIFE CYCLE COST OF WIND SYSTEM = PV OF FUEL & MAINT. COST+INIT COST
 =@NPV(F80/100,D56..D75)+@NPV(F80/100,E56..E75)+B55
 = 473569.7737

LIFE CYCLE COST-CURRENT ELECTRIC= PV OF ELECTRICITY COST
 = @NPV(F80/100,C56..C75)
 = 413598.5883

NPV WIND = LCC ELECTRICITY - LCC WIND
 = D98 -C94
 = -59971.18541

AVERAGE ANNUAL COST = LIFE CYCLE COST/PVIFA(k,n)
 = C94/(@PV(1,F80/100,20))
 = 60639.49003

AVERAGE ANNUAL REVENUE = LIFE CYCLE COST/PVIFA(k,n)
 = D98/(@PV(1,F80/100,20))
 = 52960.3215

WIND CLASS 5 INVESTMENT CASH FLOW PATTERN

YEAR	INITIAL COST	ANNUAL REVENUE	MAINTENANCE COST	NET SAVINGS
0	\$376,800.00			-\$376,800.00
1		\$65,649.87	\$14,363.23	\$51,286.63
2		\$66,962.86	\$14,794.13	\$52,168.73
3		\$68,302.12	\$15,237.95	\$53,064.17
4		\$69,668.16	\$15,695.09	\$53,973.07
5		\$71,061.53	\$16,165.94	\$54,895.58
6		\$72,482.76	\$16,650.92	\$55,831.83
7		\$73,932.41	\$17,150.45	\$56,781.96
8		\$75,411.06	\$17,664.96	\$57,746.10
9		\$76,919.28	\$18,194.91	\$58,724.37
10		\$78,457.67	\$18,740.76	\$59,716.91
11		\$80,026.82	\$19,302.98	\$60,723.84
12		\$81,627.36	\$19,882.07	\$61,745.29
13		\$83,259.90	\$20,478.53	\$62,781.37
14		\$84,925.10	\$21,092.89	\$63,832.21
15		\$86,623.60	\$21,725.68	\$64,897.93
16		\$88,356.07	\$22,377.45	\$65,978.63
17		\$90,123.20	\$23,048.77	\$67,074.43
18		\$91,925.66	\$23,740.23	\$68,185.43
19		\$93,764.17	\$24,452.44	\$69,311.73
20		\$95,639.46	\$25,186.01	\$70,453.45

COST OF CAPITAL(K) =(COST OF DEBT AT)*.5 + (REQ'D RTN ON STOCK)*.5
 REQ'D RTN ON STOCK =T-BOND RTE+BETA*(1+DEBT/STK AT)*MKT RISK PREM.
 T-BOND RTE =5.0 BETA = 1.0 D/S AT =1*.6 MKT RISK PREM = 8.0
 DEBT CST =8.0 K=(8.0 0*0.6)*.5+(5.0+1.0*(1+0.6)*8.0)*.5= 11.3

PRESENT VALUE OF NET SAVINGS:PV =@NPV(F80/100,F56..F75)= 446322.8805

NET PRESENT VALUE OF PROJECT:NP V=PV-INIT COST(F82-B55)= 69522.8805

INTERNAL RATE OF RET TURN: IRR[@IRR(0.3,F55..F75)*100] = 13.90114678

MODIFIED R: MIRR = [(PV*(1.113)^20/INIT COST)^(1/20)-1]*100
 = [(F82*(1.113)^20/B55)^(1/20)-1]*100
 = 12.24631112

LIFE CYCLE COST OF WIND SYSTEM = PV OF FUEL & MAINT. COST+INIT COST
 =@NPV(F80/100,D56..D75)+@NPV(F80/100,E56..E75)+B55
 = \$513,121.45

PV OF ELECTRICITY COST
 = @NPV(F80/100,C56..C75)
 = \$582,644.33

NPV WIND = LCC ELECTRICITY - LCC WIND
 = D98 -C94
 = \$69,522.88

AVERAGE ANNUAL COST = LIFE CYCLE COST/PVIFA(k,n)
 = C94/(@PV(1,F80/100,20))
 = 65703.98898

AVERAGE ANNUAL REVENUE = LIFE CYCLE COST/PVIFA(k,n)
 = D98/(@PV(1,F80/100,20))
 = 74606.22948

WIND CLASS 6 INVESTMENT CASH FLOW PATTERN

YEAR	INITIAL COST	ANNUAL REVENUE	MAINTENANCE COST	NET SAVINGS
0	\$376,800.00			-\$376,800.00
1		\$95,998.64	\$21,003.10	\$74,995.54
2		\$97,918.62	\$21,633.19	\$76,285.42
3		\$99,876.99	\$22,282.19	\$77,594.80
4		\$101,874.53	\$22,950.65	\$78,923.87
5		\$103,912.02	\$23,639.17	\$80,272.84
6		\$105,990.26	\$24,348.35	\$81,641.91
7		\$108,110.06	\$25,078.80	\$83,031.26
8		\$110,272.26	\$25,831.16	\$84,441.10
9		\$112,477.71	\$26,606.10	\$85,871.61
10		\$114,727.26	\$27,404.28	\$87,322.98
11		\$117,021.81	\$28,226.41	\$88,795.40
12		\$119,362.25	\$29,073.20	\$90,289.04
13		\$121,749.49	\$29,945.40	\$91,804.09
14		\$124,184.48	\$30,843.76	\$93,340.72
15		\$126,668.17	\$31,769.07	\$94,899.10
16		\$129,201.53	\$32,722.14	\$96,479.39
17		\$131,785.56	\$33,703.81	\$98,081.75
18		\$134,421.28	\$34,714.92	\$99,706.35
19		\$137,109.70	\$35,756.37	\$101,353.33
20		\$139,851.89	\$36,829.06	\$103,022.83

COST OF CAPITAL(K) =(COST OF DEBT AT)*.5 + (REQ'D RTN ON STOCK)*.5
 REQ'D RTN ON STOCK =T-BOND RTE+BETA*(1+DEBT/STK AT)*MKT RISK PREM.
 T-BOND RTE =5.0 BETA = 1.0 D/S AT =1*.6 MKT RISK PREM = 8.0
 DEBT CST =8.0 K=(8.0 0*0.6)*.5+(5.0+1.0*(1+0.6)*8.0)*.5= 11.3

PRESENT VALUE OF NET SAVINGS:PV =@NPV(F80/100,F56..F75)= 652650.0922

NET PRESENT VALUE OF PROJECT:NPV V=PV-INIT COST(F82-B55)= 275850.0922

INTERNAL RATE OF RETURN: IRR[@IRR(0.3,F55..F75)*100] = 20.99087202

MODIFIED IRR: MIRR = [(PV*(1.113)^20/INIT COST)^(1/20)-1]*100
 = [(F82*(1.113)^20/B55)^(1/20)-1]*100
 = 14.39937185

LIFE CYCLE COST OF WIND SYSTEM = PV OF FUEL & MAINT. COST+INIT COST
 =@NPV(F80/100,D56..D75)+@NPV(F80/100,E56..E75)+B55
 = 576140.4603

LIFE CYCLE COST- CURRENT ELECTRIC= PV OF ELECTRICITY COST
 = @NPV(F80/100,C56..C75)
 = 851990.5525

NPV WIND = LCC ELECTRICITY - LCC WIND
 = D98 -C94
 = 275850.0922

AVERAGE ANNUAL COST= LIFE CYCLE COST/PVIFA(k,n)
 = C94/(@PV(1,F80/100,20))
 = 73773.42397

AVERAGE ANNUAL REVENUE= LIFE CYCLE COST/PVIFA(k,n)
 = D98/(@PV(1,F80/100,20))
 = 109095.3762

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