Renewable Energy Technologies: Analysis and Policy Tools for Utility Integration

by

Judith Bernitt Cardell

B. S., Electrical Engineering, Cornell University (1989)
A. B., Government, Cornell University (1989)

Submitted to the Department of Electrical Engineering and Computer
Science in Partial Fulfillment of the Requirements for the Degree of

Master of Science
in Technology and Policy

at the

Massachusetts Institute of Technology

February, 1994

Signature of Author ___
puter Science
uary 15, 1994

Certified by ___
Richard D. Tabors, Thesis Supervisor

Approved by ___
Rich
Technology and Policy Program

Approved by ___
F. R. Morgentha
ittee on Graduate Students

RENEWABLE ENERGY TECHNOLOGIES: ANALYSIS AND POLICY TOOLS FOR UTILITY INTEGRATION

by

Judith Bernitt Cardell

Submitted to the Department of Electrical Engineering and Computer Science on January 14th, 1994 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Technology and Policy

ABSTRACT

Non-dispatchable renewable energy technologies have beneficial environmental, financial and planning characteristics, yet are not readily included in electric utility sector planning for many reasons. This thesis addresses two factors contributing to the minimal use of non-dispatchable renewable energy technologies (RETs) in the electric utility sector: the lack of appropriate analysis tools for RETs, and the lack of familiarity with their behavior. The lack of publicly available renewable energy resource data is a third significant factor hindering analyses of RETs which is addressed in this thesis.

Renewable energy technologies can not be modeled or analyzed in the same manner as conventional power plants, thus an alternative methodology must be employed for determining their usefulness and overall effect on the power system, in terms of system reliability and environmental and economic impacts. A methodology was developed for this research, to be used in conjunction with a utility standard production-costing model, to both build the required resource databases, and to analyze this data in order to quantify the impacts of RETs on power system operation.

The methodology is demonstrated through a simulation and analysis of the impacts of 1500 MW_p of both wind power and photovoltaics as part of the New England electric power grid. The total energy generated by the installed RET capacity is one and one-half times the amount of energy conserved through the region's utility sponsored DSM programs. The analysis shows that these technologies have positive contributions in the form of system wide pollutant emissions reductions, decreased fossil fuel use, and a firm capacity value. The results further identify barriers to increased RET use in the electric utility sector, and policy options to overcome these barriers.

Thesis Supervisor: Dr. Richard D. Tabors

ACKNOWLEDGMENTS

The first round of thanks goes to my thesis advisor, Dr. Richard D. Tabors, for all the technical guidance and moral support he has given me throughout this endeavor.

I also give my thanks to all the people working with me in the Energy Lab – Steve, Nick, Jeff, Mort and Scott for endless help on the AGREA project, to Chris, my tireless editor, and to the people at the National Renewable Energy Lab and the New England utilities for technical support.

Deepest gratitude goes to my family for always letting me know that whatever I choose to do is great with them!

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

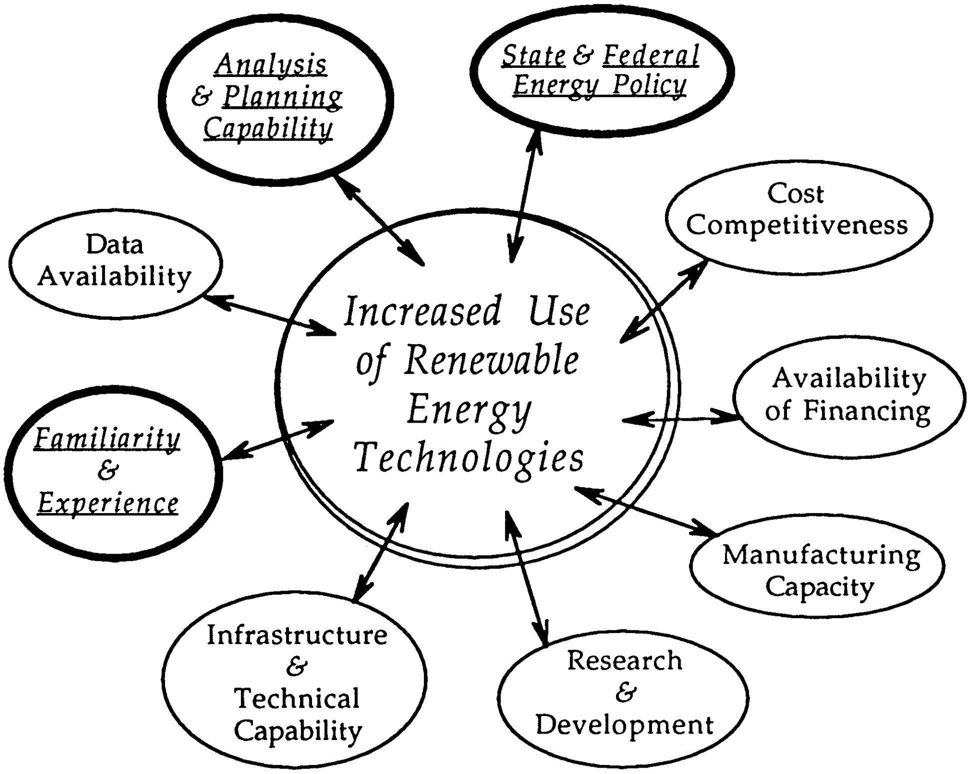
NON-DISPATCHABLE RENEWABLE ENERGY TECHNOLOGIES

The research presented in this thesis examines the potential impacts of electric power generation from wind turbines and photovoltaics on New England's electric utility grid. Such technologies have relatively benign environmental properties, beneficial financial and planning characteristics[1], and offer a long-range sustainable energy supply. Wind turbines and photovoltaics are both renewable energy technologies which differ from conventional thermal generators in that the resource used for generating electricity is inexhaustible, or renewable. In addition, they are termed "non-dispatchable" renewable energy technologies, due to the intermittent nature of their resources, which means they generate power only when the resource is available, and can not be "dispatched," or turned on at will by utility operators. This intermittent behavior has caused people to view these technologies as unreliable and made them difficult to include in standard analysis and planning procedures, thus discouraging their use. If this situation is to change, many factors must be addressed, particularly if renewable energy technologies are to be incorporated in significant amounts into electric utility grids. These factors are pictured below in figure 1.

---

[1] These properties are discussed in detail in chapter 3.

Figure 1: Avenues to Increased Use of Renewable Energy Technologies



Two major non-dispatchable renewable energy technologies are wind and solar power[2]. Some factors, shown in figure 1, such as manufacturing and product costs are currently larger barriers for photovoltaics[3] than wind power. Other issues, such as control systems, and possible impacts on grid stability from fluctuations in power generation (infrastructure and technical capability) concern wind power slightly more. The remaining factors are likely to impact all renewable energy technologies (RETs) equally. These include the availability and quality of renewable energy resource data, the availability of financing for these technologies perceived as risky, the ability to analyze RETs and their resources, and the general lack

---

[2] Solar power encompasses both solar thermal and photovoltaic technologies. Photovoltaic technology, which uses semiconductors to convert sunlight directly into electricity, is the solar technology analyzed in this thesis since it is better suited to the New England environment than solar thermal technologies. This is discussed further in chapter 3.

[3] See note 2 above.

of familiarity experience with RET performance. State and federal energy policies have the potential to impact all of these factors.

US ENERGY POLICY SINCE 1978

Common threads of federal energy policy are perhaps most easily found in what these policies have historically aimed to *avoid,* rather than in what they have aimed to achieve. These areas can be summarized as i) avoiding high real costs of energy to the domestic economy, ii) avoiding national insecurity from importing fuel, and iii) avoiding sudden real income shocks caused by volatile fuel prices (Schmalensee, 1980). The "energy crisis" of 1973 lead to a fear that the price of oil would continue to rise rapidly, with estimates that fuel prices could reach $100/bbl by 2000 (Nola, 1990). Reflecting the nation's fear of the economic impact of dependence on foreign energy supplies, the National Energy Act of 1978 aimed to enhance national (energy) security and encourage the development of cleaner, less environmentally damaging sources of energy. One component of this act, the Public Utility Regulatory Policies Act, or PURPA, had the four goals of i) reducing the national dependence on foreign oil by encouraging the development of renewable and alternative energy technologies, ii) stabilizing electricity costs through competition in power generation, iii) diversifying the supply mix of electric utilities, and iv) accelerating the commercialization and deployment pace of renewable and alternative energy technologies (Nola, 1990). As a concrete step toward these ends, PURPA guidelines[4] required electric utilities to buy power from small independent power producers and cogenerators at the "avoided cost," or the marginal cost of operating the generator the utility avoided bringing on line due to the renewable power generation[5]. In this manner, PURPA guaranteed a key requirement for increased RET use - a market for the power generated by the targeted renewable and alternative energy technologies.

---

[4] As established by FERC - the Federal Energy Regulatory Commission

[5] The producers had to meet FERC guidelines to be considered a "qualifying facility" which included < 80 MW capacity and < 25 % of this capacity from natural gas or oil.

The 1978 Energy Act also established financial incentives for the use of renewables. For residential solar systems there was an income tax credit, and for investment in renewable energy sources there was a 15 % federal tax credit. In addition to this federal tax credit, the state of California offered a 25 % tax credit for investment in wind turbine installations. The California Public Utility Commissioners added to the package by requiring utilities to offer renewable and alternate technology power producers standardized power purchase contracts based on the avoided cost principle from PURPA. By 1983 these "standard offers" were based on forecasts of escalating marginal fuel prices, with the power purchase rates for the first ten years of thirty year contracts tied to these forecasts. Thus the guaranteed market for the generated power established by PURPA, the federal and state tax credits, and the standard contracts spurred the rapid growth of wind turbine installations in California. Unfortunately, these solar and wind power financial incentives focused on capital investment rather than energy conversion efficiency, and came to serve more as tax shelters than as the means to developing improved technologies. Also, the justification for these incentives as short-term subsidies grew stale as extensions of the subsidies were sought, yet neither the escalation in oil prices nor the reduction of RET capital costs occurred to the extent forcasted.

Table 1: Federal Funding for Photovoltaics and Wind Power

Year	Photo-Voltaics	Wind Power
1981	155.0	83.7
1989	35.5	
1990	25.0	8.2
1993	64.0	22.0

(million 1981 $)

* Note: The 1993 values are budget requests and not appropriations.

Table 1 above shows the changing federal funding for photovoltaics and wind turbines since 1981. The federal level of funding for RETs is certainly improving, yet it pales when compared to that given to the well established energy technologies. The Reagan administration upheld the belief that renewable energy technologies should achieve commercial viability through free market interactions and not through government subsidies, even though this ideal was not imposed on conventional energy technologies. In 1984 the US energy industries received $44 billion in federal subsidies, with $41 billion going to the nuclear, oil, gas and other mature energy technologies. President Bush continued this trend by pushing for $2.5 billions in tax breaks for the oil and gas industries. Most recently, a government study in December 1992 found that direct appropriations for the nuclear industry were $890 million with an additional $3 billion in reduced insurance costs; coal received $1.1 billion; natural gas received $1.7 billion; $635 million went to conservation; and $847 million went to renewable energy technologies[6] (Wald, 1992).

Money for research, development and demonstration projects is one factor required for promoting the use of RETs, and as shown above, renewable energy has received a relatively small amount of funding. There must also be an understanding of the technologies and a willingness to use them however, before their use will increase, and this requires a base of raw resource data necessary for analysis. Unfortunately the federal government under Republican administrations, has revealed strong institutional biases against RETs. In the 1970's funding for and interest in renewable energy expanded. As a consequence of the Reagan-Bush emphasis on free market policies though, all components of RET research suffered, including the fundamental collection of raw data. The Department of Energy and the National Climatic Data Center do provide access to some data bases containing wind and solar resource data[7]. However, data collection for these data bases was allowed to lapse, and they were not maintained for many years, making the data difficult to use and obsolete in some cases[8].

---

[6] RETs here include hydro-electric, geothermal, biomass, hot dry rock, wind power, solar thermal and photovoltaics.

[7] The most well known of these data bases is the SOLMET data.

[8] Some SOLMET data is being 'reconstituted' by the federal government.

More important than the age of the data however, is the quality. The research for this thesis relied only on *publicly* available data[9]. Most weather data recorded by the government is collected at airports. For solar data this does not present a problem, since sunlight falling on one area is basically the same as sunlight in a nearby region. However, airports are typically located in non-windy sites, while wind turbines are best located in the windiest sites. Thus the wind speed measurements from airports can *not* be assumed to represent wind speeds on a nearby mountain ridge[10]. In addition to problems arising from location, all data sets used suffered from many missing data points rendering the data useless in some cases[11].

Data acquisition is one problem for RETs; perceptions remain a second problem. Two reports commissioned by Congress in 1991, by the Office of Technology Assessment and the National Academy of Sciences, both slight renewables. The analyses emphasize the use of cheap energy from nuclear plants, natural gas technologies and very aggressive conservation programs, while barely mentioning the potential of renewables. They ignore that nuclear energy is proving to be very expensive and that an increased demand for natural gas might easily force up its price (Rader, 1992). The Energy Information Administration, in developing a National Energy Modeling System, specifically discredits wind power generation by stating that "the output from a WECS[12] is *unpredictably* intermittent, ... [and] because of its intermittent nature, availability of wind capacity is not expected to replace other generating capacity."[13] (italics added) (EIA, 1992).

---

[9] SOLMET data was used for solar data. TD-3280 and 'Candidate Site' data from the National Climatic Data Center (in Asheville, NC) was used for the wind power analysis.

[10] See chapter 2 for a detailed discussion of adapting wind speed measurements from airports to possible wind turbine sites.

[11] For example, two of the three SOLMET data sets purchased for the research presented in this thesis were unusable. These two sets were missing two complete fields of data required for determining the electricity generation from photovoltaics. The data base of wind speeds for a Vermont site was also unusable due to most data points missing as a result of measurement instrument failure during winter storms. In other cases, data was so sparse that corresponding data, of up to one month from a different year, had to be 'patched' into the data stream. See chapter 2 for a detailed discussion of the resource data used in this thesis.

[12] WECS stands for Wind Energy Conversion System.

[13] This report was prepared by the 'Coal, Uranium and Renewable Fuels Analysis Branch' of the Energy Information Administration – having one branch analyzing coal, uranium *and* renewable fuels does invite a less than objective analysis of renewables!

Industry experience however refutes both of these suppositions, showing that wind resources are predictable, and that wind capacity can displace conventional capacity.[14]

Within this policy environment though, an interest in renewables remains in the public in general. A poll conducted by the Union of Concerned Scientists and the Alliance to Save Energy in December 1990 revealed that a majority of those polled (80 %) supported i) providing incentives to use alternate fuels, ii) re-establishing federal tax credits for RETs, iii) requiring regulators to provide incentives to utilities to make energy efficiency improvements in customers homes and buildings, and iv) offering tax rebates for cars with better than national standards for gas mileage. This poll also found that 70 % of those polled were opposed to i) developing oil reserves on publicly owned wilderness lands, ii) opening off-shore areas to drilling, and iii) increased use of coal (Narum, 1992)

INTEGRATED RESOURCE PLANNING

Integrated resource planning is a method for acquiring new generation resources which has the potential to encourage the use of renewable energy technologies. State regulators are moving away from allowing the planning of generation expansion to occur with no input from the public, instead requiring utilities to open the process up to competitive bidding[15]. Competitive bidding itself is biased against including renewable energy technologies, since it emphasizes economic efficiency, low capital costs, and relies on discount rates appropriate for conventional technologies. It ignores the benefits of renewables such as relatively benign environmental properties, insulation of risk from volatile fuel prices and potential benefits of distributed, modular generation. As a consequence of this recent trend in resource acquisition, only 17 % of new capacity from competitive bidding has been from RETs, where 40 % of new capacity was from RETs under PURPA and its "avoided cost" guidelines (Kozloff, 1992).

---

[14] These points are discussed in the bulk of this thesis, and are refuted by the results of the research presented here.

[15] Competitive bidding is the process in which a utility puts out a "request for proposals," or RFP, for x MW of net capacity, and accepts the lowest bid from competitors in the private sector.

Within the competitive bidding framework lies "least cost" or "integrated resource" planning, and it is this approach that encourages the use of renewables. The objective of integrated resource planning (IRP) is to meet future electricity demand by combining, among other things, the use of renewable energy technologies and conservation measures with the traditional path of expanding conventional fossil fuel capacity. To accomplish this goal, IRP opens resource acquisition to competitive bids, yet seeks to establish as criteria for selecting among the bids full social cost - which includes the benefits of environmental preservation, distributed generation and reduced financial risk - and thus brings RETs back into the competition. States in which RETs have recently won in the bidding process have used either IRP or included environmental externalities in the criteria for resource planning (Hamrin, 1992).

New England is one of the nation's leaders in demand side management programs, with well established procedures for including such programs in the region's electricity planning. Renewable energy technologies such as hydro-electric and biomass are also readily included in planning as they are dispatchable technologies, and can be included in existing electricity planning and analysis methodologies. However non-dispatchable renewable energy technologies (RETs)[16] are not readily included in integrated resource planning for two main reasons: the lack of familiarity in the utility sector with their behavior, and the lack of appropriate analysis tools. These two factors are highlighted in figure 1 above.

THESIS OVERVIEW

The research reported in this thesis was performed as part of an ongoing research project with the Analysis Group for Regional Electricity Alternatives (AGREA) in the MIT Energy Laboratory. The AGREA team works with New England electric utilities, environmental groups, state and federal regulators, and industry, to obtain mutually acceptable, long-range strategies for meeting the region's future electricity demand. In response to

---

[16] 'RET' will be used as the abbreviation for 'non-dispatchable renewable energy technologies' for the remainder of this thesis.

the increasing interest in renewable energy technologies, photovoltaics and wind power were included for the first time in the 1992/1993 AGREA study.

The research presented here addresses the goal of increasing the use of RETs through two of the necessary avenues depicted in figure 1[17], specifically focusing on:

- Developing and demonstrating a methodology for analyzing RETs as part of power system operation, in order to quantify their potential electricity, economic and environmental impacts, in New England,
- Increase familiarity with these technologies and their behavior on the part of utility planners and other stakeholders (such as environmental groups, regulators and consumers).

The impacts of and potential benefits derived from non-dispatchable power generation technologies are not fully captured by tools developed for conventional power plants. The data and analysis tools required to directly analyze the potential value and contribution of RETs to the electric utility sector are not widely available, thus inhibiting any such analysis. For RETs to become better understood in terms of their impacts on system reliability, environmental pollution and electric utility rates, alternative analysis methodologies were developed as part of this research, to determine their usefulness and overall effect on conventional power systems.

In addressing the two goals listed above, the analysis in this thesis focuses on the hypothetical installation of wind turbines and photovoltaics in New England. Results of this analysis and of the potential impact on the New England utility sector are presented.

This thesis is divided into four sections:

- Understanding and modeling intermittent renewable energy resources,

---

[17] It is important to emphasize that a major obstacle in performing this analysis of RETs was the lack of *publicly* available, accurate resource data.

- Understanding the behavior and technical development of non-dispatchable renewable energy technologies,
- Modeling and analyzing non-dispatchable renewable energy technology impacts on electric utilities, and
- Quantifying the potential impact of including renewable energy technologies in the New England utility sector.

The section on renewable energy resources has two goals; to provide a general overview of the resources, their behavior and the terminology commonly associated with them; and to present mathematical equations and the methodology developed to model, analyze and predict renewable energy resource data.

Section two focuses on providing an understanding of photovoltaic and wind turbine technologies themselves. This will hopefully increase overall familiarity with the technologies, and also highlight the technical trade-offs between decreasing cost and improving efficiency.

Section three then combines these concepts, providing the complete picture of how the resources and the technologies are modeled and analyzed. This section explains the analysis tools developed as part of this research and how they are used in conjunction with the existing electric utility tools used by the AGREA team.

The fourth section presents results of the analysis performed for the New England region. This analysis includes 1500 MW_p each of wind power and photovoltaics, installed over a ten year time span, with seven years at the end of the study to analyze the impacts. This section also addresses some of the other components presented in figure 1, via sensitivity studies on the costs of the technologies. In as much as increased energy conversion efficiencies, improved manufacturing processes and public policies addressing RETs can be represented as a net decrease in cost, all of these additional factors are addressed in the sensitivity analyses.

CHAPTER 2
INTERMITTENT ENERGY RESOURCES

INTRODUCTION

The study undertaken for this thesis includes two non-dispatchable renewable energy technologies used for electric power generation – wind turbines and photovoltaics. These technologies are referred to as non-dispatchable since they generate electricity when their energy source (i.e. sunlight or wind) is available, and not necessarily when energy is demanded by utilities and consumers.

Due to their non-dispatchable behavior, these technologies can not be modeled or analyzed in the same manner as conventional power plants, requiring that an alternative methodology be deployed for determining their usefulness and overall effect on the power system, in terms of environmental and economic impacts. As one of the defining features of RETs is the behavior of their resource, an analysis of RETs requires input data on both the technologies and the resources. An overview of the technologies and the potential impacts on the utilities of including RETs is in chapter 3. This chapter discusses the first steps of the resource analysis – including the steps required for this research to repair and adapt the poor quality resource data available. It the describes how to define and model this resource. The wind resource is presented first, followed by a discussion of the solar resource.

THE WIND RESOURCE

Every ten days, the earth receives solar energy of an amount equal to the world's entire fossil fuel reserves, and approximately one percent of this is converted to wind energy (Freris 1990). This solar radiation is converted to wind energy as a result of the unequal heating of the equator as compared to the poles, and of the oceans as compared to the continents. This unequal heating leads to motion within the atmosphere as it tries to equalize its pressure – resulting in what we know as wind. A second cause of wind is the motion of the earth.

The basic properties of the wind are its speed, direction, and fluctuations in this speed and direction. These properties are affected both by local terrain, in terms of vegetation, buildings, and topography, and by the height of the wind above these features. Increased height results in less influence from these surface features, and also leads to an overall increase in wind speed. The relationship between wind speed and height is shown in the equation below, where speed increases from V_1 to V_2 as height increases from H_1 to H_2. (For further derivation see Coty, 1975):

$$V_2 = V_1(H_2/H_1)^a$$

The exponent, a, depends on atmospheric pressure and stability, as well as the roughness of the terrain and wind direction. A standard lower value for 'a' is 1/7 (= 0.143), which loosely represents most terrains. This value is not appropriate for use with mountain ridges, which have rather extreme terrain; an upper boundary for 'a' for the New England study was calculated from data for Stratton Mt. VT at a value of 0.426. A conservative value of 0.250, between these two boundaries, is used in this analysis since we are modeling neither rolling hills nor the harshest mountainous areas, but rather regions between these two extremes.

The hub height of the turbine (H_2) is modified by the height of the tree canopy by decreasing the effective hub height by 3/4 of the tree height. For example, with a hub height of 50 meters and a tree height of 12 meters, the effective hub height is (Ralph 1992):

$$H_2 = 50 - 0.75(12) = 41 \text{ meters}$$

Wind speed is an important characteristic of the wind, yet for wind power generation we are ultimately concerned with the power in the wind, and not specifically with its speed. The equation relating wind power to wind speed is shown below, where P=power, ρ=air density, A=area (the area swept by the turbine blades) and v=velocity (wind speed):

$$P = (1/2)\rho A v^3$$

This equation shows that wind power increases with the cube of wind speed, which means for example that a doubling of the wind speed results in an eight-fold increase in power. This fact reveals the importance in taking great care when siting wind turbines, since a small difference in wind speed makes a large difference in available wind power.

CLASSIFYING AND MODELING A WIND RESOURCE

Average Wind Speed

The wind can not be controlled by people, yet it can be well understood and predicted through wind speed and direction measurements, and probabilistic models. The simplest measure of the wind resource at a given location is the average annual wind speed, with seasonal and monthly averages providing a more complete description of the resource.

Wind Power Class

Wind power class categorizes a site in terms of its wind speed and its available wind power. The different wind power classes are presented in table 1 which shows the range of wind speeds and wind power densities relating to each wind power class, and demonstrates how the wind speed and power increase with height.[1]

A wind power class is constant for a given site, at any elevation, and provides a convenient measure for determining the suitability of a site for

---

[1] The wind speeds associated with wind power density values are calculated assuming a Rayleigh distribution of wind speeds, and may have an error as large as twenty percent.

wind turbines. For example, for current technologies a wind power class of five or greater is required for a site to be a viable wind farm location (Freris 1990). New technologies are expected to perform well at sites with a wind power class three or greater, due to increased energy capture from both improved efficiency and increased hub height. The improvements from these new technologies allow many areas in the New England region, such as the mountainous areas throughout Maine, New Hampshire, Vermont and Massachusetts to be considered viable wind farm sites (Elliott 1991).

Table 1: Wind Power Class

	(height)	10m			30m			50m	
Power Class	**Power Density**	**Wind Speed**	**Wind Speed**	**Power Density**	**Wind Speed**	**Wind Speed**	**Power Density**	**Wind Speed**	**Wind Speed**
	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
1									
	100	4.4	9.8	160	5.1	11.5	199	5.5	12.4
2									
	150	5.1	11.4	240	6.0	13.3	299	6.4	14.4
3									
	200	5.6	12.5	320	6.6	14.7	399	7.0	15.8
4									
	250	6.0	13.4	400	7.0	15.7	498	7.6	16.9
5									
	300	6.4	14.3	480	7.5	16.7	598	8.1	18.0
6									
	400	7.0	15.7	641	8.2	18.3	797	8.8	19.7
7									
	1000	9.4	21.0	1601	11.0	24.6	1993	11.8	26.5
	(W/m2)	(m/s)	(mph)	(W/m2)	(m/s)	(mph)	(W/m2)	(m/s)	(mph)

Hourly Wind Speed

Annual and monthly average wind speed and wind power class values are useful for broad classifications of the wind resource at any site. However, they are not detailed enough to capture the true complexity of a wind regime needed for modeling. For modeling the potential impact of wind turbines on an existing power system, much more detailed information is required.

Power generation from wind turbines is determined by the wind speed and direction at each moment. Thus, in order to accurately model the power generation from the turbines, and their impact on the power system, information on the wind speed and direction at each moment is required. Actual continuous data representing the wind for *every* moment would be unwieldy though, so a common method is to take measurements every two to fifteen minutes, and then average these to an hourly value. Using data from multiple years is also important for any analysis, so that long-term weather patterns and other variations are fully represented.

For this analysis multi-year, hourly wind speed data for two sites was used. Since we are modeling hypothetical sites rather than actual ones and directional variability is particularly dependent upon the specific local terrain, wind direction data was not included. Instead a loss factor is included to account for the inaccuracy.

DATA PREPARATION AND MODELING

Most of the publicly available hourly wind speed data is inappropriate for direct use in wind technology and power systems analyses since it is most often recorded at airports, and contains numerous gaps. Wind resources at airports are different from those at likely wind farm sites due to differences in terrain and elevation, and more basically due to the opposing criteria of seeking low wind for airplane take-off and landing, and strong wind for wind turbines! Also, most wind measurements recorded at airports are from heights unsuitable for wind turbine operation (10 meters versus 50 meters). A methodology for preparing hourly airport data for a power systems analysis, which includes repairing any gaps in the original data, shifting the data to the appropriate height, and then adjusting it to reflect a better wind site, is described below.

Repairing

Data sets often have groups of hours for which there is no data, due to problems with measurement instruments and other factors. The first step in preparing the hourly wind data is to "repair" the data by filling the missing hours with a linear interpolation of the good data points on either end of the missing hours. Through examining more complete sections of hourly wind data, we feel a linear interpolation for periods less than twenty four hours adequately represents an actual wind regime. For groups of missing hours longer than one day, actual data from a similar time period is patched into the missing data.

Shifting

The next step in preparing the data is to shift it to the appropriate hub height. Most wind speed data at airports is recorded at either 7 or 10 meters, and must be shifted to the hub height used for wind turbine analysis (usually 30 to 50 meters). To increase the height from H_1 to H_2, the velocity is increased from V_1 to V_2, according to the equation below:

$$V_2 = V_1(H_2/H_1)^a$$

This equation is explained more fully earlier in this chapter.

Adjusting

This step in modeling the hourly data is the most complex, and perhaps controversial, in the analysis since it entails "geographically adjusting" data for a wind regime at one site to represent a wind regime at a different geographical location. Since wind data is available for only a few non-airport sites though, it is also necessary. The raw data comes from the site with available data closest to each hypothetical wind turbine site, and this data is then "geographically adjust" to represent the wind resource of a mountain ridge – a more appropriate wind farm location. In short, the process developed allows the user to specify monthly average wind speeds, as well as adjustments to the overall diurnal variation, including the hour of the day at which the peak should occur. This high degree of control allows the wind regime from an airport location to be adjusted to adequately represent that of a mountain ridge.

The adjustment process utilizes the probability distribution of a wind regime to increase (or decrease) the average monthly wind speeds, and alter the diurnal variation; it is described below. The "Wind Energy Resource

Atlas of the United States" (Elliott 1987) provides good initial data on the appropriate average wind speed. For this analysis, the resultant data has been benchmarked against actual (proprietary) data from the New England region[2].

The probability distribution generally used to represent wind regimes is the Weibull distribution[3] (McGowan, Freris, Hock), and this is the distribution utilized in performing the geographical wind speed adjustment. The parameters which characterize a Weibull distribution are the shape, k, and the scale, c. The equation for this distribution is given below, where v is the velocity, and f(v) is the equation for the probability density. The equations for the Weibull parameters of shape k, and scale c, in terms of the better known Normal distribution parameters of mean wind speed ϖ, and standard deviation σ, are also provided below. A generic Weibull distribution is plotted in figure 1.

$$(1) \quad f(v) = (k/c)(v/c)^{k-1} \exp[-(v/c)^{k}]$$

$$(2) \quad k = -3.078 - 20.962(\sigma/\varpi) - 9.516 \exp[\sigma/\varpi]$$

$$(3) \quad c/\varpi = 2.7323 + 2.1846(\sigma/\varpi) - 1.9361 \exp[\sigma/\varpi] + 0.1827 \exp[2\sigma/\varpi]$$

In order to transform the original hourly wind speed data to that of the new geographical location, the cumulative distribution function is used. This contains the same statistical information as the simple distribution function, yet is easier to use for the data transformation. Each point on a simple distribution function represents the percentage of time the wind *equals* a given wind speed; each data point on a cumulative distribution function represents the percentage of time the wind is *greater than or equal to* a given wind speed. Figure 2 shows the cumulative distribution function for the Weibull distribution of figure 1.

---

[2] The resultant data used in this analysis was benchmarked against proprietary data from Green Mountain Power, a Vermont utility very active in wind power projects, and US Windpower, which is currently involved in a project to install 50 MW of turbines (150 turbines) in Maine by 1995.

[3] The generalized form of the Weibull distribution, with an exponent of 2, is the Rayleigh distribution.

Figure 1: Weibull Distribution

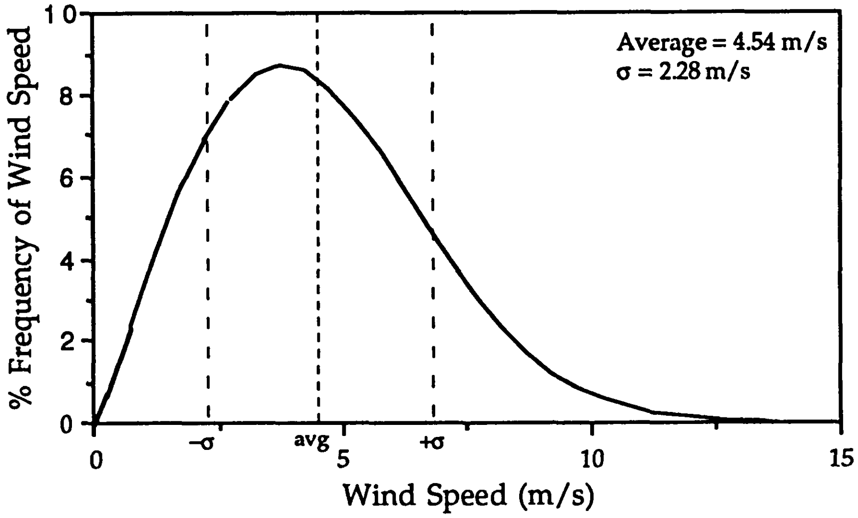
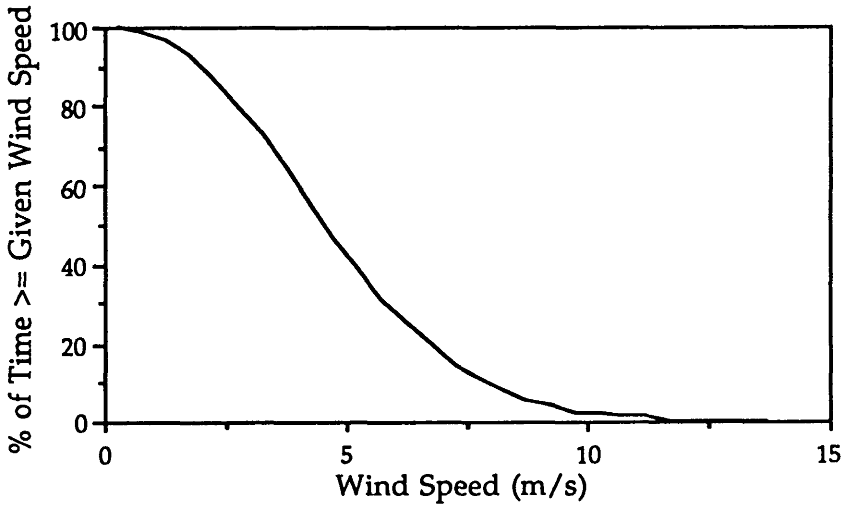


Figure 2: Cumulative Distribution



To transform the data, the first step is to calculate the Weibull distribution of the original hourly data. Next, the shape and scale parameters of the original data are transformed to those of a site with the specified higher (or lower) mean velocity using equations (1) through (3) above, resulting in a new Weibull distribution. The two Weibull distributions are then represented as cumulative distribution functions (CDFs), as shown in Figure 3. The new hourly wind speed database is then calculated, hour by hour, by translating each wind speed value from the original CDF to the new one.

Figure 3: Original and Adjusted Weibull CDFs

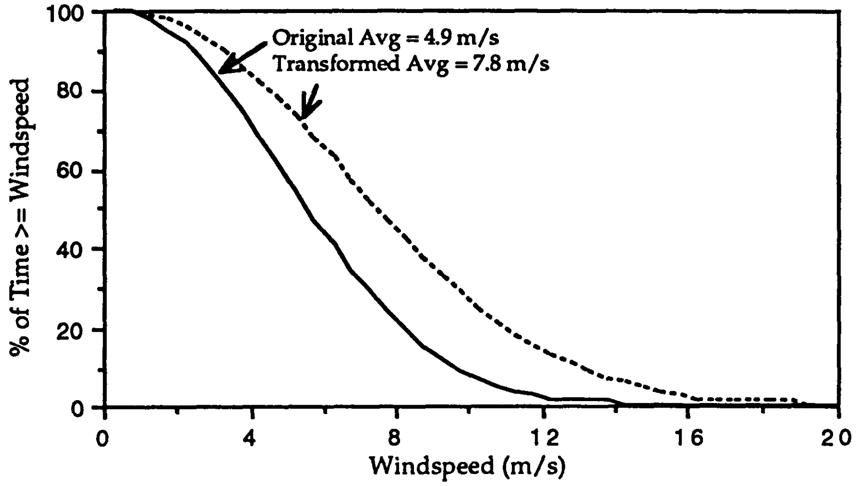
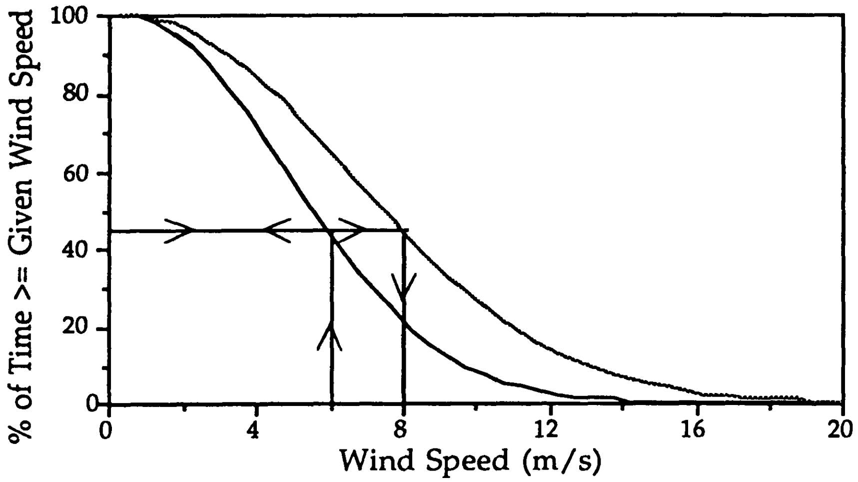


Figure 4 demonstrates the method of using the cumulative distribution function for this data transformation. For example, in the original data set, an hourly wind speed value of 6 m/s occurs about 45% of the time (see figure 4). In the wind regime with higher average wind speed, the wind speed occurring 45% of the time is approximately 8.1 m/s. Thus, every occurrence of 6 m/s in the original data set is increased to 8.1 m/s for the

Figure 4: Data Transformation via Cumulative Distribution Functions



geographically adjusted data set. This process is repeated for each hourly wind speed value.

A different Weibull distribution is calculated for each month, rather than relying on a single distribution to represent the entire year. In addition to the Weibull data manipulation, this adjustment process allows for manipulation of the diurnal (daily pattern) variation. Mountain ridge wind regimes tend to have flatter diurnal variations than airports, with the peak wind speed occurring around 8 pm. The methodology developed here allows the necessary changes to the diurnal variation, as well as the general increase (or decrease) in the average wind speeds. The procedure results in a new wind regime which reflects the weather patterns and hour-to-hour variability of the original data, yet has average monthly and hourly wind speeds and diurnal variation representative of the desired wind farm location.

Graphs for original and adjusted wind speed data for a site in Maine are presented below. The adjusted data is the result of shifting the original data from Caribou ME from a height of 10 meters to 50 meters, and then increasing the average wind speed from 4.9 m/s to 7.8 m/s (11.0 to 17.4 mph), so that it represents a wind regime appropriate for the Longfellow Mountains.

Figures 5 and 6 plot the actual hourly wind speed data, in bar graph format, for the original and adjusted data. Each graph is overlaid with the Weibull representation of this data. These graphs, along with figures 9 and 10 show that the variability of the data is maintained throughout the transformation.

Figure 7 compares the Weibull distributions for the original and adjusted data directly. Figure 8 compares the cumulative distributions.

Figure 5: Original Data with Weibull Representation

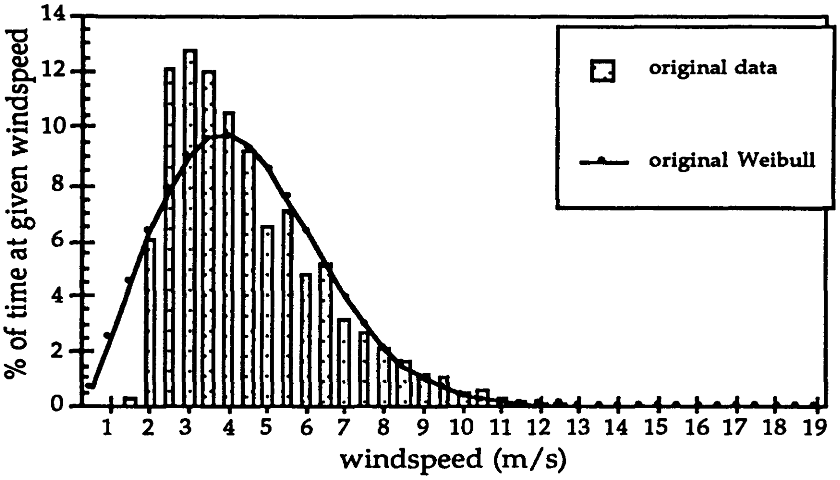


Figure 6: Adjusted Data with Weibull Representation

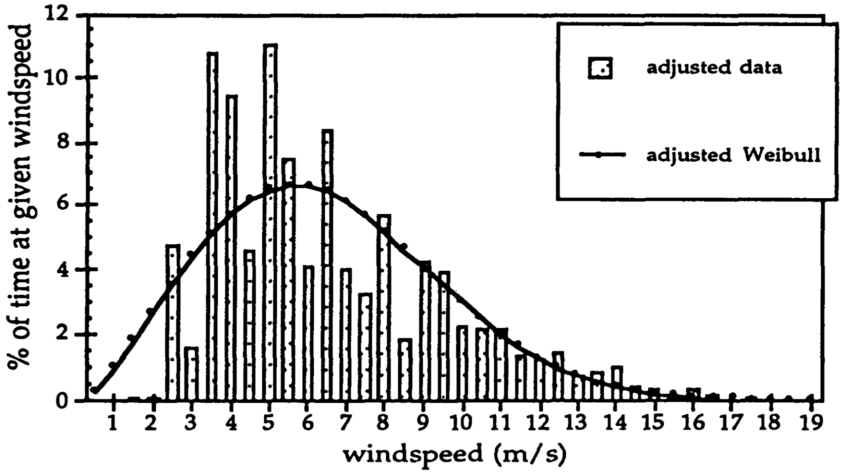


Figure 7: Weibull Distributions of Original and Adjusted Data

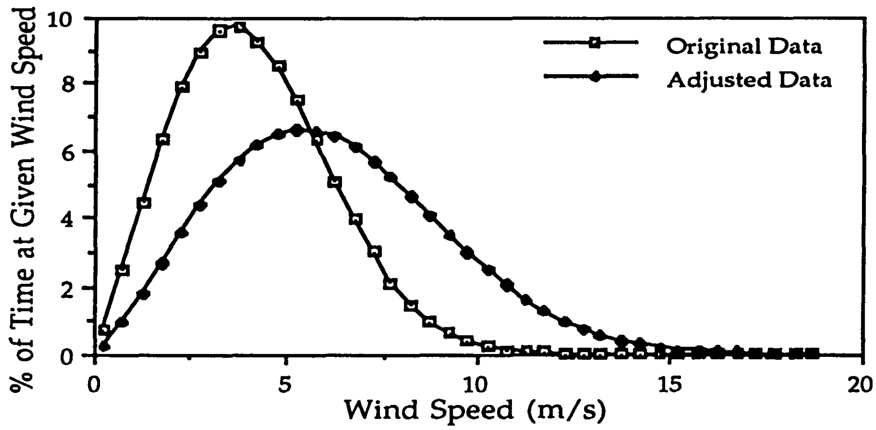
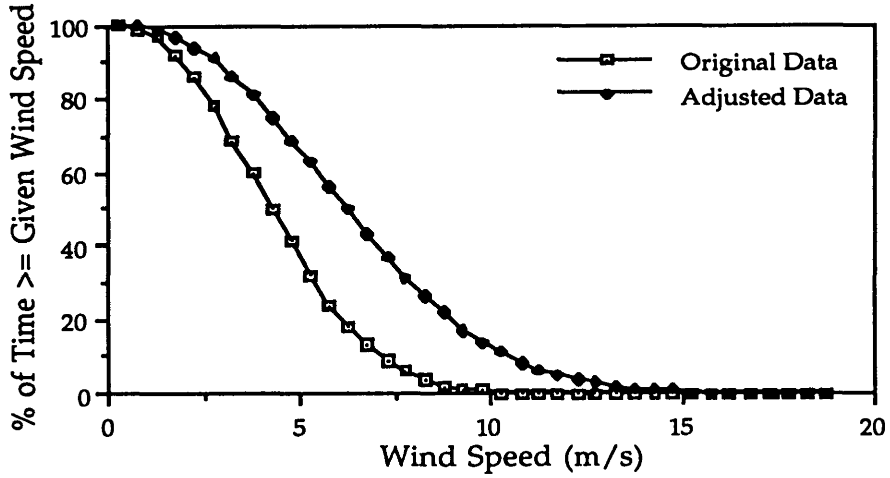


Figure 8: CDFs of Original and Adjusted Data



NEW ENGLAND'S WIND RESOURCE

It is commonly thought that New England does not possess as good wind resources as the Great Plains or the California mountain passes. As a comparison though, good wind turbine sites in the West are those with an average wind speed of 8 m/s (17.9 mph), while numerous mountain ridge sites in New England also have average wind speeds of 7 to 8 m/s. The total land area in New England with a usable wind resource (for new technologies), after accounting for environmental, residential and other land use exclusions, is presented above in table 2 (Elliott 1991). Table 3 then

Table 2: Windy Land Area in New England

	Square Kilometers per Power Class					Windy	% of Total
State	3	4	5	6	7	Land	State
Connecticut	507	33	2	0	0	542	4%
Maine	5287	435	148	57	4	5931	7%
Massachusetts	2009	121	246	119	0	2495	12%
NewHampshire	141	109	95	25	1	371	2%
Rhode Island	86	14	0	0	0	100	4%
Vermont	111	142	128	12	0	393	2%
Total	8141	854	619	213	5	9832	6%

(square km)

* The land values are based on moderate land use exclusion: 100% environmental and urban land excluded, 30% agricultural and 50% forest.

shows the equivalent available energy from the wind, in GWhs, for the available windy land area assumed in table 2.

Table 3: Energy Available from the Wind (GWh)

State	Power Class 3	4	5	6	7	State Total
Connecticut	4578	298	18	0	0	4894
Maine	47742	3928	1336	515	36	53558
Massachusetts	18142	1093	2221	1075	0	22530
NewHampshire	1273	984	858	226	9	3350
Rhode Island	777	126	0	0	0	903
Vermont	1002	1282	1156	108	0	3549
Power Class Total	73514	7712	5590	1923	45	88784

* Calculated for a 50m hub height (GWh)

These are not precise measurements, yet they do reveal that there is a sufficient wind resource in New England to warrant further study. For further reference, consult the "Wind Energy Resource Atlas of the United States" (Elliott 1987) which contains maps of the wind power class for all areas of the country. These maps show that the coastal and mountainous regions of New England in particular, have good wind resources.

Site Selection

For this analysis we obtained hourly wind speed data for selected locations in New England from the National Climatic Data Center (NCDC), in Asheville, North Carolina, which maintains the only publicly available multi-year, hourly data. Two hypothetical wind farm sites were selected based on the available wind resource data, and on data from regional wind resource maps provided in the "Wind Energy Resource Atlas of the United States" (Elliott 1987). These two areas are around the Berkshires in Massachusetts and the Longfellow Mountains in Maine. Coastal areas have an excellent wind resource, yet none of these sites were considered due to land use, cost and demographic constraints. The mountainous areas we did select both have good wind resources (average wind speeds around 7 and 8 m/s or 15 to 18 mph), and do not suffer from the same constraints as the coastal regions.

The hourly wind speed data we will use for these sites is the Holyoke/Mt. Tom data for the Berkshire site, and the Caribou ME data for the Longfellow Mountains site. The data from Caribou was taken at an airport, and thus required much manipulation before being used in the analysis. Mount Tom however was selected by the US Department of Energy as a "candidate site," and thus had data recorded specifically for the potential siting of wind turbines.

RESULTANT HOURLY WIND SPEED DATA

It is very important to note that before any actual wind turbines are installed, data from the exact site must be recorded and analyzed. For purposes of gaining a general understanding of the affect of including wind power on the region's generation mix however, geographically adjusted data for hypothetical sites is acceptable. Results of the complete data modeling process are presented below.

Figures 9 and 10 show the average hourly and average monthly wind speed for the original, diurnally adjusted and fully geographically adjusted data from Caribou ME. The diurnal adjustment includes the height shift, diurnal adjustment and time-of-day peak shift. The data in the graphs is shifted from 10 meters to a hub height of 50 meters, and the peak is shifted five hours later to more closely reflect the mountainous wind regime. The full geographical adjustment step then adds the monthly average wind speed adjustment. The resultant annual average wind speed is adjusted from 4.9 m/s (11.0 mph) to 7.8 m/s (17.4 mph). Note that the hourly data for Mt. Tom did not require any diurnal adjustment, and therefore serves as a good comparison for our resultant Longfellow Mountain data. This comparison can be seen in graphs 11 and 12.

The appendix to this chapter provides more extensive wind resource graphs for the hypothetical wind farm sites in the Longfellow Mountains and Mt. Tom areas.

Figure 9: Average Hourly Wind Speed: Caribou ME

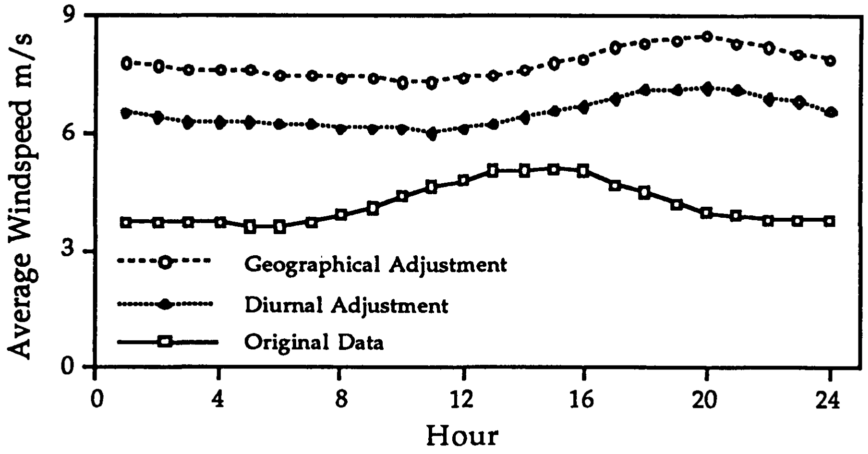


Figure 10: Average Monthly Wind Speed: Caribou ME

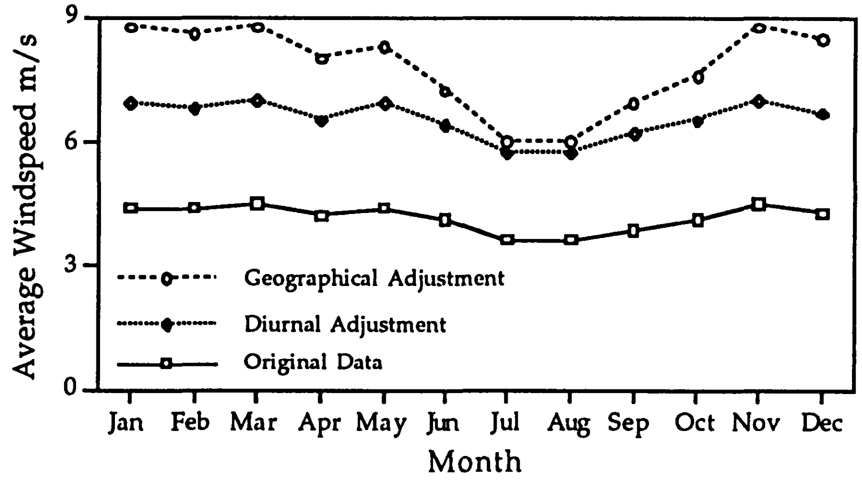


Figure 11: Average Hourly Wind Speed Comparison of ME and MA

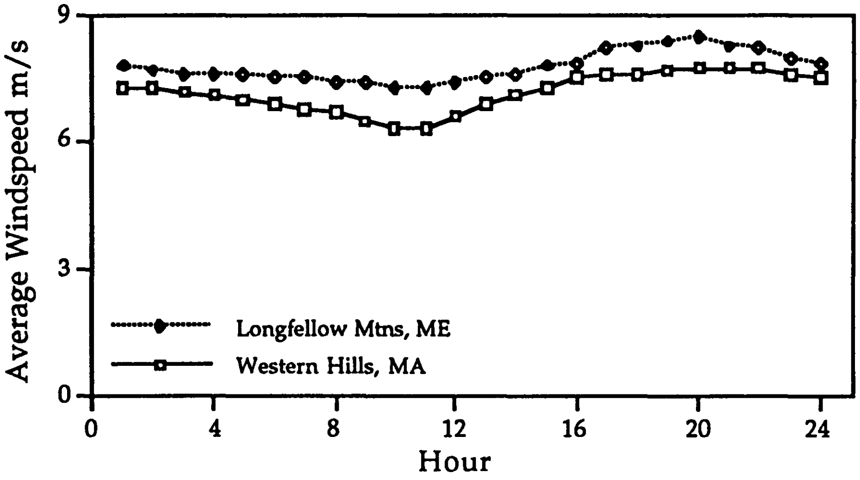
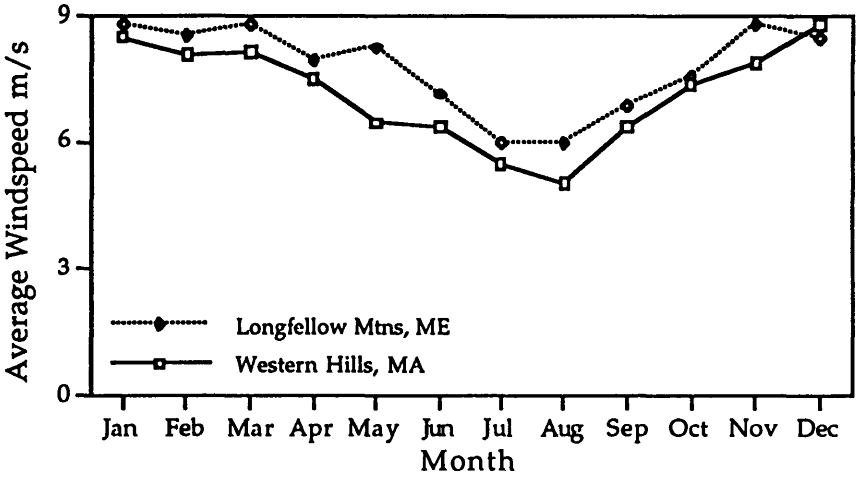


Figure 12: Average Monthly Wind Speed Comparison of ME and MA



THE SOLAR RESOURCE

This section discusses the solar energy resource, including common terminology, methods for measuring the resource, and equations for simple data manipulation. It then presents data on the solar insolation resource in New England, and the region selected for the analysis of photovoltaics in New England.

Solar radiation is a main source of electromagnetic energy in our environment, and is the resource used by solar cells to generate electric power. To understand how solar cells operate, it is important to understand the fundamentals of this resource. Electromagnetic radiation can be discussed interchangeably in terms of frequency, wavelength or directly as energy. These quantities are related by the equations below, where c is the speed of light, λ is wavelength, ν is frequency, E is energy[4] and h is Plank's constant:

$$c = \lambda\nu$$
$$E = h\nu$$

The corresponding ranges of these parameters for solar radiation, or solar insolation, are shown below in Table 3 (Cook 1991).

Table 3: Frequency, Wavelength and Energy Ranges in Solar Radiation

Frequency, ν	0.75	to	1.5	THz
Wavelength, λ	4.0	to	0.2	μm
Photon Energy, E	0.5	to	4.0	eV

The Solar Spectrum

As implied above, electromagnetic energy spans a continuum of wavelengths, or frequencies; a spectrum is a specified range of these wavelengths. The total energy in a spectrum is the sum of the energy contained in each wavelength (or equivalently in each frequency), in the specified range. The solar spectrum begins at a wavelength of 0.2 μm, peaks at 0.45 μm, and then falls off nearly to zero as the wavelength increases beyond 4 μm. (One μm = 10E-6 meters, or about 40 millionths of an inch. As a comparison, note that electricity generated at 60 Hz has a wavelength of 5 million meters, or about 3000 miles!)

The solar spectrum is divided into three categories: the visible range which contains the wavelengths from 0.38 μm to 0.78 μm; infrared and

---

[4] Energy can be measured in Joules, J, or electron volts, eV, with one eV equal to the amount of energy acquired by an electron that is accelerated through a potential of one volt: 1 eV = 1.6E-16 J. Note also that Watt = Joule/second.

Table 4: Energy Ranges in the Solar Insolation Spectrum

Wavelength Range (μm)	Ultraviolet 0 to 0.38	Visible 0.38 to 0.78	Infrared 0.78 to 4.0
Radiation in Range (%)	7.0%	47.3%	45.7%
Energy in Range (W/m2)	95	640	618

microwaves at longer wavelengths (lower frequencies); and ultraviolet and x-rays at shorter wavelengths (higher frequencies). Table 4 shows the energy contained in each range of the solar spectrum (Duffie 1980).

Variations to the Spectrum

At the top of the earth's atmosphere the energy in the solar spectrum is essentially constant, although it does vary slightly (± 3%) due to seasonal differences in the earth-sun distance. This constant value, measured in units of power density, is referred to as the 'solar constant,' and is equal to 1353 Watts/meter^2.

Once inside the atmosphere, solar radiation is significantly altered by both absorption and scattering of the energy by molecules and particles in the earth's atmosphere. Differences in altitude, latitude and time of day require the solar energy to travel different distances through the atmosphere, thus affecting the spectrum at the earth's surface to greater or lesser extent. As solar energy travels through the atmosphere, the gas molecules in the atmosphere absorb the high energy frequencies of the spectrum more readily than low energy ones, thus altering the *frequency composition* of the spectrum. (The concept of air mass number, defined below, quantifies the relative atmospheric depth due to the time of day, altitude, latitude and air density.) The spectrum is also altered by weather conditions and air pollution. Cloud formations and air pollution particles tend to scatter the energy, thus decreasing the *intensity* of the energy which reaches the earth's surface. (The intensity of the energy is proportional to the amount of energy of each frequency.)

Patterns of solar insolation vary across the globe due to varying degrees of absorption and scattering of solar energy in different regions. For an example of differences in the United States, the yearly solar energy density received around Phoenix, AZ, is greater than 2000 kWh/m^2, while in New England it is closer to 1400 kWh/m^2.

TERMINOLOGY

A number of terms which will be used throughout this discussion and in the following documents on photovoltaics are defined below (Duffie 1980):

Air Mass: This is the ratio of the distance solar radiation must travel before reaching the earth's surface to the distance it would travel if the sun were at the zenith. Air mass differs with altitude and time-of-day, with the minimum distance the radiation must travel each day occurring at noon when the sun is directly overhead (at the zenith). Table 5 shows the relationship between air mass, sun position and solar power density (Fan 1978). (Note: θ_z used in the table is the zenith angle, defined below.)

Azimuth, γ: The solar azimuth is the (horizontal) angular displacement of the sun with respect to South, with West positive: $-180° \leq \gamma \leq 180°$. See Figure 13 below.

Table 5: Air Mass, Sun Position and Solar Radiation

Air Mass	Solar Power Density (W/m^2)
0 (above the atmosphere)	1350
1 (sun at zenith)	930
2 (for sea level, $\theta_z = 60°$)	750
3 (for sea level, $\theta_z = 70.5°$)	620

Day Number, n: The day of the year, with the days numbered between 1 and 365.

Declination, δ: The (vertical) angular position of the sun at solar noon with respect to the plane of the equator, with North as positive:

$-23.45° \leq \delta \leq 23.45°$

Diffuse (Horizontal) Radiation, D_H: Radiation reaching the earth's surface after it has been scattered or reradiated by the atmosphere. This radiation is measured on a horizontal plane at the earth's surface.

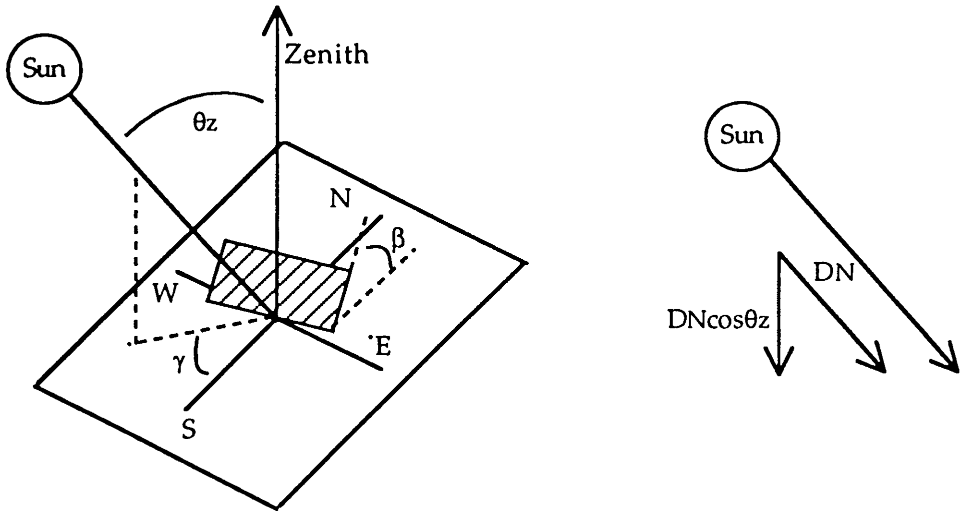
Direct (Normal) Radiation, D_N: Radiation which has traveled directly from the sun to the earth's surface without being scattered or absorbed by the atmosphere. This radiation is measured on a plane perpendicular to the direction of the incoming radiation.

Global (Horizontal) Radiation, G_H: The total radiation reaching the earth's surface. This is the sum of the direct and diffuse radiation *measured on a horizontal plane* at the earth's surface:

$$G_H = D_N \cos\theta_z + D_H$$

(Note: The zenith angle, θ_z, is defined below.)

Figure 13: Solar Insolation Terms



Hour Angle, h: The angular displacement of the sun east or west of the local longitude due to the rotation of the earth on its axis, at 15° per hour, with morning negative and afternoon positive.

Irradiance: Solar power density, W/m^2

Irradiation: Solar energy density, J/m^2

Latitude, ϕ: The angular position North or South of the equator, with North as positive: $-90° \leq \phi \leq 90°$

Pyranometer: This instrument measures total or global solar irradiance data.

Pyrheliometer: This instrument measures only the direct normal component of solar irradiance data.

Slope, β: The angle between the plane surface in question and the horizontal: $0 \leq \beta \leq 90°$

Solar Time: Time based on the motion of the sun across the sky. True solar noon is the time, in local standard time, that the sun crosses the local longitude.

Zenith Angle, θ_z: The angle subtended by a vertical line to the zenith (the point directly overhead) and the line of sight to the sun.

DATA PREPARATION

Diffuse radiation data is not included with any of the SOLMET data, yet is required for modeling the energy generation from photovoltaics, as will be explained in the following chapter. The SOLMET data does include global and direct radiation data, as well as the corresponding solar time, however, allowing diffuse radiation data to be calculated via the zenith angle. These parameters are calculated according to the equations below, where δ is declination, n is the day number, θ_z is the zenith angle, ϕ is the latitude, h is hour angle, D_H is diffuse (horizontal) radiation, D_N is direct (normal) radiation, and G_H is global (horizontal) radiation, all defined above. (Equations in Duffie 1980; SOLMET 1988)

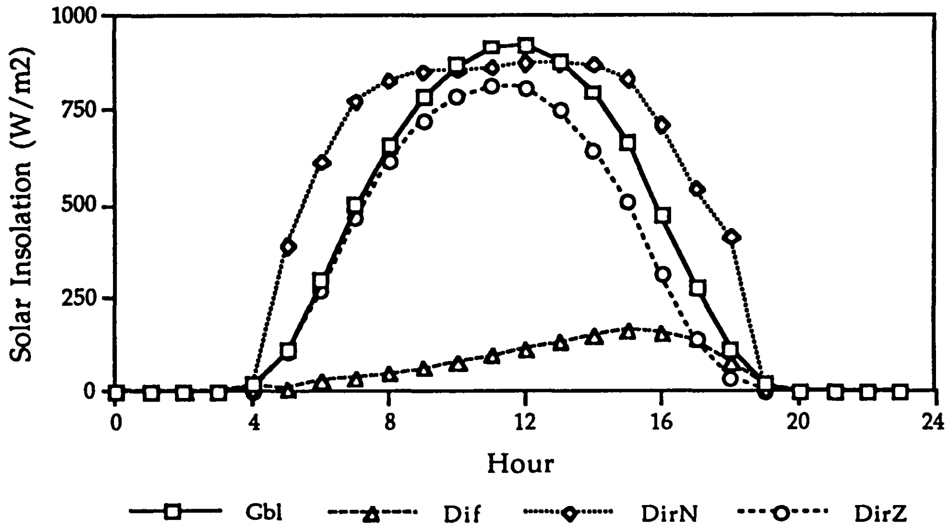
$$\delta = 23.45 \sin[(360/365) \times (284 + n)]$$

$$\cos(\theta_z) = \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \cos(h)$$

$$D_H = G_H - D_N \cos\theta_z$$

Figure 14 shows the relationship between global (Gbl), diffuse (Dif), direct-normal (DirN), and $D_N \cos\theta_z$ (DirZ) solar radiation components. DirN is greater than the global radiation for much of the day since DirN is measured in a plane perpendicular to the radiation, while Gbl is measured on a horizontal plane, which therefore does not record the horizontal component of DirN parallel to this plane. The curve for DirZ represents D_N $\cos\theta_z$, the component of the direct radiation falling on a horizontal surface. Thus DirN is greater than Gbl when the sun is low on the horizon and most of the direct radiation is lost to a horizontal plane. At midday however, most of the direct radiation does fall on a horizontal plane, and thus the global radiation (which includes diffuse radiation) exceeds DirN. Gbl = Dif + DirZ.

Figure 14: Components of Solar Insolation



NEW ENGLAND'S SOLAR RESOURCE

As with the hourly windspeed data, we obtained multi-year, hourly solar insolation data, SOLMET data, from the National Climatic Data Center (NCDC) in Asheville, NC for three sites in the southern New England area; Boston, MA; Hartford, CT; and Albany, NY. Table 6 lists the sites, and the years for which we have data.

Table 6: Sites for Solar Insolation Data

site	years
Albany, NY	January 1952 – December 1976
Boston, MA	July 1952 – November 1968
Hartford, CT	January 1952 – December 1976

The Boston location is an NCDC 'rehabilitated' SOLMET center, which has measured global solar radiation and meteorological data, and modeled direct solar radiation data. Albany and Hartford are SOLMET centers where all solar insolation data is calculated, using both regression estimates from local meteorological data, and solar insolation data from the rehabilitated SOLMET stations.

Site Selection

Unfortunately, both the Albany and Hartford sites are missing much data, so for the AGREA analysis, only hourly data from Boston was used. In 1992, the National Renewable Energy Laboratory upgraded SOLMET data sets for sites throughout the country and released them as the National Solar Radiation Data Base (NSRDB). These were not ready in time for the 1992/1993 AGREA study, yet data for thirty year monthly averages for numerous New England sites from the NSRDB will be compared to the data we are using to ensure that our data fairly represents the region's solar resource.

RESULTANT SOLAR INSOLATION DATA

Figures 15, 16 and 17 show graphs of direct, diffuse and global solar insolation for a summer and winter day in Boston MA. As stated earlier, the seasonal difference in distance between the earth and the sun accounts for only a 3% difference in solar insolation. The major source of the seasonal difference in insolation, seen for example in figure 17, is due to the difference in declination and air mass in the summer and winter months.

Figures 18, 19 and 20 graph average global insolation data for Boston, calculated from sixteen years of hourly data. Figure 18 graphs the diurnal variation for an average winter day (October to March), an average summer day (April to September) and an average day for the year. Figure 19 graphs the monthly variation in solar energy, showing the average insolation for sixteen daylight hours, and also the average insolation for midday, from 12 noon to 1 pm. The surface in figure 20 shows the daily and monthly variations in the average solar radiation for an entire year.

Figure 21 graphs NSRDB data to compare the yearly solar energy averages for various southern New England locations, demonstrating that there is not much variation in solar energy across Connecticut, Rhode Island and Massachusetts. Figure 22 then compares the yearly average for Boston to other sites around the country.

Figure 15: Boston Solar Insolation in January

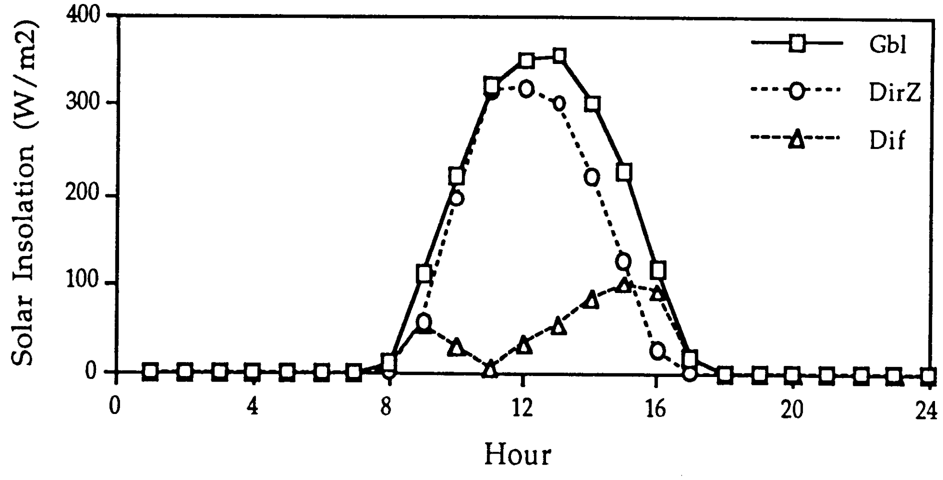


Figure 16: Boston Solar Insolation in August

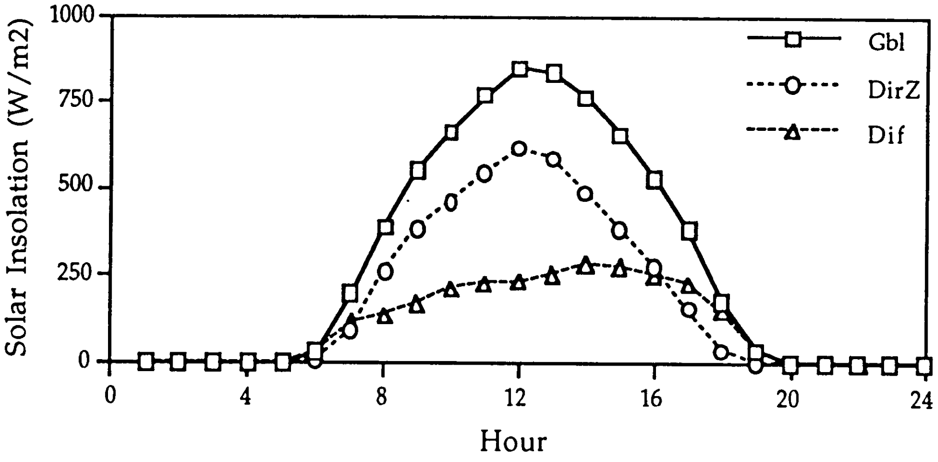


Figure 17: Boston Global Solar Insolation in January and August

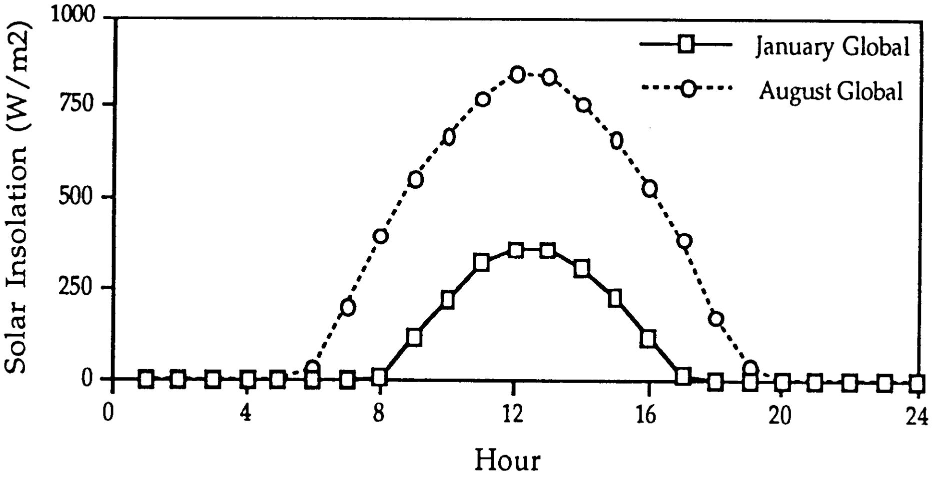


Figure 18: Average Hourly Global Insolation, Boston MA

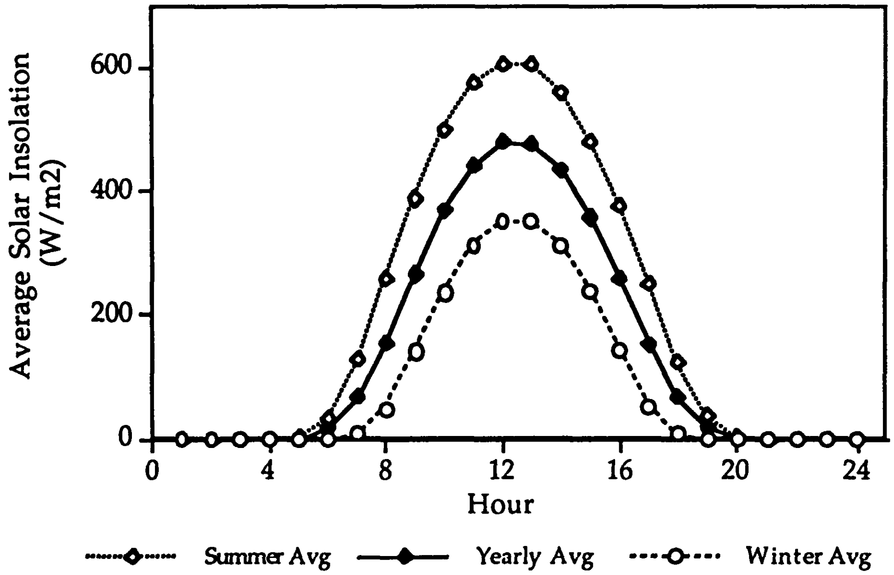


Figure 19: Average Monthly Global Insolation, Boston MA

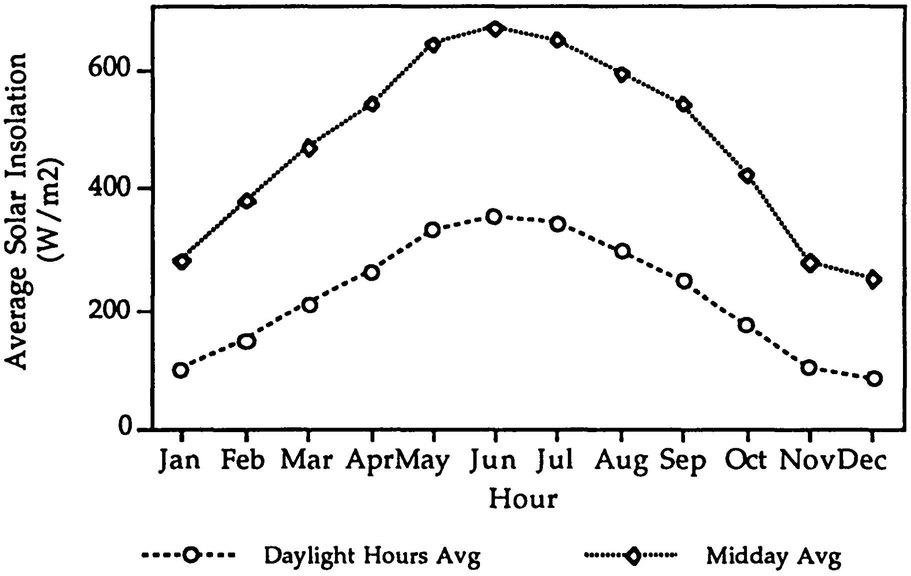


Figure 20: Average Yearly Insolation, Boston MA

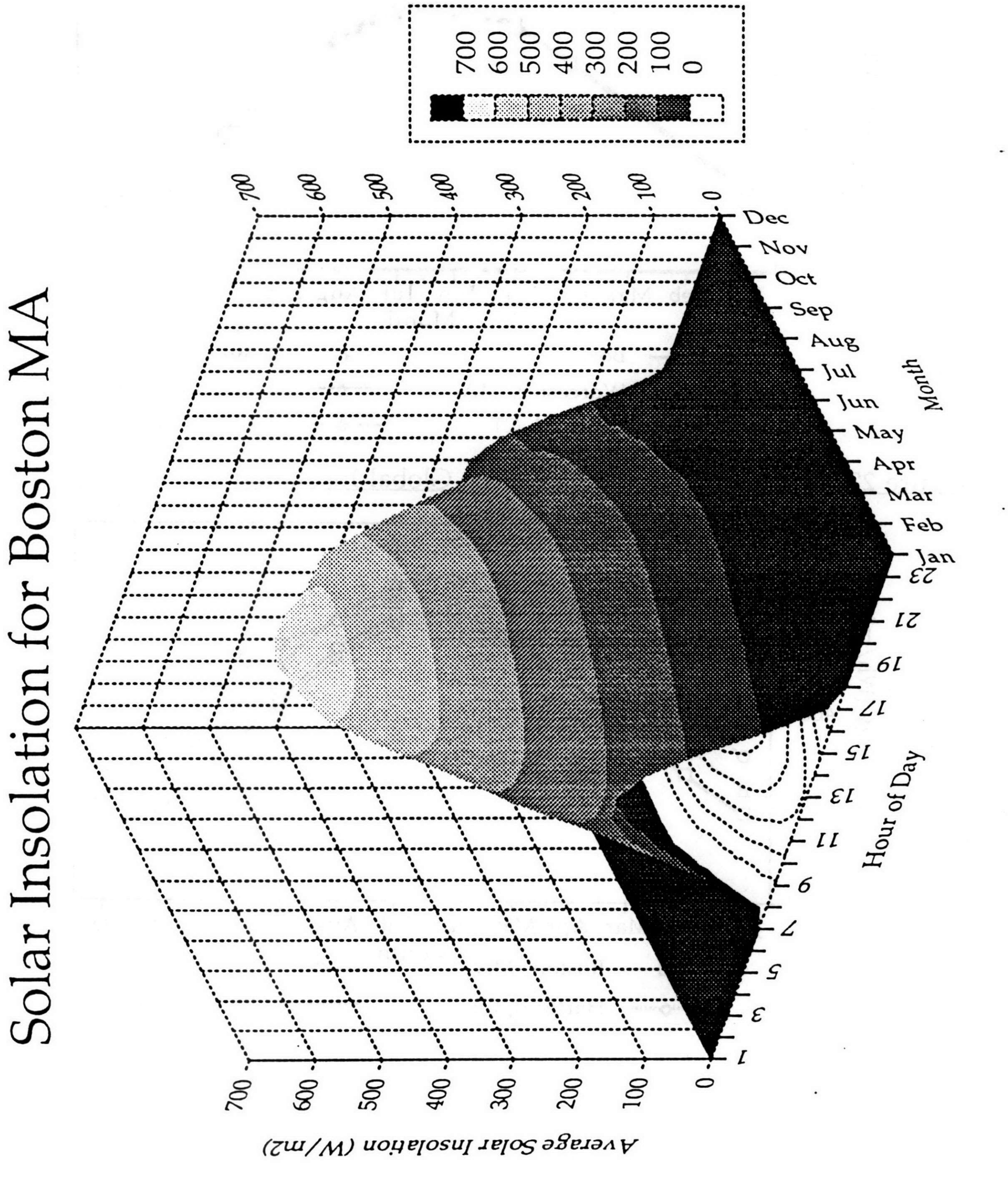


Figure 21: Southern New England, Average Monthly Global Insolation

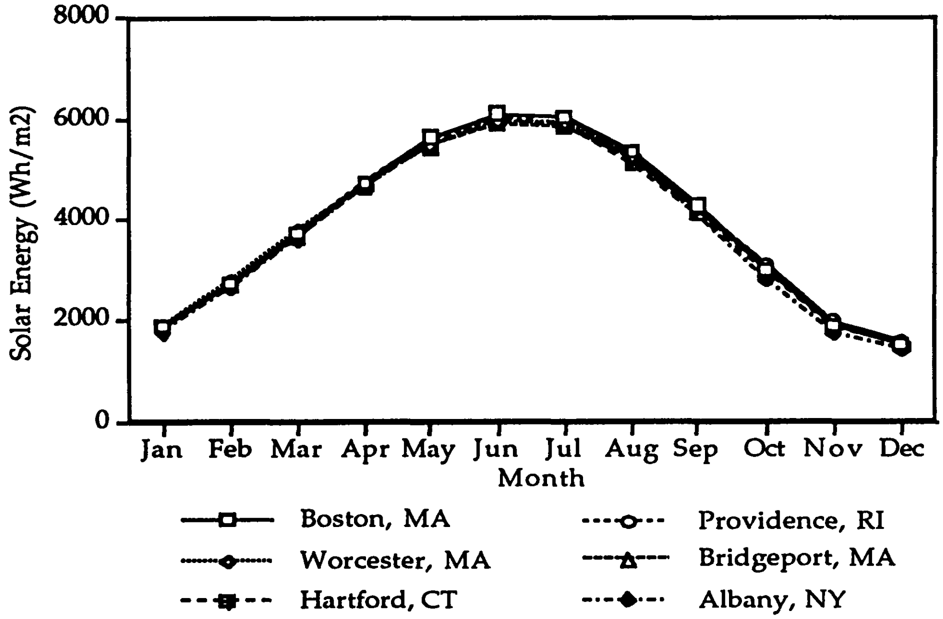
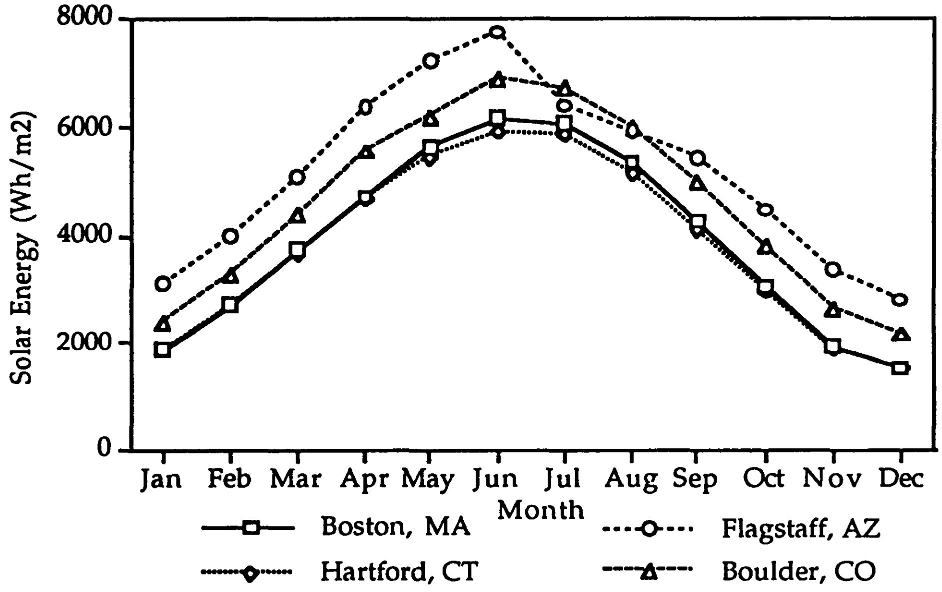


Figure 22: US Cities, Average Monthly Global Insolation



CHAPTER 3
NON-DISPATCHABLE RENEWABLE ENERGY TECHNOLOGIES

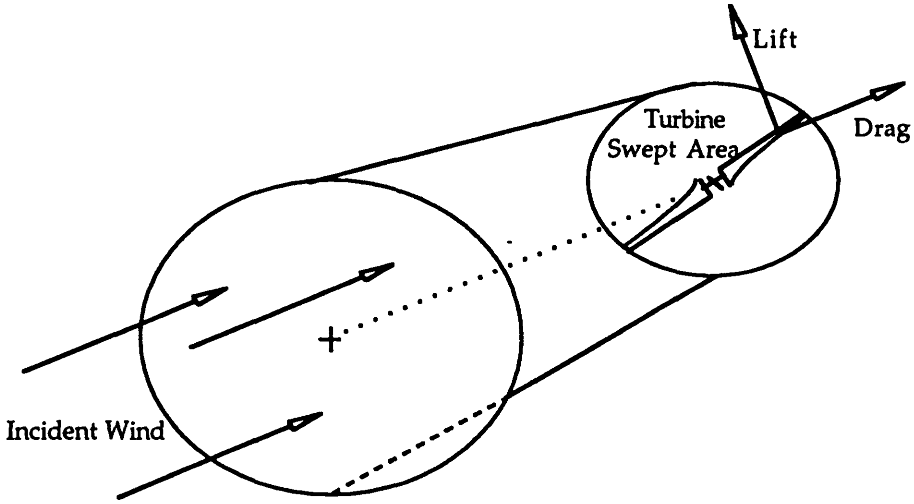
INTRODUCTION

This chapter presents an overview of current wind turbine and photovoltaic technologies and presents various recent values for their performance characteristics and costs. The potential environmental impacts of each technology are presented, and then this chapter concludes with a discussion of the potential positive and negative impacts on a power grid of including non-dispatchable technologies in the supply mix.

WIND TURBINE TECHNOLOGY

Wind technology has changed considerably from the centuries old picture of a Dutch wind mill pumping water to the current high speed wind turbines used for electricity generation. Wind energy conversion systems, or WECS, convert the kinetic energy in the wind to mechanical energy, and then to electrical energy. Wind turbines use the aerodynamic forces of lift and/or drag to produce a torque on a rotating shaft, which is then coupled to the shaft of an electric generator to produce electric power. These force components are shown in figure 1.

Figure 1: Lift and Drag Forces on Turbine Blades



WIND ENERGY CONVERSION SYSTEMS

Wind turbine systems can be categorized broadly by the orientation of their axis: horizontal or vertical; with horizontal axis turbines relying mainly on the lift component of the force to produce the rotation, and vertical axis machines using drag. The basic elements of a WECS are the turbine and blades, the control systems for rotor speed and direction, the electric generator, the tower structure, and the electronics to connect the system to the power grid. These elements are discussed briefly below. They are discussed in greater detail in the books listed in the references, by Eggleston (1987), Freris (1990), Golding (1977), Hunt (1981), Johnson (1985) and Twidell (1986).

Turbine Components

Number of Blades: Wind blowing on the turbine blades, or airfoils, produces an angular force, or torque, on the blades, which causes energy in the wind to be converted into rotational energy of the turbine. The solidity of the turbine is defined as the total blade area divided by the total swept area of the blades. The number of blades therefore gives a rough idea of the solidity. High solidity (many blades) leads to easy start-up with high initial torque at low wind speeds, and with maximum power output reached at low rotational frequency. Conversely, turbines with low solidity may be more difficult to start, yet have high rotational frequency at their maximum power output. Since high frequency is required for electricity generation, most turbines used for electricity generation have either two or three blades. Wind machines with high solidity are most appropriate to be used for water pumping.

Upwind vs. Downwind Turbine: The direction of the turbine relative to the wind is important since maximum power is generated only when the turbine faces directly into (or directly opposite, for downwind machines) the wind. Turbines can be designed with yaw, or direction, control to maintain either downwind or upwind orientations. Downwind designs, where the blades are behind the tower (relative to the wind direction), do not require complex yaw controls since they are essentially steered by the wind into the correct position. With a downwind turbine though, the tower casts a "wind shadow" on the blades as they rotate past the tower, causing cyclic stresses on the blades. Small upwind turbines can be kept facing the wind through tail fins or wind vanes mounted on the hub. Turbines of capacity greater than 50 kW typically require electric motors to control their direction.

Turbine Speed: Control of the turbine speed is important since this directly impacts the frequency (and thus the quality) of the power generated. When there is low penetration of wind turbines on a strong power system, the turbines usually rely on the inertia in the power grid itself to keep the turbine speed constant at 60 Hz. With no additional controls though, the load and stresses on the blades and thus the generator, will increase continually with wind speed, and may become excessive at high wind speeds. A simple drive train with a low speed shaft for the wind turbine rotor, a transmission, gear box and a high speed shaft for the electric generator allows the wind turbine to operate at more than one discrete speed. For horizontal axis machines the lift force of the wind, and thus the turbine speed, can also be controlled by changing the pitch of the blades so that they present less surface area to the wind, controlling the tips of the blades to act as brakes or turning the turbine out of the wind. In addition to these approaches, newer variable speed wind turbines (VSWT) use electronic controls to allow the rotor to operate at variable speeds.

The Electric Generator: The electric generator may be either synchronous or induction. Induction generators are cheaper, yet have the problem that they require an external source to start. When connected to a power grid, an induction generator can draw the necessary induction current from the grid to begin operation. This means though, that the reactive power which the turbine draws from the grid must be compensated for, adding additional cost. The alternative to this is a synchronous generator, which is more expensive and must operate precisely at the synchronous speed, yet is self starting and does not draw the high reactive power from the grid. Currently, most grid connected turbines use induction generators.

CONVERSION EFFICIENCY LIMIT

As stated in chapter 2, the power in the wind is calculated according to the following equation where :

$$P = (1/2)\rho A v^3$$

For the wind turbine rotor to produce mechanical power, it extracts power from the wind. To do this the rotor physically slows the wind down, so that the wind 'down wind' from the rotor is actually slower than the approaching wind. As more and more power is extracted, the wind will begin to flow around the rotor though, rather than through it, and in the limit there would be no wind moving through the rotor at all. The wind begins to flow around the rotor when the wind speed of the wake is 1/3 of the incident wind speed, or when the rotor experiences a wind speed 2/3 of the incident speed, which marks the maximum possible power extraction from the wind. Using equation (1) above and these limits on the wind speed experienced by the rotor, the maximum power extraction can be calculated as (Lysen, 1983):

$$P = (16/27)*(1/2)\rho A v^3$$

Thus 16/27, or 59.3 %, is the physical limit, known as the Betz limit, on the power conversion efficiency of a wind turbine. This efficiency is further decreased by loss throughout the WECS system[1].

WIND TURBINE OPERATION

The Power Curve

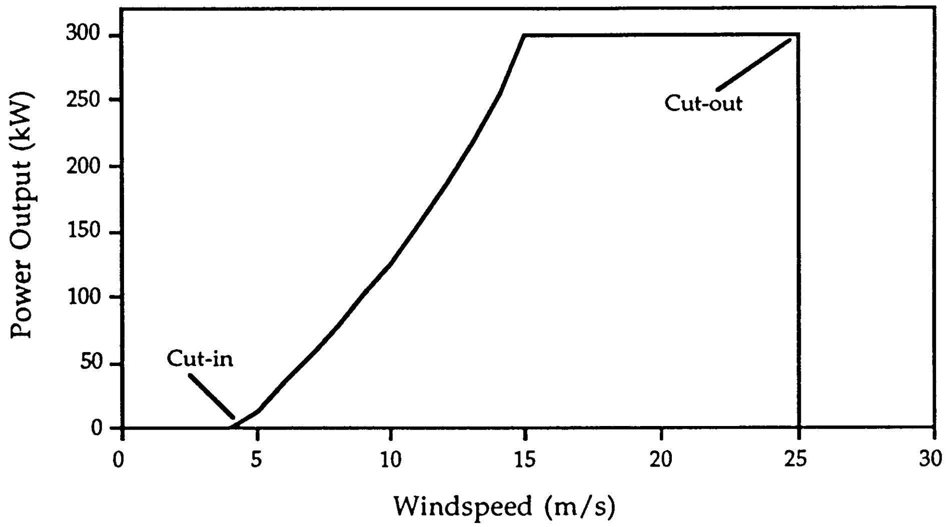
The power generation from a wind turbine is represented graphically by a power curve, as shown in figure 1. The power curve in figure 1 shows that wind turbines have three regions of operation: zero power output, power output increasing with wind speed, and maximum power output. As seen on the graph, there is zero power output when the wind speed is either less than the cut-in speed (4 m/s in this example) or is greater than the cut-out speed (25 m/s). Between the cut-in and cut-out speeds are the remaining two regions of operation: the range where power output continuously increases (for wind speeds from cut-in to 15 m/s), and the range over which the power output is essentially constant at the maximum rated value (wind speeds from 15 m/s to cut-out at 25 m/s).

For ideal operation, the turbine would always operate at its maximum rated capacity. Not only does this range produce the most power, but it also is the region of greatest stability. Referring to figure 1, if the turbine were operating in a wind speed around 20 m/s, small fluctuations in the wind speed would not cause the power output to fluctuate – it would remain constant at the rated capacity. If the turbine were to be operating at a wind speed of 10 m/s however, small fluctuations in the wind speed *would* cause significant fluctuations in the power output.

Figure 1: Wind Turbine Power Curve

---

[1] Note though, that conventional plants also do not achieve 100 % efficiency, with new coal plants having an efficiency limit around 34 %.



Horizontal Axis Turbines
Most wind turbines in use today are horizontal axis machines, and therefore we will emphasize horizontal axis machines over vertical axis ones in this discussion and in the 1993 AGREA study. New horizontal axis technologies being developed today are designed to increase energy capture by both improving the efficiency of the system as a whole, as well as by increasing the hub height. (As explained in the Chapter 2, increased height leads to increased wind speed which leads to increased wind power.) The cost of electricity generated is expected to decrease from both increased energy capture, and lower manufacturing costs (Dodd, 1990). Three machines actively being used and/or researched today are the advanced stall controlled turbine, the variable pitch, constant speed turbine, and the variable speed wind turbine. These turbines are each discussed below.

Constant Speed: A constant speed turbine requires direct control of the rotor speed in order to maintain the frequency output constant at 60 Hz. Without rotor speed control the power and frequency output by the rotor would increase unabated with increased wind speed. The generator would therefore need to act as a brake on the rotor to maintain the necessary 60 Hz output, and at very high speeds the stress on the blades and the high power output could damage the turbine. Referring to Figure 1, the power curve for a constant speed turbine shows a region of increasing power output for wind speeds between 5 m/s and 15 m/s, and a region of constant output between 15 m/s and 25 m/s. In this second region the power output and frequency must remain constant in spite of increasing wind speed.

There are two common constant speed wind turbine designs (CSWT): stall controlled and variable pitch. Both of these designs control the rotor speed by utilizing the fact that as wind speed changes, the angle of attack of the wind, which affects the lift, also changes. For the stall controlled turbine, the blades are designed so that as the wind speed increases to 15 m/s, the changing angle of attack increases the lift on the blades, thus increasing the power output. For wind speeds greater than 15 m/s however, the fixed pitch of the blades is such that the angle of attack of the wind causes no lift, causing the turbine to stall.

Use of the stall controlled turbines in New England is problematic because icing effectively changes the characteristics of the turbine blades so that they no longer cause the turbine to stall at the desired wind speeds, which can damage the turbines. The National Renewable Energy Laboratory is involved in projects with others in the industry, for improved stall controlled turbine designs (Tangler 1988, 1990).

A second common constant speed turbine is the variable pitch design – referring to the pitch of the turbine blades relative to the wind. The rotor speed is controlled by controlling the pitch of the turbine blades so that the lift increases with wind speed until the turbine output reaches its rated capacity. At that point the lift is kept constant by feathering or rotating the blades out of the wind, thus decreasing the lift.

Variable Speed: Variable speed wind turbines, which can be either discretely or continuously variable, allow the rotor speed to increase as wind speed increases, until the cut-out speed is reached. Variable speed turbines allow higher energy capture at many wind speeds, but more significantly they absorb gust energy more easily and have better power regulation, making them more compatible with utility systems (Manwell 1991). They are also expected to last longer than CSWTs since the stresses experienced by rotors forced to maintain a constant speed are avoided by allowing the turbines to rotate at a variable speed.

A significant difference between these and earlier turbines is that variable speed turbines require advanced electronics to convert the variable frequency ac power generated to dc, and then to 60 Hz ac power as required by the power grid. The drawback to this approach is that the additional electronics add to the cost, complexity and maintenance needs of the turbine. One industry alliance, composed of US Windpower, Pacific Gas and Electric, EPRI and Niagara Mohawk Power Company has developed a VSWT. This project is currently operating prototype 300 kW turbines which generate good quality electricity (e.g. little power conditioning required) at 5¢/kWh at good locations (~8 m/s or ~18 mph average wind speed). Two of these turbines are currently being tested by Niagara Mohawk, at Tug Hill Plateau, near Lake Ontario. These turbines are expected to be commercially available by 1994 (Douglas 1991).

Vertical Axis Turbines

Although less common, vertical axis machines are still designed and used. Two of the more common vertical axis machines are the Savonius and the Darrieus. The Savonius rotor can be described as a hollow vertical cylinder cut in half lengthwise from top to bottom, with the two halves then shifted to overlap each other. (A diagram can be found in Hunt, 1981.) The Darrieus, the more common of the two, is most easily described as an 'egg-beater' (Hunt 1981). Projects and analyses of these two machines as well as others can be found in current literature (Hunt 1981; Nahas 1987; numerous articles in "WindPower Proceedings" ASME Conferences).

WIND TURBINE COSTS AND PERFORMANCE

A good idea of current wind turbine performance characteristics and costs can be obtained from looking at wind industry experience around the world, and at the California wind farms in particular. This section discusses current trends in wind turbine costs and performance.

Currently providing eighty percent of the world's wind power generation via 1600 turbines, California's wind farms produce electricity at 5-9 ¢/kWh with an average wind turbine rating of 100 kW to 400 kW (Freris 1990; OTA 1985; Douglas 1991). Even though the Renewable Energy Tax Credits ended in 1985, wind power is considered cost-effective, with manufacturers guaranteeing a mechanical reliability of 95%, at a cost of $1400/kW installed (in 1990). (Roughly 10% in additional costs should be allotted for land, administrative and interconnection costs.) In addition to cost data, the California wind farms provide information on load factor – with the average capacity factor around 25% percent, reaching a maximum of thirty to thirty-five percent (Chapman 1992; Freris 1990).

As with conventional power plants, which require maintenance throughout the year, wind turbines have operation and maintenance costs. In addition to the general maintenance of the turbine, system and site, turbine blades must be cleaned periodically, since fouling (insects and other matter sticking to the blades) decreases their aerodynamic performance.

Table ·1: Wind Energy Characteristics and Costs

System Costs	O&M Costs	Energy Capture	Cost of Energy	For Year:	Estimated In year:	Source Notes
			7 - 9	1991	1991	EPRI Journal, June 1991 (91$, for CA)
			4 - 5	2000	1991	EPRI Journal, June 1991, (91$)
			3.5	2005	1991	"
1400				1990	1990	Freris 1990, (for CA)
800			5	(seeking site)	1991	USWP & IA-IL G&E Co; NYT 11/14/91
2500 (offshore)			9.5	1991	1991	Danish offshore wind farm, MPS 1991
						Hock 1990; for "good sites" with avg. wind speed 6.5 - 8.5 m/s; (89$) **
1050	0.01	330 - 550	5 - 8	1990	1990	- baseline design
1050	0.005	56% increase	3 - 5	1995	1990	- variable speed
924	0.004	49% increase	3 - 5	1995	1990	- stall controlled
1000	0.022 *	42% increase	4 - 6	1991	1990	- industry design 1
580	0.015	0% increase	3.5 - 5.5	1990	1990	- industry design 2
625	0.008	45% increase	2 - 4	1996	1990	- industry design 3
						Dodd 1990; current R&D funding levels
			8	1990	1990	- 5.8m/s avg speed
			6.5	1990	1990	- 7.2m/s avg speed
			5.2	1990	1990	- 8.5m/s avg speed
			6.4	1995	1990	- 5.8m/s avg speed
			5.2	1995	1990	- 7.2m/s avg speed
			4.2	1995	1990	- 8.5m/s avg speed
1013	0.007	350	7.5	1991	1991	SERI/Utility Wind Interest Group 6.7m/s site; EPRI TAG calc method.
1000				1992	1992	Jamie Chapman, OEM Development Corp., Boston MA.
600 - 800				near future	1992	
($/kW)	($/kWh)	(kWh/yr xE3)	(¢/kWh)			

* includes amortization for major retrofits

** The 'system costs' for this study include only turbine capital costs and NOT cost of installation.

Wind turbine maintenance costs average 0.9¢/kWh (ranging between 0.01¢ to 5.0¢/kWh) (Freris 1990; Hock 1990). Table 1 presents a survey of cost and performance values for current and future wind turbines and systems.

ENVIRONMENTAL IMPACTS OF WIND TURBINES

Electricity generated from wind power has the environmental benefit of zero pollutant emissions. There are however environmental considerations such as large land requirements and potential visual and acoustic pollution that need to be considered. These detriments are discussed below.

Land Use

Early studies of wind turbines show that they can require anywhere between fifteen and eighty acres per megawatt (OTA 1985 - Table A3), with an analysis of the Altmont Pass wind farm estimating 4.3 acres/turbine, or 43 acres/megawatt (The average turbine rating there is 100 kW) (Smith 1991). The difference in land requirements depends on the diameter of the turbine blades, and on the spacing between turbines in the wind farm.

Although the turbines only occupy between one and twenty percent of the land in a wind farm, negative impacts on the land arise from the fact that the land often needs to be cleared of trees and other vegetation in installing the facilities. Since most of this damage occurs in the initial installation phase though, the land can be replanted once the wind farm is in operation. A recent study performed by Green Mountain Power in Vermont estimates actual land use closer to 4 acres/megawatt, including access roads and new transmission lines (Ralph 1992).

Noise Impacts

Noise from wind turbines comes from two sources; mechanical noise from the rotating machinery, and vibrational noise from the wind itself interacting with the turbine blades and tower structure. The amount of possible noise pollution has been shown to be of considerable concern to the Dutch, English and California residents, and should not be overlooked when siting an actual wind farm (van Beek 1991; Bosley 1992; Larke 1991; Pitcher 1991). The various studies listed above have suggested that public relations campaigns which involve local residents in WECS projects, can result in higher levels of acceptance. There are current efforts to optimize the new designs to minimize noise, and develop siting methods which reduce the noise impact on neighboring communities. Based on experience in New England where most wind farm sites are on mountain ridges which are further than one mile from residences, Green Mountain Power finds that noise is not a significant problem in the siting or operation of wind farms (Ralph 1992).

Visual Impacts

Visibility issues may arise from the fact that wind turbines tower above trees and most buildings, and can be considered unattractive. The possible need to remove trees from an area for turbine installation only exacerbates this problem. However, drawing on experience from Green Mountain Power, the potential negative aspect of wind turbine visibility can be mitigated by involving local residents in the planning phase of the project (Ralph 1992). Residents' willingness to allow wind turbine installation in their communities is based more on their interest in renewable resource use and potential financial impact on their community, than on visibility issues. In fact, experience of GMP from operating two clearly visible turbines in Vermont since 1990 reveals that local residents are interested in having more turbines installed – provided they remain operational.

Other studies find similar results – efforts to decrease the destruction of vegetation, combined with campaigns to increase the involvement of local residents leads to improved acceptance of the projects (Bosley 1992; Larke 1991; Pitcher 1991).

PHOTOVOLTAIC TECHNOLOGY

Numerous technologies use solar energy to generate electricity. Solar thermal technologies focus the solar energy directly onto a working fluid which is then used to create steam to drive a turbine for power generation. These technologies rely on direct radiation only, which requires a location with a better solar resource than that in New England. A technology which uses both direct and diffuse radiation, making it better suited to the New England environment, is photovoltaic (PV) technology which converts sunlight directly into electricity via semiconductor technology. Although there are some concentrator PV systems which utilize only direct radiation, "flat-plate" PV systems, or simply solar cells, use direct and diffuse energy.

This section discusses photovoltaic technologies, focusing primarily on flat-plate systems whenever these differ from concentrator systems. A detailed discussion of semiconductors and how they convert sunlight to electricity is necessary for understanding both why PV efficiency is not 100 %, and the direction of current research. An explanation of why 100 % conversion efficiency cannot be achieved is thus followed by a discussion of current areas of research aimed at increasing the efficiency while decreasing the costs of PVs. Since photovoltaic technology is not as well established as that for wind turbines, time is invested here discussing a number of different promising PV technologies. The remaining components of a photovoltaic system are introduced next, followed by an overview of cost and performance of these systems. The section concludes with a discussion of possible environmental concerns of PV production and use.

SEMICONDUCTOR PHYSICS

Electric current is the flow of electrons. In order for electrons to flow around a circuit they must be "free," which is to say they must not be bound to any one atom in the material in which they are flowing. The basic principle behind photovoltaics is that if a semiconductor is connected to an electrical circuit and placed in sunlight the energy in the solar radiation will create free electrons which can then flow in the circuit. The challenge with PVs lies in capturing a significant amount of solar radiation and converting this to electricity at a high efficiency and a low cost.

Substances classified as metals have many free electrons, allowing current to flow easily, while the electrons in insulators are tightly bound to the atoms. Semiconductors lie between these two extremes. Most electrons in semiconductors are bound to atoms. Some electrons however, referred to as valence electrons, are very loosely bound to their atoms, and can be knocked free relatively easily when additional energy is supplied. The difference in energy between a valence electron and a free electron is defined as the energy gap or the band gap, E_g.

The most abundant semiconductor is silicon (Si), and will be the semiconductor referred to in the following discussions. Other semiconductors behave similarly. As a basic property, crystalline silicon is more stable than atomic silicon due to the fact that when in a crystal, surrounded by four other silicon atoms, each atom shares its valence electrons with its neighbors so that every atom has eight instead of the usual four valence (or loosely bound) electrons. The result of this increased (though shared) number of electrons is greater stability, with all the valence electrons bound more tightly.

Voltage Generation

To generate power a PV cell must supply both voltage and current. The first step in obtaining the voltage source is to dope the semiconductor, which allows them to conduct electricity more readily. A dopant is a second semiconductor, added to the first semiconductor, as an impurity. There are numerous methods for doping silicon, with essentially equivalent results. The result of the doping processes is that about one in every one million Si atoms is replaced by a dopant atom. The significance in this exchange is the effect on the electrical properties of the silicon. If the Si is doped with a substance such as phosphorous which has five valence electrons to silicon's four, the resultant silicon crystal has essentially extra electrons, which are easily freed from the crystal lattice by the amount of thermal energy available to the crystal at room temperature.

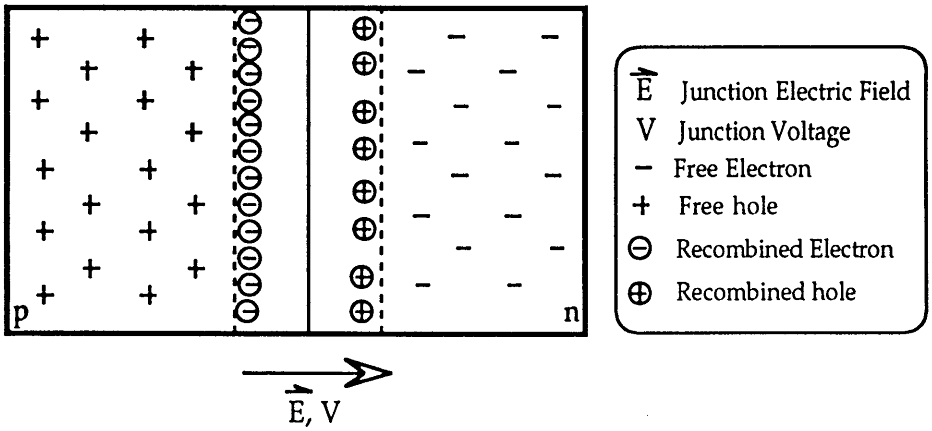
The fifth electron is readily freed because the crystal as a whole, composed predominantly of Si atoms, still requires only eight shared electrons per atom for increased stability. Thus the fifth electron from phosphorous is bound *very* loosely, and with the energy supplied by room temperatures, becomes free to move throughout the crystal lattice. This type of silicon is referred to as "n-type," or negatively doped due to the extra negative charge carriers (electrons). Note that the crystal as a whole is electrically neutral since phosphorous atoms have one more proton (positively charged particle) than silicon atoms to balance the extra electron.

The second type of doped semiconductor is called "p-type," for positive, referring to dopants with one less valence electron than silicon, such as boron. Rather than adding an extra electron to the crystal lattice, boron adds a "hole," or the absence of an electron. Although holes are artifacts, and not physical quantities, they are treated as actual positive charge carriers. As one electron moves to fill this "hole" in the lattice, it creates a new hole at its previous position. As this process repeats, the hole is said to move through the lattice.

The reason for doping semiconductors becomes apparent when n-type and p-type semiconductors are joined to form a p-n junction. When p and n silicon remains separate, the extra holes and electrons, respectively, move at random through the silicon crystal, while maintaining electrical neutrality in each. When p and n silicon are joined however, the free electrons in the vicinity of the junction move across the junction to fill the holes. In the region of the junction two interrelated processes are occurring simultaneously. First, electrons and holes recombine, with the electrons obtaining more stable positions in the crystal lattice. Second, due to this flow of charge carriers the junction region loses its charge neutrality, creating an electric field across the junction. This region is the area between the dashed lines in figure 2.

The force of the electric field is directed to resist the flow of charge carriers across the junction. The arrow in figure 2 points in the direction that *electrons* are allowed to flow in the presence of the electric field. Holes flow in the opposite direction. Equilibrium is reached when enough carriers have crossed the boundary to create an electric field strong enough to prevent any further flow of electrons or holes. In this manner a junction voltage is created, since the creation of an electric field is also the creation of a voltage. (Voltage *is* an electric field applied across a given distance, in this case the p-n junction.) The voltage is directed so that free electrons are forced to the n side and free holes to the p side. In the event of a hole or electron existing on the 'wrong' side of the junction, it is swept across by the voltage.

Figure 2: Semiconductor P-N Junction



Current Generation

P- and n-type silicon joined to form a p-n junction as introduced above, has electrons free to flow as current in the n side, and holes (which must flow in the direction opposite to the electrons to contribute to the same current) free to flow in the p side. These charge carriers, electrons on the n side, and holes on the p side, are referred to as "majority carriers." Electrons and holes generate as pairs spontaneously throughout the Si crystal, and recombine almost instantly. Thus there are both holes and electrons on both sides of the junction, with holes on the n side, and electrons on the p side referred to as "minority carriers."

The discussion of semiconductors up to this point applies equally as well to the computer industry as to photovoltaics. The process of generating current for these two applications differs however. In photovoltaic cells, current is generated when the energy in sunlight is absorbed by the valence electrons, converting them into free electrons. Creation of a free electron means the creation of a hole also, and thus the absorption of solar energy results in majority and minority carriers being generated on both sides of the p-n junction; current generation in PV cells depends upon both the majority and minority carriers.

As stated above, current is the flow of electrons around a circuit. In a solar cell, electrons flow from the n-type material, through the external circuit, into the p-type and through the junction. This process requires that electrons, as minority carriers in the p-type material, do not recombine with the majority holes so that they reach the junction voltage and are swept across into the n-type material. (Holes follow the identical cycle, except in the opposite direction.) In darkness and in equilibrium minority carriers tend to recombine before reaching the junction. Any potential net current arising from some minority carriers crossing the junction is exactly balanced by an equal drift of majority carriers moving in the opposite direction. (If this were not true, the material would not be in equilibrium.)

When placed in sunlight, the situation changes. Now, many electron-hole pairs are created on each side of the junction from the absorption of solar energy; with half of each pair joining the majority carrier population, and the other half joining the minority carriers. The goal in a PV cell is to have many of these pairs generated in the vicinity of the junction, with the carriers remaining apart long enough so that the minority carriers are swept across the junction by the junction voltage, while the majority carriers are forced to remain on the original side. With a net flow of electrons and holes (in opposite directions) across the junction, the electric circuit is complete, and the PV cell can now generate electricity.

SOLAR CELL POWER OUTPUT

Electrical power generation requires both voltage and current[2]. The manner in which a solar cell generates both of these was explained above. This section describes how to determine the maximum voltage and current which can be generated in any one cell, as well as the values of voltage and current when they are generated together.

Open Circuit Voltage

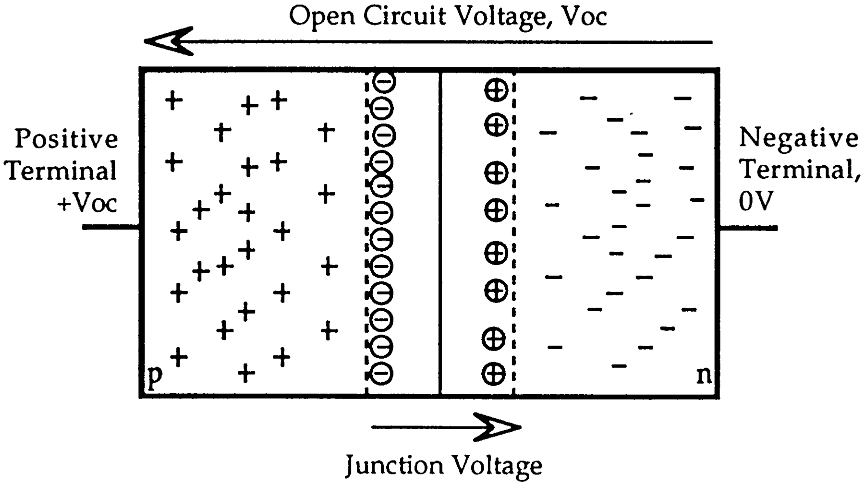
To determine the maximum voltage a solar cell can generate, the cell is placed in sunlight, without being connected to an external circuit. The solar

---

[2] Power is in fact the product of voltage and current: $P = V*I$.

energy generates minority carriers which flow through the junction. Since the cell is not connected to a circuit, the carriers, now majority carriers (having traversed the junction), can not flow as a current and thus build up on each side of the junction, as shown in figure 3.

Figure 3: Open Circuit Voltage of a PV Cell



As these carriers build up they serve to create an electric field, and thus an open-circuit voltage, V_{OC}, with opposite polarity to the junction voltage. This process continues theoretically until V_{OC} just equals the junction voltage, at which point the two voltages cancel each other out, and the charge carriers are free to move throughout the crystal.

The magnitude of the junction energy[3] is limited by the energy gap of the semiconductor, E_g, defined previously as the energy difference of a valence and a free electron. (Note that energy is voltage divided by the unit electronic charge.) The maximum possible V_{OC} is limited by this maximum junction voltage. In practice, due to imperfections in the crystal, the junction energy is always slightly less than E_g, and V_{OC} is always slightly less than the junction voltage. These discrepancies are discussed below in the section on cell efficiency.

---

[3] The junction energy in electron volts, eV, is the electron charge multiplied by the junction voltage. 1 eV = 1.6E-16 Joules.

Short Circuit Current

The maximum current a solar cell can generate is determined through a short circuit test, in which the two terminals of the cell are connected directly together without any load. The cell is placed in sunlight which generates free electrons and holes on both sides of the junction. The junction voltage then facilitates the movement of these photogenerated minority carriers across the junction, while the majority carriers are prevented from crossing the junction. These carriers are then free to flow around the external (short) circuit, resulting in the cell's maximum possible, the short-circuit current, I_{SC}. Note that in this configuration there can be no voltage at the terminals of the cell since they are shorted together.

Power Generation

Power generation as stated above is the product of voltage and current. An upper bound on the power from a PV cell is the product ($V_{OC} * I_{SC}$). However, V_{OC} is only possible when the cell is open-circuited and thus there is no current, and I_{SC} can only be generated when the cell is short-circuited, and thus there is no voltage. For power generation there must be *both* voltage and current, and thus for actual operation the limit of ($V_{OC} * I_{SC}$) can not be reached.

When the PV cell is placed in sunlight and also connected to a resistive load, the load allows some current to flow around the circuit, yet also resists some current flow, causing some majority carriers to build up in the PV cell, and creating a voltage at the terminals. Thus both a voltage, $V < V_{OC}$, and a current, $I < I_{SC}$, are generated, and the cell produces power.

SOLAR CELL EFFICIENCY

A solar cell does not achieve one hundred percent efficiency in converting solar radiation to electricity for many reasons. Some decreases in efficiency are the result of physical properties of the solar spectrum and the semiconductor materials used, while others are more the result of manufacturing and design characteristics, and hopefully will be improved with continued research.

Conversion Efficiency: Semiconductor Properties

One area of central importance to the operation of PV cells is the specific interaction of solar radiation with the semiconductor atoms in the process of creating free electrons. The most important point is that an electron bound to the crystal lattice requires a precise amount of energy, all at once, to be knocked free from the crystal. This amount of energy is defined as the energy gap, E_g[4]. Therefore it is necessary for the incoming solar energy to have this precise amount of energy, E_g, if the PV cell is to generate power. As discussed in the previous chapter, energy in electromagnetic radiation is defined as $E = h\nu$, where ν is the frequency (and h is a constant). The first impact on PV conversion efficiency arises from solar radiation with frequencies below the value for which $h\nu = E_g$, making it unavailable for electricity generation. For silicon, which has an energy gap of 1.1 eV, this means that 24% of solar radiation is useless. The other end of the spectrum consists of energy in frequencies for which $h\nu > E_g$. In this situation, the energy beyond that required to free a single electron serves only to generate heat in the semiconductor. For silicon, the energy lost from high frequency radiation amounts to about 32% of available solar energy.

A third source of loss comes from the effect temperature has on semiconductors. In solar cells, a temperature rise results in a decrease of the junction voltage, which translates directly into a lower terminal voltage and thus lower power output. To some extent, the detrimental effect of higher temperatures can be lessened by externally cooling the PV cells, yet this requires energy, and adds cost which may not be offset by the increased power output.

Conversion Efficiency: Solar Cell Construction[5]

The absorption of solar energy results in the creation of electron-hole pairs. The object in constructing a PV cell is to separate these pairs and force the

---

[4] E_g was defined before as the energy difference between a valence electron and a free electron.

[5] The loss percentages given in this section are representative of silicon technology around 1980, and have decreased over the previous decade. However, they are a consistent set of values, and present a good idea of the relative magnitude of losses due to intrinsic semiconductor properties to those from solar cell construction.

charge carriers around an external circuit before they recombine with each other. A certain amount of the charge pairs generated recombine before reaching the voltage at the junction which separates them. The loss in conversion efficiency due to this recombination is around 12%.

"Voltage factor loss" is the term used to quantify the result found above that V_{OC} is always less than E_g[6]. It is defined as the ratio of V_{OC} to E_g, and equals 0.62 or a 38% loss for silicon. A third loss factor is the "curve factor loss" which quantifies the amount by which the actual peak power generation of a solar cells falls short of the theoretical maximum of (V_{OC} * I_{SC}). This factor is the ratio of (V*I) to (V_{OC} * I_{SC}) where V and I are the voltage and current actually generated by the cell, and is 0.82 or an 18% loss for silicon. The "curve factor loss A" is a further reduction in power output caused by a small amount of current which leaks backward through the junction rather than around the circuit, through the load. This value is 0.90 for silicon, or an additional 10% loss.

Pure crystalline silicon, when cut and polished, reflects about 30% of incident sunlight. Anti-reflective coatings greatly reduce the reflectivity of silicon, yet approximately 3% of the energy is still reflected. One final source of loss arises from the need to have electrical contacts on both the top and bottom of the solar cell in order to form a complete electric circuit. A solid metal plate is often used on the bottom surface. Yet this is impractical for the top surface, because then no sunlight would reach the solar cell! Therefore a balance must be obtained between covering enough of the top surface to provide a reasonable electrical contact, without shading so much of the cell that much incoming solar radiation is lost. Loss from this source is roughly 3%. And finally, the amount of current reaching the external contacts is decreased by the electrical resistance of the semiconductor itself. This source of loss is about 3%, and is exacerbated as the semiconductor layers become thinner (as with thin-film technology, discussed below).

---

[6] Both factors here are in units of electron-volts, eV.

Table 2 lists all these loss factors, along with their cumulative effect on the efficiency of a silicon solar cell (Fan, 1978; Merrigan, 1980). The second column in the table gives the mathematical representation of the loss if appropriate. The third column lists the percent of the *remaining* solar radiation lost due to each loss factor. For example, 24% of all incoming radiation is lost due to the frequency being too low. Of the remaining *high frequency* energy, 43% is lost, or 33% of the initial, incident radiation (0.76 * 0.43 = 0.33). The final column contains the net solar cell efficiency. The combined effect of all loss factors is about 85%, leading to a net, maximum solar cell conversion efficiency of 15%.

Table 2: The Efficiency of Crystalline Silicon Solar Cells

Source of Decreased Efficiency	Representation	% of Net Radiation Lost	Net Cell Efficiency
Low Energy Radiation	$hv < Eg$	24%	76%
High Energy Radiation	$hv > Eg$	43%	43%
Temperature	-	variable	-
Voltage Factor Loss	Voc/Eg	38%	27%
Curve Factor Loss	(V*I)/(Voc*Isc)	18%	22%
Curve Factor Loss 'A'	-	10%	17%
Recombination	-	12%	19%
Reflection	-	3%	17%
Series Resistance	-	3%	15%
Contact Shadowing & other non-ideal losses	-	10%	15%

SEMICONDUCTORS AND PV CONSTRUCTION

The choice of semiconductor and manufacturing process greatly impacts both the efficiency and cost of PV cells. Originally all cells were made of crystalline silicon manufactured with the same processes developed for the computer industry. These techniques produce very high quality silicon in comparatively thick wafers (~ 300 μm thick circular slices of a silicon crystal) which are not necessarily ideal for photovoltaic use. Subsequent research has introduced the use of semiconductors other than silicon, semicrystalline and amorphous silicon, and the use of semiconductor layers only 2 to 3 μm thick.

Semicrystalline Silicon

Charge carriers can easily move throughout a single crystal. In a semicrystalline cell, which contains boundaries between each distinct crystal, the charge carriers do not readily cross crystal boundaries, increasing the internal resistance of the cell, and the likelihood of recombination. (The atoms at crystal boundaries do not have four neighbors with which to share valence electrons, leaving many open sites for electron-hole recombination.) Charge carriers do move easily *along* crystal boundaries though, which can result in a short circuit across the p-n junction, rendering the PV cell useless.

The benefit of semicrystalline cells is that they are much cheaper to produce than single crystal ones, requiring less energy to manufacture and resulting in less waste of the silicon produced. Even though semicrystalline cells are less efficient than single crystal ones, they are used almost as much as single crystal cells due to their lower cost.

Thin Films

The ability of a semiconductor to absorb solar energy, and not have the energy simply pass through the material is measured in terms of the thickness of the substance required to absorb a given percentage of incident energy. The percentages of the energy absorbed and transmitted are given by the equations:

$$\%\ \text{transmitted:} \quad e^{-\alpha t}$$

$$\%\ \text{absorbed:} \quad 1 - e^{-\alpha t}$$

where e is the natural logarithm, t is the thickness of the material, and α is the absorption coefficient. α differs between materials and with the wavelength of the incident energy. For silicon, α ranges from 10^3/cm to 10^5/cm for the solar spectrum. Using the mean value for α of 10^4/cm and assuming a thickness of a single crystal silicon PV cell of 10 μm, the above equation reveals that ~100% of the energy is absorbed. Within a thickness of 1 μm however, only 63% of this energy is absorbed.

Thin film technology, as the name suggests, produces PV cells from thin layers (from < 1 μm to several μm thick) of semiconductor material. The materials used are selected, and specially manufactured to absorb a high percentage of the incident energy in a very short distance (or thickness). These films can be produced in large sheets, thus avoiding the need for connecting many small cells together to form a module as with crystalline wafers. There is also research on using transparent sheets of metal for the top electrical contact, thus avoiding the problem of shading the cell with metal contact fingers. Another benefit of using thin films is that a higher percentage of the minority carriers reach the junction and are swept across before recombining. This decrease in recombination relative to single crystal Si occurs since the relative "thinness" of the layers means no region of the cell is far from the p-n junction and the influence of the junction voltage. Thin films can be produced at lower cost than single crystal cells while maintaining reasonable conversion efficiencies. (Zweibel, 1993) The example of absorption thickness above demonstrates that crystalline silicon is not suitable for thin film application. Instead, amorphous silicon, a-Si, cadmium telluride, CdTe, and copper indium diselenide, CIS, are used.

Amorphous Silicon, a-Si

Amorphous silicon has no broad crystalline structure at all, and thus is subject to a high degree of recombination of charge carriers. This problem can be partially overcome by adding hydrogen to the silicon to occupy some of the available "holes." a-Si has a band gap, E_g, of 1.7 eV, to crystalline silicon's 1.1 eV. This translates into higher V_{oc} and thus greater power output. a-Si also absorbs solar energy much more efficiently than crystalline silicon, requiring only 1 μm to absorb 90% of the energy (in contrast to 63% absorption by crystalline SI in the example above). One unique property of a-Si is that its efficiency actually decreases during the first 1000 hours of exposure to light. a-Si cells are assumed to stabilize around 10% efficiency, yet due to the newness of this technology, numerous stability tests have not been performed.

Cadmium Telluride, CdTe; Copper Indium diSelenide, CIS

Cadmium telluride and copper indium diselenide are both polycrystalline materials[7] which research shows to be promising for thin film PV use, and durable in long term outdoor exposure. The comparatively low band gap of 1.0 eV for CIS can be boosted by doping it lightly with gallium. CIS absorbs sunlight very efficiently however, requiring only 1 μm to absorb 99% of the available energy. Test cells have reached 14% efficiency, with full modules (many interconnected cells) achieving 9%. CdTe has an almost ideal band gap of 1.44 eV[8], and also absorbs solar energy efficiently. It tends to have a relatively high intrinsic resistance though, and there are some problems with obtaining good electrical contacts with the cells. The best cell and module efficiencies for CdTe have been 12% and 7% respectively.

Gallium Arsenide: GaAs

One final material currently being researched is gallium arsenide. Gallium is exceedingly rare, and arsenic is toxic, yet single crystal GaAs cells have achieved almost 26% conversion efficiency, and cells produced in commercial volume average 20% efficiency! GaAs absorbs solar energy very efficiently and has a nearly ideal band gap of 1.4 eV. It is also relatively insensitive to temperature changes, and is very versatile as far as design and manufacturing processes. GaAs remains too expensive for serious consideration for large scale use for flat-plate PV systems.[9]

Multilayer Junctions

---

[7] Polycrystalline materials are similar to semicrystalline materials, except the crystal grains in polycrystalline materials are smaller and stacked both horizontally and vertically. In semicrystalline materials, each crystal traverses from top to bottom of the semiconductor layer, with the crystals being lined up horizontally

[8] A large E_g results in a large junction voltage and therefore a large V_{oc} and increased power output. Yet as E_g increases the amount of radiation lost due to $h\nu < E_g$ increases. A balance of these effects results in $E_g \sim 1.4$ eV being an ideal E_g for the solar spectrum.

[9] Concentrator PV systems, mentioned in the introduction to this chapter can use GaAs economically though, and will probably be a major market for GaAs technology. (Cook, 1991)

Based upon the band gap, E_g, and the absorption coefficient, α, each semiconductor absorbs different ranges of wavelengths of solar energy more or less efficiently. One method to maximize the conversion efficiency of a PV cell over the entire solar spectrum is to use multijunction devices. Such devices layer different semiconductor materials of different thicknesses so that each layer absorbs the energy it converts most efficiently, and transmits the remaining energy to the next layer. Multijunction devices are typically used with concentrator systems, and have achieved efficiencies greater than 30%.

PHOTOVOLTAIC SYSTEMS

To generate electric power, a single PV cell must be incorporated into a larger system. A single solar cell can produce about 1 to 2 watts of power. In order to generate more useful amounts, many PV cells are joined together into modules, and modules are then grouped into arrays. These inter-cell connections are difficult to make both electrically and environmentally durable. These arrays also require support structures and some use mechanisms to track the sun throughout the day. If the power generated is to become part of a larger utility system relying on ac rather than dc power, the PV system also needs an "inverter" to convert the dc power from the PV arrays into the ac power required by the utility grid. These additional components are referred to as the balance-of-system, or BOS, and add cost, maintenance requirements and further reductions in efficiency.

Tracking Systems

Solar energy systems can have either one or two-axis tracking or no tracking mechanism. A one axis tracking system tracks the sun on its daily East-West path. A two axis tracking system adds the capability of tracking the North-South seasonal variations in sun position. Such mechanisms are required for solar concentrating systems to be effective (one axis tracking is sometimes also used for non-concentrating systems), but they do add cost and complexity and require additional maintenance.

The alternative to tracking the sun, is to mount the PV with a fixed direction, and at a set tilt so as to maximize energy capture. A rule of thumb for such a fixed axis, flat-plate system for the Northern hemisphere is to have the array face South, tilted at an angle equal to the location's latitude. This configuration maximizes the energy capture at solar noon, when the solar energy is strongest, and is perpendicular to the array. Other tilt angles may also be desirable. For the Southern New England region, a 10° tilt angle has been found to only slightly decrease the total energy capture, while making up for this loss by partially smoothing out the daily and seasonal peaks and troughs in power output, and thus providing a more constant power source (Kern, 1992).

Power Conditioners

The power, or more specifically the voltage and current output of a PV array must be regulated to maintain maximum power output, and smooth sudden changes. When connected to a grid, the power must also be converted to ac through the use of power electronics. And finally, the power conditioning unit should be equipped with a switch to disconnect the array from the grid when necessary, such as when repair work on the grid is required.

PHOTOVOLTAIC COSTS AND PERFORMANCE

Now that the basics of PV cell and system operation have been discussed, along with the current areas of research, a broader, historical perspective of PV use will be explored.

Historical Overview

Photovoltaics were first utilized in 1954 to power satellites, and survived as a federally funded area of research strictly due to their use to the space program. Since then they have both increased in efficiency and decreased in cost, yet both of these properties need to improve further before they can claim the hoped for position of baseload generation. Even so, the market is growing with a twenty-five percent growth rate per year, at a current worldwide market of $300 million; $80 million of which is in the United States. (The total current world capacity is around 55 MW.)

Currently, it is cheaper to use photovoltaic power generation than to build a power grid extension for a small load of a few tens of watts if the load is located 200 or more feet away from an existing transmission line, and the reliability is of higher priority than cost. Although this electricity is generated at a cost of 25-30 cents/kWh, stringing a new wire would be more expensive. Currently applications such as street lighting, electronic communications equipment, agricultural water pumping, remote residences and warning devices fall into this category. When costs fall to 10-20 cents/kWh, PV will become competitive for loads up to a few hundreds of watts (EPRI, March 1991).

PV technology has lagged behind that of wind turbines in spite of considerable federal funding, which increased from $35 million in 1990 to $60 million in 1992. Technological improvements have continued, and as seen in table 3, PV cell efficiencies have improved dramatically since 1978. These values represent the current technological ceiling.

Table 3: Single-Cell Photovoltaic Efficiencies

Technology	1978	1991
Thin film, flat-plate	5%	15%
Single crystal Si, flat-plate	16%	22%
High efficiency concentrator cells	23%	32%

There is both commercial interest and technological progress in PV technology in many countries. In the United States, Pacific Gas and Electric is considering placing PV modules underneath their thousands of miles of transmission lines. Niagara Mohawk is building a 16 kW array for servicing commercial buildings in Albany NY, to test the commercial viability of such a project. On the technology side, Texas Instruments is developing a new technology called Spheral Solar, which might significantly cut production costs through its use of abundant, yet less pure (99% pure) silicon.

Pacific Gas and Electric, the US Department of Energy, the Electric Power Research Institute, the California Energy Commission and many utilities around the country have joined in a cooperative effort called Photovoltaics for Utility Scale Applications, or PVUSA.

> PVUSA's objectives are to provide utilities with hands-on experience installing and operating PV systems, to compare and evaluate PV systems for performance and reliability, to assess operation and maintenance costs in a utility setting, to evaluate PV systems in differing geographic areas, and to document findings and exchange information among utilities and manufacturers. (Hester, 1992)

PVUSA is currently monitoring five 20 kW "emerging module technology" projects, four in Davis, CA, and one in Maui, HA. Additional utility scale projects, sized from 200 kW to 400 kW, are near completion. The results so far have shown an average capacity factor around 21%, with crystalline Si efficiencies averaging from 10% to 12%, and a-Si efficiency reaching only 3% to 4%!

Germany is operating a 340 kW plant consisting of varying types of PV cells and complete systems, in order to obtain data on cost, reliability, efficiency and power output. The results so far, of this project, point to a crystalline module made by Hoxan Corporation in Japan, as being the highest efficiency, commercially available module today, achieving 13.3 percent conversion efficiency. (This number is lower than what would be hoped for considering numbers quoted in table 3 above, yet this number is for the module rather than cell efficiency.)

Unfortunately results of this project show that overall costs remain very high. On average, the *total investment cost* for the systems at the German site, including the cells, balance-of-system (electronics and support system) and construction was $\$15/W_p$. Of this amount, fifty-six percent was for the solar cells themselves, nineteen percent for the electrical systems engineering, with an additional seven percent for the assembly of the modules.

Japan is also involved in PV research. The Japanese government provides $56 million per year for PV research, through a program called the Sunshine Project. The Kyocera Corporation manufactures 3 MW to 5 MW per year of modules at a cost of \$4.60 to \$5.40/W_p. For 1988, this translated to generation costs of $1.80/kWh, with a projection for 1995 of $0.80/kWh. They hope to have this drop further to $0.23/kWh by 2000. Due to the dynamics of the energy industry, with oil prices affecting the levels of manufacturing and research funding of other energy technologies, this drop in costs is likely to happen only if PV prices continue to decline, *and* oil prices rise!

Both the projects in Germany and Japan have lead to interesting results in that amorphous silicon cells have not performed as well as was hoped in the 1980s. Although they do have the potential to provide a low cost form of silicon cell production, engineering problems of inherently low conversion efficiency and deterioration of the photovoltaic characteristics have not yet been overcome. They also often do not perform to manufacturers' claimed specifications of voltage-current output at specified insolation and temperature levels. Therefore, crystalline cells are likely to continue as a major technology in mass production, due to their consistent ability to meet manufacturers' specifications, and higher reliability.

Experience from Grid Connected PV Systems

One of the largest and most successful grid connected PV projects has been in full operation since 1989 in Gardner, MA, run by New England Power Service. This project includes thirty 2.2 kW dc roof mounted residential systems, and eight systems ranging from 1.8 kW to 7.3 kW dc, mounted on the roofs of commercial and institutional buildings. All systems are crystalline silicon, with an average conversion efficiency of 11%. One of the major purposes of this project was to examine the impact of a high concentration (53%) of independent PV systems with a single distribution feeder would have on customer service and on system reliability. The results have been excellent. On clear summer days, enough energy has been generated to supply 25 other residences. There have been no major reliability problems either with the PV systems or on the distribution network. Two other projects in the US, one in Laguna del Mar, CA, and the other in Phoenix, AZ, contribute more experience. Overall the systems have had good reliability and wide acceptance by homeowners. Results have also shown benefits to utility ownership, and pointed to power conditioners as the key component in system reliability, since if the power conditioner fails, continued system operation is prevented. (Russell, 1990)

Summary

Cell production costs have fallen ninety percent since 1980, yet they need to fall much further for mass production to become a reality. The values quoted from Armech Solar Power and the Japanese project are optimistic, yet are projections, not reality, so can not be taken as fact. The value for total system cost of $\$15/W_p$ from the project in Germany is an actual cost, yet represents an isolated test project and not mass production, and so is unduly pessimistic. Figures 4 and 5 graph the trends in increasing cell efficiency and decreasing price (Carlson, 1990). Figure 4, graphing the low end of the yearly average efficiency range, shows that average module efficiency has steadily increased toward a near future average close to 17%. Figure 5 shows that the average module price has steadily decreased, from around $\$100/W_p$ in the early 1970s, to $\$3.75/W_p$ in 1988. Table 4 traces various estimates of PV costs and efficiency for different technologies, obtained from numerous journal articles, listed in the references.

<u>Figure 4: Average Commercial Crystalline Silicon Module Efficiency</u>

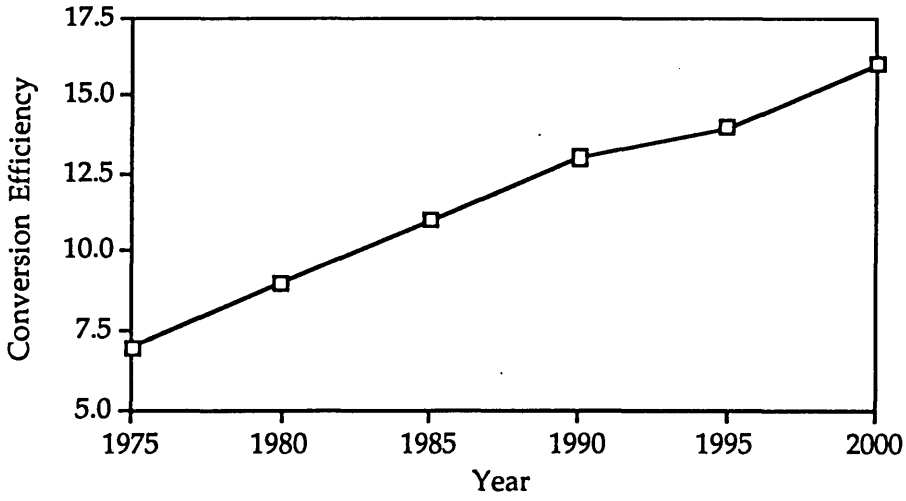
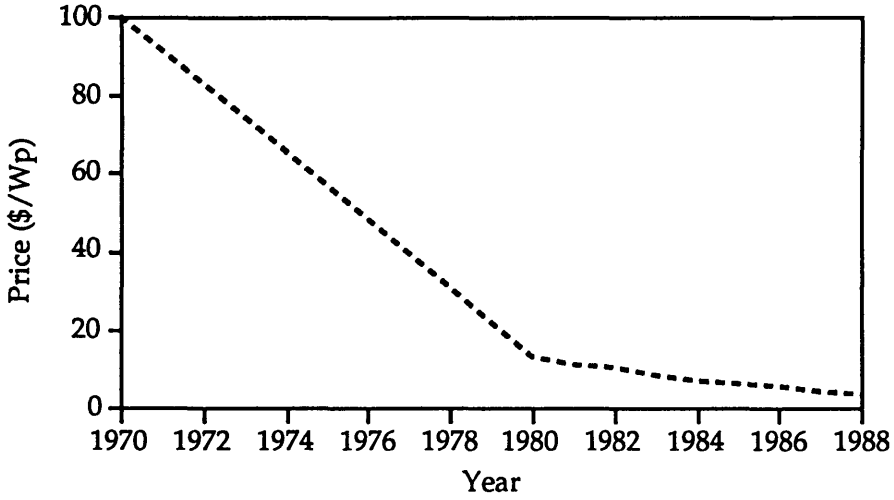


Table 4: Photovoltaic Characteristics and Costs

System Costs	Technology	O&M Costs	Cost of Energy	Conversion Efficiency	For Year:	Estimated In year:	Source Notes
			30 - 40		1991	1991	EPRI Journal, June 1991 (91$, for CA)
			10 - 20		1995	1991	
$4.60 - $5.40/Wp	semicrystalline				1990	1990	Kyocera Corp. Japan; MPS 1991
	silicon		$1.20		1992	1990	
	modules		$0.80		1995	1990	
			$0.15-$0.23		2000	1990	
$15/Wp - system	average of many				1990	1990	German test project; MPS 1990
$3.00 - $3.75/Wp	crystalline Si module				near future	1991	Indep. Energy; 1991
$7.00/Wp	cell average	0.5	30 - 35		1988	1988	1990 White Paper
$3.50/Wp	cell average	0.2			2000	1988	
$2.10/Wp	cell average	0.2	7 - 9		2010	1988	
$1.00/Wp	module ave., industry est.		12 - 15		1995	1988	
	flat plate, fixed	0.4 - 1.4			1990	1990	IEEE Trans. on E C; June 1990
	axis systems	~0.1			future	1990	
			6 - 8		2000	1991	EPRI Journal, June 1991, (91$)
	flat, thin film cells			15%	1990	1990	
	flat, crystalline Si cells			22%	1990	1990	
	high-effic, conc. cells			32%	1990	1990	
	a-Si thin film modules			10% - 12%	1993	1991	SERI - Solar Engr. ASME 1991
	a-Si thin film modules			15% - 20%	2000	1991	- 30yrs @ >= 90% initial rating
$150/m2	mass produced thin		12	12%	1993	1993	American Scientist, 1993
$150/m2	film modules		6	15%	near future	1993	- m2 = square meter
$50 - $150 /m2	thin film module				1993	1993	
$300 - $500/m2	crystalline Si module				1993	1993	
$5/Wp - system	current average				~1995	1992	Ed Kern - EPRI contractor
		(¢/kWh)	(¢/kWh)				

Figure 5: Average Photovoltaic Module Price



ENVIRONMENTAL IMPACTS OF PHOTOVOLTAICS

The two main environmental concerns surrounding solar energy are the land requirements of the systems for collecting the solar radiation, and the toxic materials used both as the raw materials and in the manufacturing processes.

Land Use

Both solar thermal and photovoltaic concentrator systems require large, desert tracts of land when operated as central station power plants, in order to collect enough solar energy to produce significant power. These desert regions are fragile eco-systems which would likely be destroyed by the installation and maintenance of the solar power systems. Also, these systems require external cooling, most likely with water, which would exacerbate the problems with water shortages inherent in desert regions. Any water runoff could also cause erosion.

A centralized flat-plate PV system also requires much land, with 100 MW covering approximately one square mile. One alternative available for flat-plate PV systems is to roof mount them, and operate them as a distributed system. This is the method used in this analysis, with PV installation assumed to take place on the roofs of new commercial buildings.

Toxicity of Solar Cells

The second environmental concern is over the toxic substances used by PVs. Solar cells have the potential to be toxic to people and to the environment. The main toxic raw materials used for PV cells are cadmium, gallium and arsenic. The two main pathways for the toxins to enter the environment are through fire (possibly caused by building fires or lightening) and disposal at the end of their useful lives. At temperatures easily reached by fire, cadmium produces extremely toxic fumes, and gallium and arsenide form harmful oxygen compounds. Arsenic trioxide in particular is highly toxic, carcinogenic and highly soluble in water, presenting the possibility of poisoning water supplies. (Silicon, at comparable temperatures reacts to merely produce silica – common beach sand.)

At the end of their lives, after twenty to thirty years, if not recycled, PV cells are likely to end up in landfills. Although cadmium and arsenic are both listed as hazardous substances and thus subject to regulation under the Toxic Substances Control Act, the small amounts present in rooftop PV arrays releases individual home or business owners with such arrays from this regulation. Cadmium or arsenide finding its way into local landfills, could cause problems if it were incinerated (thus producing the compounds discussed above) or allowed to leach into local ground water.

The release of toxic substances during the manufacture of PV cells has the potential to be a larger danger than release from the cells themselves. This danger is mitigated though since solid, liquid and gaseous wastes are regulated by the Clean Air Act, the Clean Water Act and the Resource Conservation and Recovery Act. Available technology can and does remove 95% of heavy metals (cadmium in particular) from liquid wastes and 98% from gaseous wastes. In general it is very unlikely that enough of any of these toxins would be released to be a danger (Stoloff, 1986; Slusarczuk, 1981). Overall, if awareness of the potential danger, and regulation of the materials used as raw materials in the manufacturing processes continues, any potential danger from PV use can be avoided.

POTENTIAL IMPACTS ON UTILITIES OF RET GENERATION

This section moves away from discussing the specific renewable energy technologies of wind power and photovoltaics, focusing instead on topics common to both of them. Incorporating renewable energy generation into the power system offers numerous economic and environmental benefits to utilities, but also raises some concerns. In calculating the potential impact of RET generation on utilities, several parameters need to be quantified. Possible benefits from renewable energy generation can be categorized as fuel savings, system-wide emissions reductions, long-term price stability, and decreased long term capital costs due to capacity credit and capacity displacement. There are also concerns about renewable technologies in terms of their mechanical reliability, availability, firm capacity contribution and their effect on the flexibility of the overall system. These benefits and concerns are addressed below.

Potential Benefits

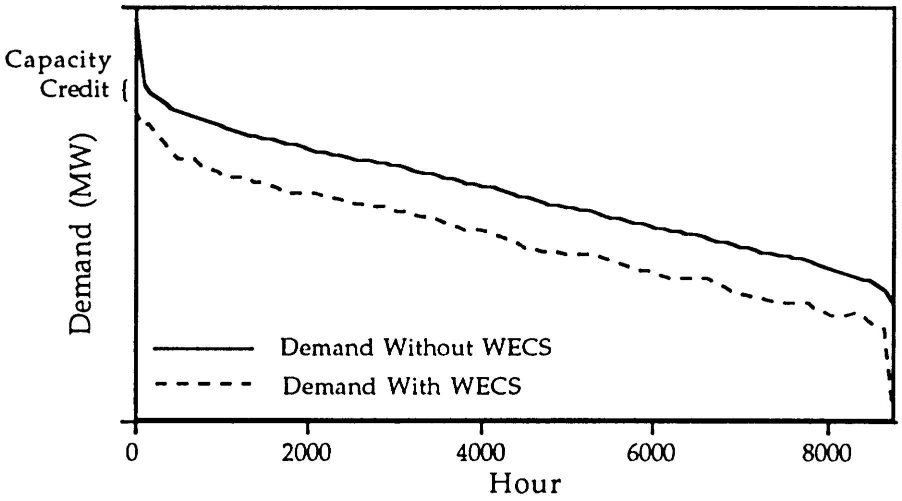
For conventional plants, construction lead times of five to six years are normal. Wind and photovoltaic systems have a distinct advantage over conventional generators since they can be completed in as few as one to two years. They can also be built modularly, allowing utilities to determine the final capacity of the plant according to actual demand, and not according to a long-range forecast of demand. They provide utilities with more flexibility in expansion planning, both in terms of the need to plan ahead, and in savings on interest to be paid during construction. Currently more time than the one to two years stated above is needed before a wind system begins operation, due to regulatory delays. However, as the wind farms' impacts become better understood, this added delay should be avoided.

Any electricity generation from renewable resources directly decreases the amount of generation required from fossil fuel sources, which reduces both fossil fuel consumption and also overall pollutant emissions. Identical to the electricity impact of conservation programs, the monetary savings from a decreased fossil fuel consumption is credited to the renewable energy source as "fuel savings."

Other possible benefits to a utility are termed capacity credit and capacity displacement (or plant mix reoptimization). Subtracting the hourly generation of the renewable source from the system's hourly demand, results in a new net demand. This change to effective system demand can be seen on the change to the load duration curve (LDC), as represented in Figure 6. (Note: the change to the LDC is increased by a factor of 10 for the graph.)

The new LDC reveals that the system now requires less total conventional capacity to meet peak demand, and also may show a shift of new capacity requirements toward a greater percentage of peaking capacity, and thus away from baseload capacity. Since peaking capacity is typically cheaper to construct than baseload capacity, the total investment necessary for additional conventional capacity is less.

Figure 6: Load Duration Curve With and Without WECS Generation



The decrease of overall conventional plant construction is termed the capacity credit, while a shift toward peak capacity construction versus baseload construction is referred to as capacity displacement or plant mix reoptimization. Both of these results can provide savings to utilities, though the actual impact upon conventional system load and energy requirements can only be assessed by modeling the impact of a specific RET installation for the resource at than location. (The modeling process used for this analysis is presented in chapter 4.)

Increased price stability is another benefit anticipated from the inclusion of renewable energy sources onto the utility grid. This increased stability results from the fact that once a renewable power source is installed and paid for, there are reduced variable costs from fuel consumption and variations in those costs.

Common Concerns

Power generated from non-dispatchable, renewable energy sources will be absorbed by the utility as long as the penetration level of the renewable source remains below about twenty percent. This rough capacity cap arises due to the need to maintain spinning reserve equal to the expected contribution from the non-dispatchable source. At penetration levels greater than twenty percent, either greater expense must be incurred to increase the amount of spinning reserve, or the flexibility of the power grid may become compromised due to the decreased conventional, "dispatchable" capacity (Cox 1982; Freris 1990). With penetration below this level however, all the energy supplied by the renewable source can be used by the utility without compromising the grid reliability, which directly decreases the required generation from conventional capacity.

Doubts as to the firm capacity contribution from renewable generation raises concerns over the actual capacity credit awarded to these sources. The perception that renewable generation is not as reliable as other sources of power is refuted by recent experience with RETs, which show these technologies to be very reliable (Freris 1990 (wind); Bzura 1990 (PV)). The long-run probability of RET generation depends on both the probability distribution of the renewable resource, and also on the reliability of the technology. Thus the probability of generation is less than the technology's technical reliability, due to the intermittent nature of the resource supply. Renewable energy resources are well defined though (see chapter 2), with the result that the overall generation reliability of an RET installation is not much lower than that of conventional power plants (Freris, Bzura).

As the analysis performed here includes rooftop PV systems only, the main difference between the PV analysis and that for wind power is the fact that the PV systems are distributed. As discussed above, New England Electric's Gardner, MA, project demonstrated the distribution system was not adversely affected by the PV systems, which did represent up to 53% of the power generation when the PV systems were generating maximum power.

In fact, contrary to *concern* over the effects of PVs on the distribution system, they are often seen as one option for improving the reliability of the distribution system when they are used as distributed, rather than central station, generation. Also, a study looking at a number of grid connected PV projects found that during times of scheduled outages for intermediate load maintenance, the overall utility system reliability was improved by the inclusion of the PV systems, by reducing the loss of load probability (Katzman, 1982).

CHAPTER 4
MODELING RENEWABLE ENERGY TECHNOLOGIES WITHIN THE ELECTRIC UTILITY ENVIRONMENT

INTRODUCTION

This chapter describes the methodology for modeling renewable energy resources and technologies to determine both their potential energy generation, and the possible impacts of this generation on the electric power grid. These impacts are measured in the quantities of capacity factor, capacity credit, emissions reductions and fossil fuel savings. The specific modeling assumptions made for the analysis of RETs, including technology, cost and performance assumptions for both the wind power and PV analyses are presented, along with the specifics of the land use requirements in the appendix to this chapter.

THE AGREA[1] PROJECT

The Setting: The New England Power System

The total energy demand in 1992 in New England was 110,000 GWh, with a peak of 19,500 MW. Figures 1 and 2 graph the growth in the region's

---

[1] AGREA - the Analysis Group for Regional Electricity Alternatives - is an ongoing project in the MIT Energy Lab.

annual electricity and peak power demands. They graph the future electricity demand at a growth rate of 2.0 % per year[1].

Figure 1: New England's Annual Electricity Demand

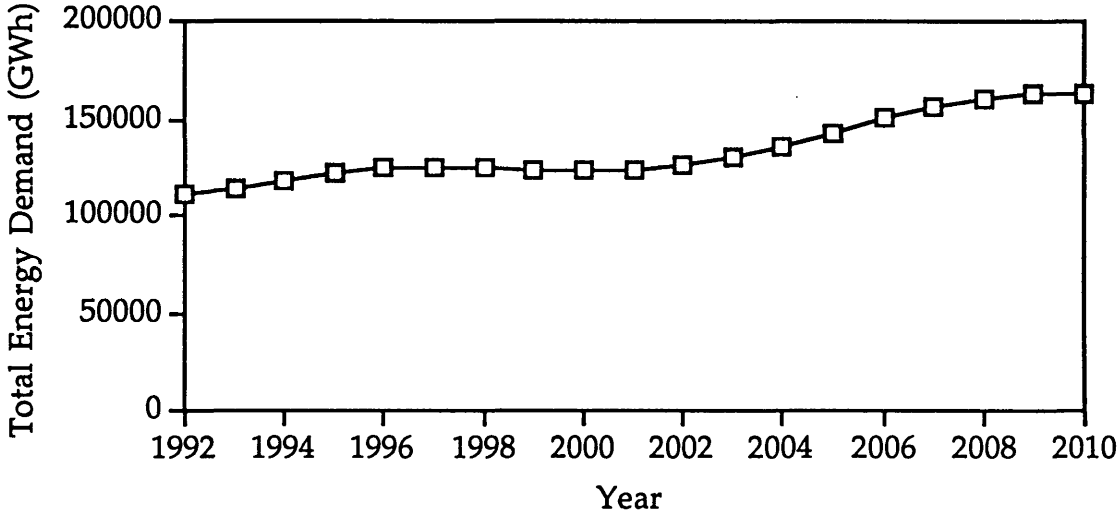
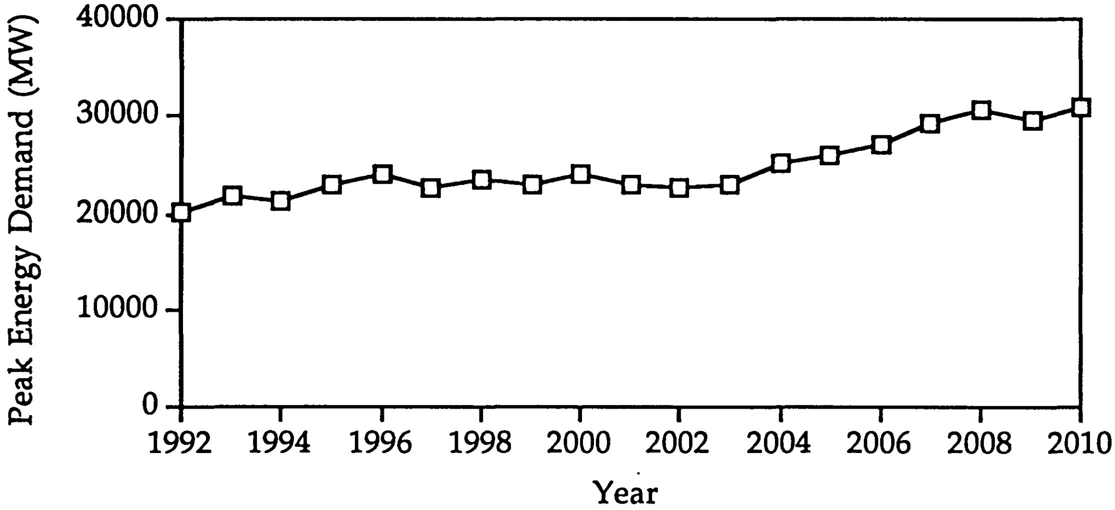


Figure 2: New England's Peak Electricity Demand



New England utilities are very active in demand side management (DSM), with the existing utility sponsored DSM programs saving about 3100 GWh, or 3% of the total energy demand, in 1992. The current generation supply

---

[1] This is the average load growth future used in the analysis. Random fluctuations for weather and cyclic economic recessions are superimposed on the otherwise smooth exponential growth.

mix is 30% natural gas and oil, 25% nuclear, 10% coal, 7% hydro-electric, and 10% combustion turbines and pumped storage for peaking capacity (with the remaining capacity coming from non-utility generation). Regional emissions from the electricity sector in 1990 were 370 thousand tons of SO_2, 160 thousand tons of NO_x, and 53590 thousand tons of CO_2[1]. The Clean Air Act Amendment of 1990, as implemented in New England, aims for a 30 % to 40 % "Phase I" reduction of NO_x emissions from the 1990 level by 1995, with additional "Phase II" reductions by 2000. These reductions can be met by decreasing demand and thus the generation of emissions (DSM), cleaning up the existing system (combustion controls and repowering), and by generating electricity with technologies that emit no pollution, such as RETs. The best strategy will use a combination of all available resources to meet the region's electricity needs while controlling environmental impacts, as promoted by integrated resource planning.

Analysis Approach: Multi-Attribute Tradeoff Analysis

The goal of the AGREA project is to bring together the stakeholders in New England's electric utility sector as "the Advisory Group" - which includes utilities, environmental and public interest groups, state and federal regulators, and industry - to find mutually agreeable long-range strategies for meeting the region's future electricity demand. The strategies examined include different levels of demand side management programs, different repowering versus life extension tradeoffs for the existing generation, and expanding current generation with various mixes of gas, oil and coal technologies. Future situations based on different fuel costs and economic growth are then projected for twenty years and each strategy is then examined on its relative performance on cost and pollutant emissions[2] for each of these futures. Using the economic concept of a tradeoff frontier, the results are displayed on two-dimensional graphs with cost as the y-axis and emissions as the x-axis, allowing the strategies that are both cheap and clean

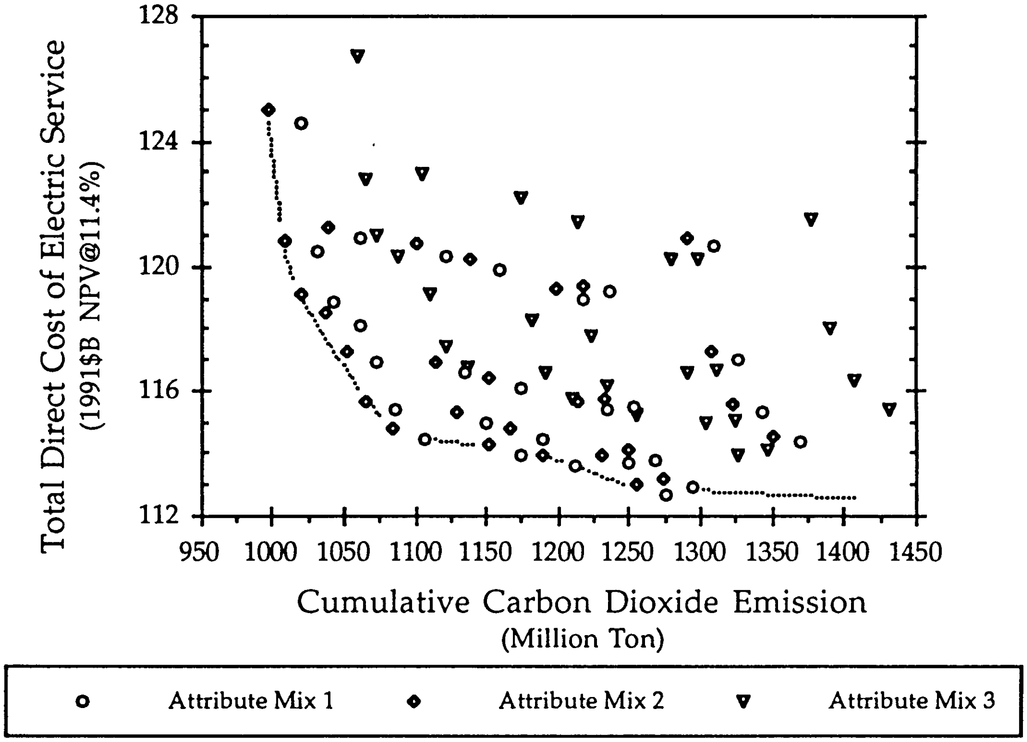
---

[1] These values are from NEPOOL. The comparable values for 1990 from the Energy Information Agency are 380 thousand tons of SO_2, 140 thousand tons of NO_x, and 48440 thousand tons of CO_2

[2] The analysis focuses on emissions of SO_2, CO_2, and NO_x.

- those strategies on the tradeoff frontier - to be identified. Figure 3 shows one such graph for CO_2 emissions.

Figure 3: Tradeoff Curve for Cost versus CO_2 with Average Load Growth



Similar graphs are made for NO_x and SO_2, and for the different possible futures[1]. The "best" strategies are those which remain on or near the tradeoff frontier for all emissions and across all the possible futures. The term given to this type of analysis is "multi-attribute tradeoff analysis," where the attributes are the different levels of DSM programs, amount of repowering, new supply side mixes, and future possibilities, and tradeoff graphs used to express the results.

RET MODELING METHODOLOGY

Due to increased interest in renewable energy, both wind power and photovoltaics have been added to the AGREA analysis. As part of the AGREA project, the analysis of RETs must be incorporated into the multi-

---

[1] "Futures" are a combination of a load growth and fuel costs.

attribute tradeoff framework, and use the existing analysis tools as much as possible.

Existing Modeling Tools

The main simulation program used in the AGREA study is a production-costing model called EGEAS[1], which calculates the cost of electricity production for a given electric utility system. For each twenty year study period of the AGREA project, the model is given data on each plant in the existing New England system, schedules for building new plants, trajectories of fuel costs and hourly electricity demand data. The electricity demand reflects the different possible economy growth rates, and is a "net demand" in that each hourly value is de-rated by the expected savings from DSM programs. Using the logic of economic dispatch, which dispatches the generating plants in order of ascending marginal cost, EGEAS simulates the dispatching of plants for generating electricity, under the constraint of meeting the projected demand. The overall cost of electricity production for each year in the twenty year study is calculated, along with pounds of pollutant emissions, amounts of different fuels used, and system reliability.

Analyzing Non-Dispatchable Renewable Energy Technologies

EGEAS was designed with the capability of analyzing non-dispatchable technologies such as photovoltaics and wind power. The algorithm used to perform this analysis in EGEAS first constructs probability distributions for both the load and RET generation, and then calculates a joint distribution to represent the net load (Caramanis 1982, 1983). This method, one of the probabilistic methods for modeling RETs, allows the flexibility of calculating the *probability* of RET generation, without determining the total RET capacity and thus the *actual* RET generation a priori. One reason this method was selected for EGEAS was to allow the optimization mode to run faster (Caramanis 1982). One problem with probabilistic methods is that

---

[1] EGEAS - Electricity Generation Expansion Analysis System - was developed by MIT under an EPRI contract, and is currently distributed by Stone & Webster Management Consultants (EGEAS, Version 6 User's Manual, Stone & Webster Management Consultants, Inc., Englewood, CO, June 1991.)

they obscure *time* correlation between the hourly peak demand and hourly peak generation (Thurber 1992). Determining this correlation between the peaks is important for our study of renewable energy technologies, since that is what determines the capacity credit[1] awarded to the project. This method also delays the calculation of energy capture, capacity factor and capacity credit of RET installations until the full EGEAS simulation is completed, rather than allowing these factors to be calculated independent from the full utility model.

An alternative to the probabilistic approach is the chronological method (Caramanis 1982, Milligan 1993), which calculates the RET electricity generation for each hour, and then subtracts this generation from the hourly demand. This method allows up-front calculation of energy capture, capacity factor and capacity credit, yet does not reflect the probabilistic behavior of intermittent resources.

For accuracy both of these methods require time correlated data. For a joint probability distribution (as used in the probabilistic method) to have meaning, the two original distributions must in fact be correlated. Likewise, to perform hour-by-hour subtraction of generation, the two hourly data streams should represent the same hours, not only the hours in different years. Due to availability of data, the AGREA study uses historical renewable resource data and future load data! Thus either method would suffer inaccuracies. Different reports advocate one or the other of these methods. There is some consensus that each has its benefits and drawbacks, suggesting that utilizing both methods, if possible, and comparing the results would provide the most complete analysis. The chronological method is used in this study so that the desired parameters[2] can be calculated directly, and also to parallel the DSM analysis which relies on the chronological method. Since EGEAS is not used in the optimization

---

[1] Capacity credit refers to the amount of conventional construction rendered unnecessary due to the generation from the renewable energy source. Most of this credit usually comes from the displacement of peak generation, and thus correlating the peaks accurately is important. Capacity credit is explained more fully in chapter 3.

[2] As listed before, these are energy capture, capacity factor and capacity credit.

mode by AGREA, the chronological approach does not suffer from the possibility of excessively long simulations.

Thus the AGREA methodology analyzes RETs in three stages. The first step, as discussed in chapter 2, is to obtain appropriate hourly resource data. This data is then converted to hourly generation data used to de-rate the hourly demand, and the output of this stage is then used by EGEAS to calculate the remaining parameters. These final two steps are explained below. Results of the parameters calculated are presented in chapter 5.

Step 2: Renewable Impacts Module

A computer program referred to as the Renewable Impacts Module was developed to directly calculate the impact of RET generation on the power system. This module, utilizing the chronological method, reads in multi-year hourly data for both the forecaster load and the hourly renewable resource, calculates the electricity generated from the RET based on the characteristics of the technology and the capacity installed, and then subtracts this generation from the load on an hourly basis.

Comparison of the hour and level of peak demand for scenarios with and without renewable energy generation allows an accurate evaluation of the reduction in peak demand due to renewable energy. This comparison leads to a measure of the capacity credit, without obscuring this data as EGEAS alone does. The Renewable Impacts Module also calculates the energy capture and capacity factor of the RET installation, as well as a net hourly load data file to be used by EGEAS.

For the wind power analysis the wind speed data is processed through the power curve of the desired turbine, and multiplied by the installed capacity. 15% of the energy thus calculated is then subtracted off to account for loss from wake and other wind farm effects, icing and weather conditions, and forced outages. The energy generated from photovoltaics is obtained from a separate computer simulation of PVs adapted from a program written by

Ascension Technology, Inc[1]. The specific wind turbine power curve and PV system characteristics are presented in the appendix to this chapter, along with the cost and land requirement assumptions.

Step 3: EGEAS

After running the Renewable Impacts Module, EGEAS is run using the net hourly loads file from the Renewable Impacts Module together with cost information. Two results of this step are the calculation of the cost of energy, shown in figures 13 and 14 in chapter 5, and the net load duration curve, as seen in figure 1 in chapter 5.

Further analysis occurs by comparing the results from EGEAS runs with and without renewable energy power generation (holding all other attributes constant). This comparison allows calculation of the impact of wind power and photovoltaic generation on both fossil fuel consumption and system-wide pollutant emissions.

In particular, these results are calculated as follows. The output of each EGEAS run includes the number of tons of emissions (including CO_2, SO_2 and NO_x) generated by the power system, the total capacity in the system from each category of generating plant (such as coal, oil, nuclear, wind and PV), the amount of energy generated from each fuel type (in number of GWhs), and total system cost.

A comparison of the output from the different EGEAS runs (or different scenarios) with and without wind turbines or PVs included, allows the impacts from including the RETs in the power grid to be quantified. For example, if the CO_2 generated from the power system without wind power included is 938.44 million tons at a total system cost of $118.24 billion[2], while the system with wind power emits 915.99 million tons of CO_2 at a cost of $118.68 billion, then the impacts of including wind power are a 2.4 % decrease in CO_2 emissions (along with reductions in other emissions and

---

[1] PVSim - Ascension Technology, Inc., Waltham, MA.

[2] The total system cost reported here is the net present value in terms of 1991$, discounted at the rate of 11.4 %.

fossil fuel use), for a 0.4 % increase in system cost. The capacity credit for the RET is determined by calculating the difference in the amount of new conventional generating capacity built in order to meet demand growth, during the simulation for scenarios with and without RET capacity.

By quantifying the potential effects on the electric utility sector of including wind power and PVs, such results can increasingly be included in planning decisions about these technologies, rather than having these decisions heavily rely on impressions and ideology. The results for the analysis of 1500 MW_p each of wind turbines and PVs in New England are presented in chapter 5.

CHAPTER 5
RENEWABLE ENERGY POWER GENERATION IMPACTS

INTRODUCTION

This chapter presents the results of the analysis of the simulation of 1500 MW_p each of wind power and photovoltaics installed in the New England power system, obtained from the computer simulations[1]. Wind power is found to contribute more energy generation and emissions reductions than PVs, while PVs have a higher capacity credit.

POTENTIAL RET CONTRIBUTION TO ELECTRIC POWER SUPPLY

The 1500 MW_p each of wind turbines and photovoltaics are installed gradually over the twenty year study period, according to the schedule shown in table 1.

The Renewable Impacts Module and EGEAS together calculate the parameters shown below, which are used to quantify the impacts of including RET generation on a power grid, in terms of electricity generated, economic benefits and costs, and environmental impacts.

- Energy Capture – GWh/year
- Capacity Factor – Equivalent available capacity

---

[1] Modeling is described in chapter 4.

- Capacity Credit – New dispatchable capacity rendered unnecessary by RET contribution
- Emissions Reductions – Percent decrease in NO_x, CO_2 and SO_2
- Fuel Savings – Monetary savings from decreased fossil fuel use
- Capacity Displacement – Where in the loading order the RET generation occurs
- Cost of Electricity from RET – ¢/kWh

The results of each of these parameters for the windpower, photovoltaic and combined analysis are presented below.

Table 1: Installation Schedule of Wind Turbines and Photovoltaics

Year	Photo-voltaics	Wind Turbines
1995	50	50
1996	100	100
1997	100	100
1998	150	150
1999	150	150
2000	150	150
2001	200	200
2002	200	200
2003	200	200
2004	200	200
	(MW)	(MW)

Net Load Duration Curve

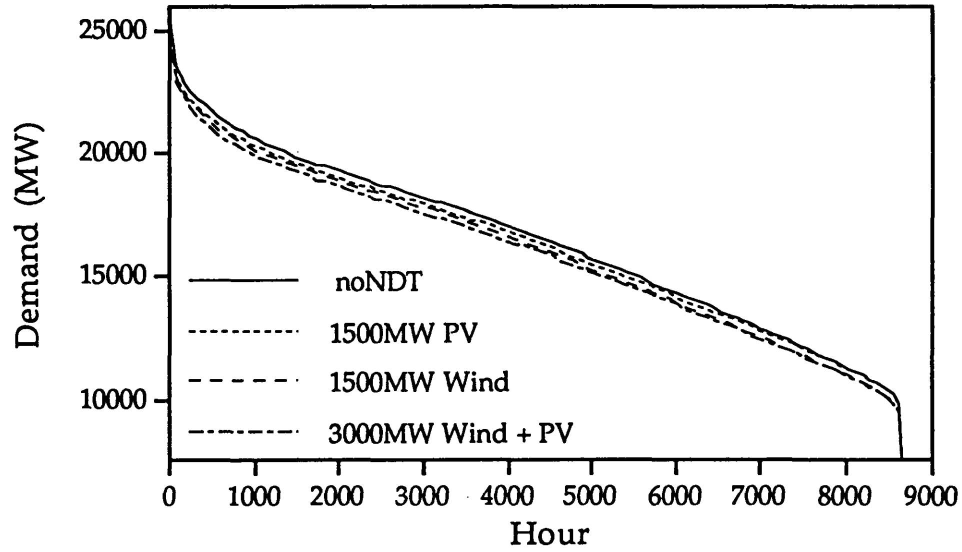
The net load duration curve[1] (LDC) for the windpower, photovoltaic and combined generation in New England for the year 2005 is shown in Figure 1. The top, solid line represents the LDC for New England without any windpower generation in the supply mix. The middle two lines represent

---

[1] A load duration curve is like a cumulative distribution function in that it shows the number of hours in a year, along the x-axis, for which the electricity demand is equal to or greater than the corresponding MW level along the y-axis.

the net LDC for the region after the photovoltaic and windpower generation has been subtracted from the original LDC. The bottom line is the net LDC with both wind power and photovoltaics contributing. Parameters useful in quantifying the impact of the windpower generation, the capacity credit, capacity displacement and energy capture, are all represented on this graph. These parameters are explained below.

Figure 1: Annual Load Duration Curve Net RET Generation in 2005

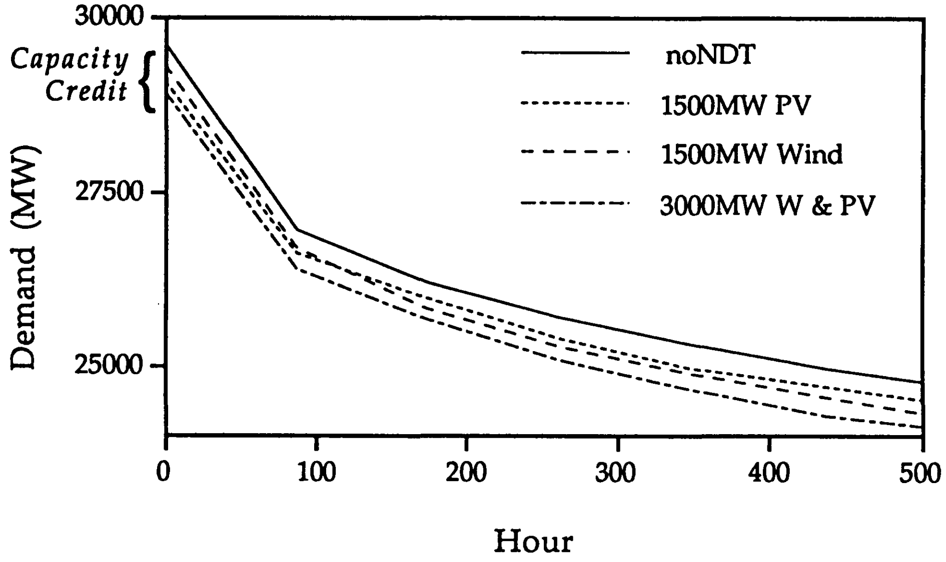


Capacity Credit

Capacity credit refers to the amount of conventional construction rendered unnecessary due to the generation from the renewable energy sources. The capacity credit for one year in our 20 year study can be seen on figure 1 as the difference in peak demand at hour 0 (on the y-axis). The first 500 hours of the LDC are shown in figure 2 below.

The average capacity credit for the wind power generation is 350 MW, or 23 % of the 1500 MW_p installed, and is 450 MW for PV, or 30 % of the installed capacity. The minimum annual capacity credit for both technologies as calculated in the Renewable Impacts Module is 0 MW. A capacity credit of 0 MW in our calculation occurs when there is no wind generation for the *exact hour* of peak demand for the year, which is an exceedingly conservative method for calculating capacity credit. One alternative would be to calculate a weighted average of the capacity credit from the ten (or so) peak demand hours (NREL, 1993), which would be facilitated by relying on spinning reserve, interruptible contracts,

Figure 2: Capacity Credit for RET Generation in 2009



or other available options during hours of peak demand. A second accepted

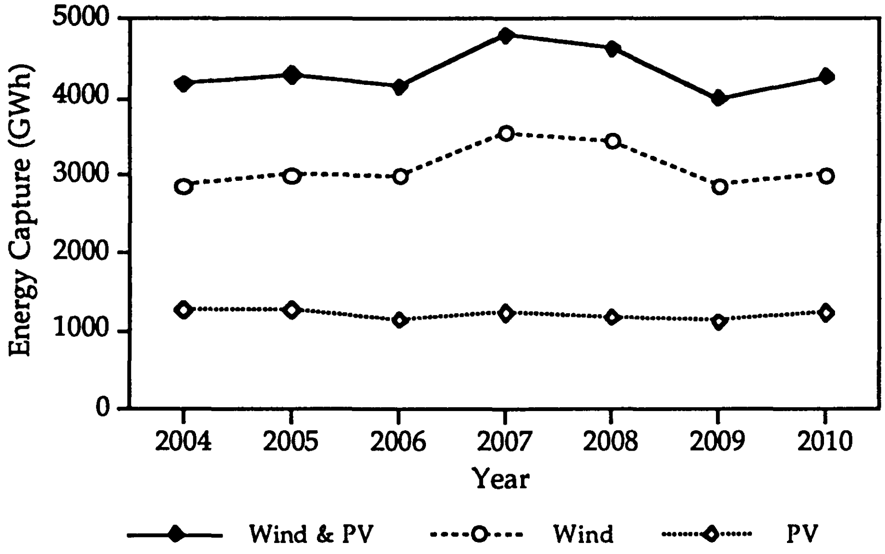
method for modeling capacity credit is to use the effective load carrying capability, which is an indication of how much load a plant displaces (Finger, 1979; Garver, 1966). Using these alternative methods would likely increase the average capacity credits stated above, since the probability of having a year with zero capacity credit would be very low.

Energy Capture

The difference in electricity demand between the original and net LDCs in figure 1, represents the energy capture from the RET generation in one year. The average energy capture from photovoltaics is 1200 GWh/year. Wind power generates an average of 3000 GWh/year, which represents 3 % of New England's total demand in 1992. For comparison, utility sponsored DSM programs at present also represent about 3 % of the region's annual demand, while New England's annual energy purchase from Hydro-Quebec represents about 7 % of the region's demand. This energy savings also translates into fuel savings[1] and region-wide emissions reductions, which are presented below.

The energy capture for the final years of the study are presented below in Figure 3. The energy capture changes over the years due to the variability in available wind energy and solar insolation.

Figure 3: Energy Capture from 1500 MW_p each of Wind Power and PV



Capacity Factor

As with conventional plants, the capacity factor for a non-dispatchable RET represents the equivalent available capacity of that technology; or the actual energy generated in one year divided by the peak energy generation possible. For the two wind farms modeled in New England, the average capacity factor is 25 %, ranging between 22 % and 28 % over our 20 year study. A capacity factor of 25 % in the California wind farms is considered good, while some of the best California sites have achieved a 33 % capacity factor. The average capacity factor for the PV installations is 10 %, ranging from 8 % to 13 %, which is considered very low (NREL, 1993), as some of the best sites in Arizona reach 25 % capacity factor.

---

[1] The potential fuel savings for New England due to the inclusion of RETs in the supply mix is quantified through comparing fuel consumption results from EGEAS runs with and without the RET. As a rough estimate, assuming a heat rate of 10000Btu/kWh and 5.8 million Btu/barrel of oil, results in 3000 GWh being equivalent to about 5 million barrels of oil.

Table 2 shows the average capacity factor of each of these technologies, along with the percentage of total 2011 installed capacity represented by these technologies. Column three in the table shows the percentage of the total system capacity based on the peak or installed capacity of the RET. Column four shows the percentage of the system capacity accounted for by the "equivalent" renewable energy capacity, where the equivalent RET capacity is the total installed capacity multiplied by its capacity factor. The percentage of the total capacity accounted for by an RET gives a measure of the penetration level of the RET.

Table 2: RET Percentage of Total 2011 Installed Capacity

			% of Total 2011 Capacity	
Technology	RET Installed Capacity	RET Capacity Factor	RET Installed Capacity	Equivalent RET Capacity *
Wind Power	1500 MWp	25%	5%	1.2%
Photovoltaics	1500 MWp	10%	5%	0.5%

* For example, 5% * 25% = 1.2%. Or, for wind power, 25% of 1500 MW is 375 MW, and 375 MW is 1.2% of total system capacity in 2011.

IMPACTS OF NDT GENERATION ON THE POWER SYSTEM

The parameters discussed above do not provide information on the cost or emissions impacts of the RETs on the power system, but rather focus on the operating characteristics of the RETs themselves. For the full analysis

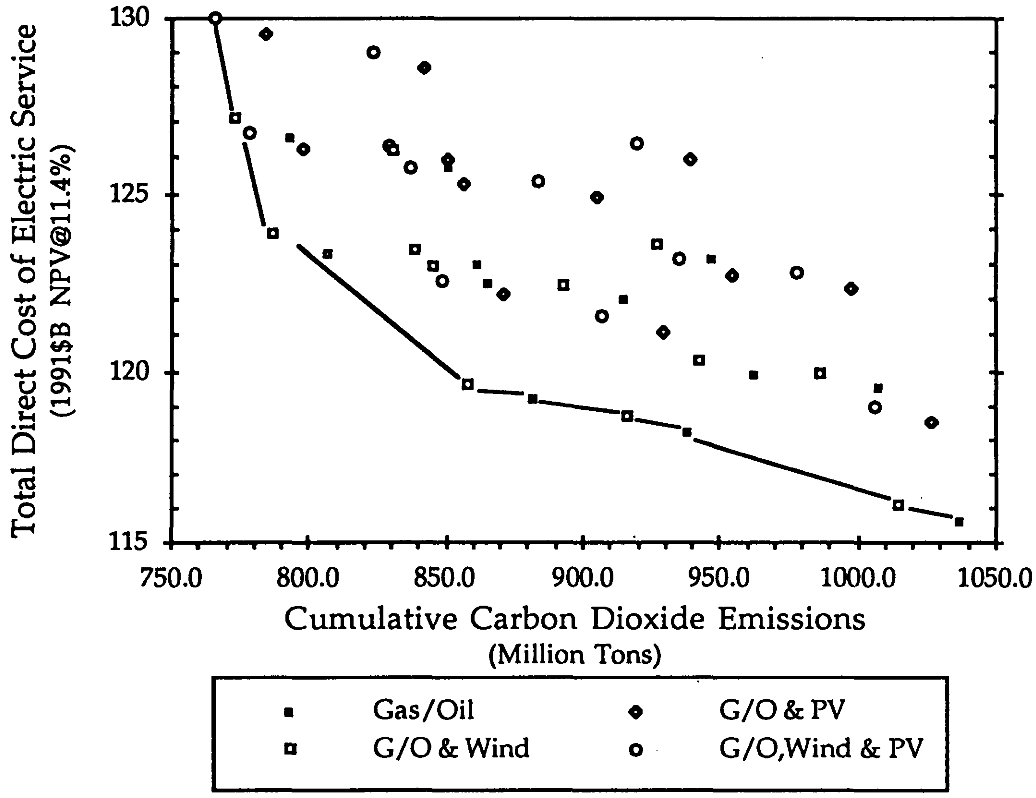
Table 3: The Different Scenario Attributes used for Analysis

Supply SideTechnology Mixes • Gas/Oil • Gas/Oil and Wind • Gas/Oil and PV • Gas/Oil, Wind & PV	*Treatment of Existing Plant* • Life Extention • 20 % Repowering • Phase I NOx Controls • Phase II NOx Reductions
Demand Side Management • 1992 Reference Level • Double Conservation Programs • Triple Conservation Programs	*Fuel Cost Uncertainties* • Base/Stable Fuel Costs • Natural Gas Constraint

presented here, the desired information on cost and emissions is obtained from running the full power system simulation with EGEAS. The different scenarios used in this analysis mix one attribute from each category – supply side technology mixes, utility sponsored DSM levels, repowering of existing plants, levels of Clean Air Act compliance, and assumptions for fossil fuel costs. These options are listed above in table 3[1]. The results from simulating the different scenarios are graphed on multi-attribute trade-off curves as described in chapter 4. These graphs plot the scenarios on graphs of cost versus emissions.

For new supply side technology mixes, the Gas/Oil option assumes that new capacity requirements will be met with natural gas (fuel switching with Oil2/distillate) technologies. The Wind, PV and Wind & PV options

Figure 4: System Cost versus CO_2 for Changing Supply Side Mixes



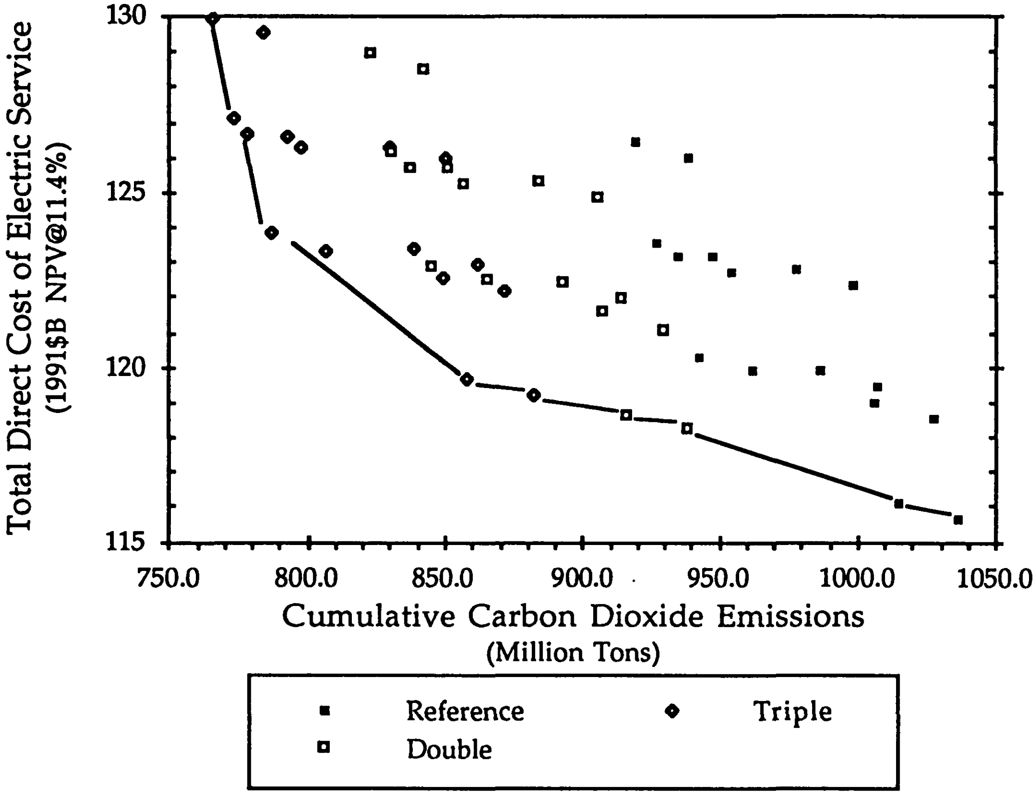
---

[1] The options discussed here, and their implementation were developed by the entire AGREA team as part of the full 1993 Analysis.

incorporate 1500 MW_p of each of the RETs, and meet the remaining capacity needs with Gas/Oil technologies. Figure 4 graphs cost (in terms of net present value in 1991$, discounted at a rate of 11.4%) versus million tons of CO_2, keyed for the different supply side mixes. The graphs for SO_2 and NO_x are analogous to the onew for CO_2 shown here.

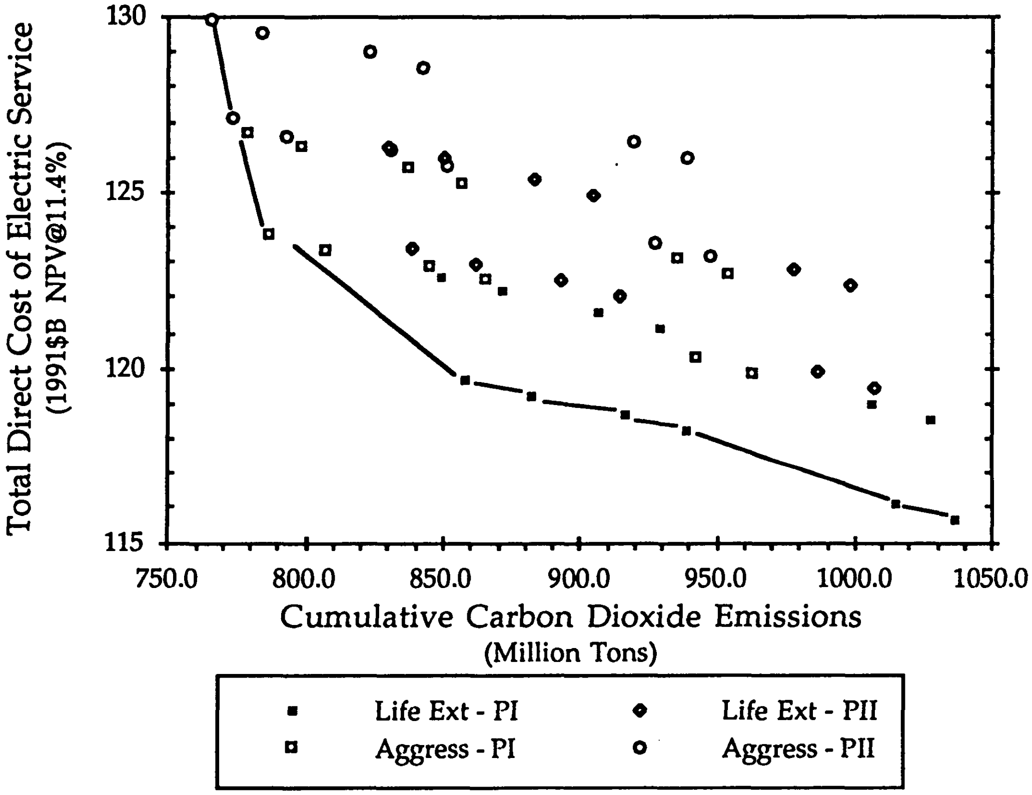
New England utilities report their expected DSM programs for the future to NEPOOL, the regional power pool. This analysis uses this level, the reference level, as its baseline. It also looks at the impacts of doubling and tripling the level of conservation programs. Figure 5 replicates figure 4, yet highlights the different levels of demand side management, rather than supply side mixes. Note that the data points, each representing a complete scenario, are identical to those in figure 4.

Figure 5: System Cost versus CO_2 for Changing Levels of DSM



The 1990 Clean Air Act Amendment (CAAA) requires large reductions in NO_x emissions in New England[1]. "Phase I" reductions of 40 % from the 1990 levels are aimed to be achieved by 1995. Additional "Phase II" reductions are as yet unspecified (the requirements are expected to be defined by 1994). For this analysis, an assessment of the potential requirements assumes that the goal will be 80 % reduction from the 1990 emissions levels. For the existing plant treatment, the life extension option assumes that all no plants (other than those already scheduled for retirement) are retired over the twenty year study, with the assumption that maintenance costs increase. The repowering option retires 20 % of the existing capacity (based on criteria of efficiency, age and size), building a new (more efficient and cleaner) plant on the same site. Figure 6 repeats figures 4 and 5, with the treatment of existing capacity highlighted.

Figure 6: System Cost versus CO_2 for Treatment of Existing Capacity



---

[1] New England is able to meet the required SO_2 reductions by switching to low sulfur fuels.

The final set of options is the fuel cost uncertainties. The base trajectory assumes that annual fuel cost changes are small and predictable, projecting that oil2 (distillate) increases from an average of $4.75/MMBtu in 1992 to $5.75/MMBtu in 2011, and natural gas increases from about $2.25/MMBtu to $4.25/MMBtu (1991 $). The "Gas Constraint" option, an attribute representing a future uncertainty, recognizes that if New England in fact meets new capacity demands predominantly with natural gas technologies, the increased demand for gas (arising from other sectors of the economy also) may cause the price to increase. In this option, the oil2 trajectory remains unchanged, but the cost of natural gas is assumed to increase from $2.25/MMBtu to $7.00/MMBtu by 2011. As gas and oil become more expensive, the scenarios including wind and PVs in the supply mix become relatively less expensive (see table 4 below).

By tracing back through figures 4 to 6 we can see that the scenarios with gas and oil, or gas/oil and wind are consistently on the frontier of the trade-off graphs. The higher DSM levels each move onto the trade-off frontier as higher system cost is accepted in exchange for greater reductions in CO_2. For treatment of the existing system, the life extension/Phase I CAAA mix is the least expensive. However, life extension is often not an option due to regulations, and Phase I of the CAAA will move in to Phase II 1996!

The baseline strategy for this analysis is that strategy including the Gas/Oil technology mix, reference DSM level, life extension of existing plants, Phase I NO_x compliance and base/stable fuel costs. The impacts of including RETs in the supply mix, as well as the dynamics of changing the other options along with adding RETs are presented below.

System Reliability

The measure of system reliability used in this analysis is predominantly that of the system reserve margin. A decrease (or increase) in reliability due to the inclusion of RETs would show up as a decrease (or increase) in the reserve margin. The results of the wind power and photovoltaic analyses show that given the low penetration levels of the RETs in this study (see table 2 above) there is no decrease in the reserve margin, and therefore no reliability problems. To analyze the reliability impacts from stochastic generation sources, such and wind power and PVs, using the reserve margin is not actually the most appropriate method. However, the nature of this analysis is such that the dynamics of the intermittent or probabilistic behavior of RET generation, which could become important at higher penetration levels[1], are not included. (A study being performed along side this project is analyzing the dynamics of the fluctuations in wind power generation, and the potential impacts on the New England power system.)

System Cost Impacts

EGEAS is a production costing model, and as such calculates the total system cost from dispatching the defined electric system to meet the given demand. The percent increase to system cost of including both wind power and photovoltaics, individually and together, is presented below in table 4 along with trajectories of the RET capital costs in figure 10. The *relative* cost of the RET options improves if the gas constraint fuel cost uncertainty is used, since in this case the natural gas prices result in gas technologies becoming more expensive relative to the renewable fuel technologies. The capital cost assumptions for PVs shown in figure 7 result in the Gas/Oil & PV strategies *not* being on the tradeoff frontier. Alternative trajectories are used in sensitivity studies, presented at the end of this chapter.

Table 4: Percent Increase in System Cost Due to RETs[2]

Technology Mix	Base/Stable Fuel Uncertainty	Gas Constraint Fuel Uncertainty
Wind	0.34%	0.15%
PV	2.93%	2.73%
Wind & PV	3.28%	2.90%

Capacity Displacement, Fuel Savings

Capacity credit measures the decrease in required conventional capacity, yet is not useful in determining whether this decrease is in baseload,

---

[1] A common rule of thumb is that system reliability is unaffected below a 20 % penetration level of RETs.

[2] The values in this table are from the end of the study period, year 2011.

intermediate or peaking capacity. Figure 1 shows that for the New England study, the RET generation can be seen to "displace" not only peaking capacity, but intermediate and baseload capacity as well. Thus the supply side plant mix should be re-optimized to reflect the fact that proportionately less intermediate capacity is required – the percentage of intermediate capacity required has decreased while the percentage of peaking capacity has increased. Figures 8, 9 and 10 show the percent reduction in GWhs generated from fossil fuel due to the RET generation, which directly reveals which type of generating plant is displaced by the inclusion of RET generation. The significance of these results is discussed in the following section, on emissions reductions.

Figure 7: Capital Cost Trajectories for Wind Turbines and Photovoltaics

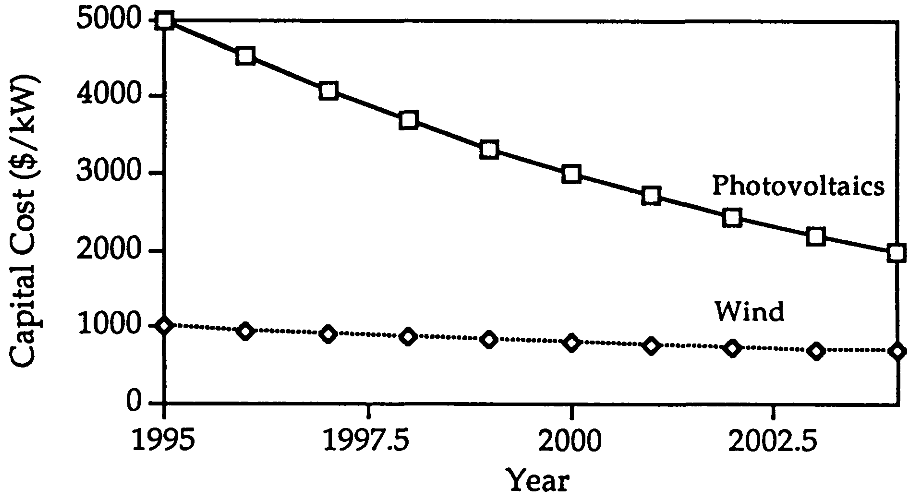


Figure 8: Decrease in Fuel Use in 2007 and 2011 for Reference DSM

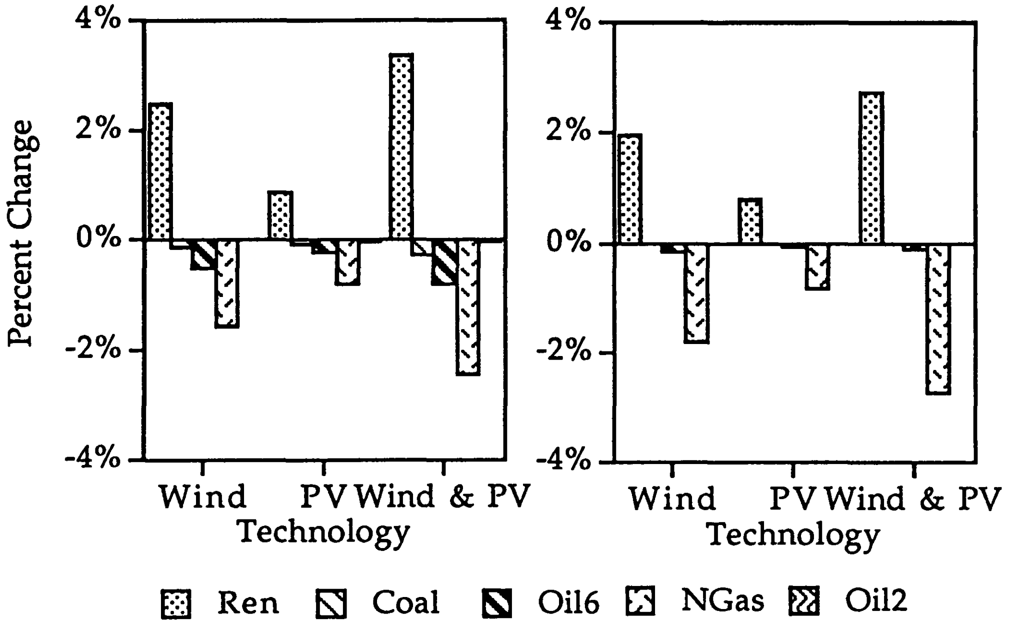


Figure 9: Decrease in Fuel Use in 2007 and 2011 for Double Conservation

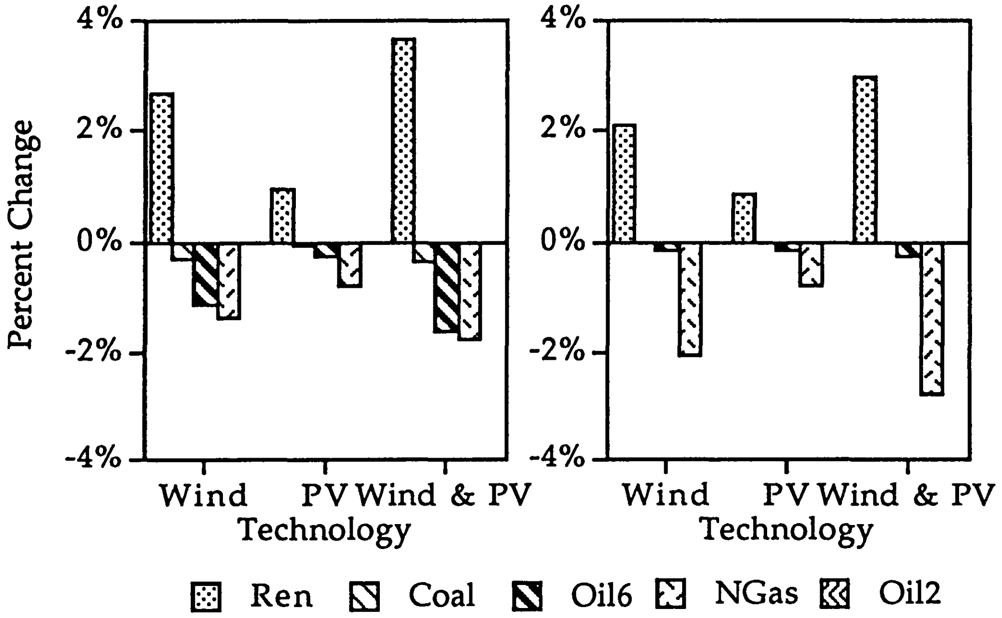
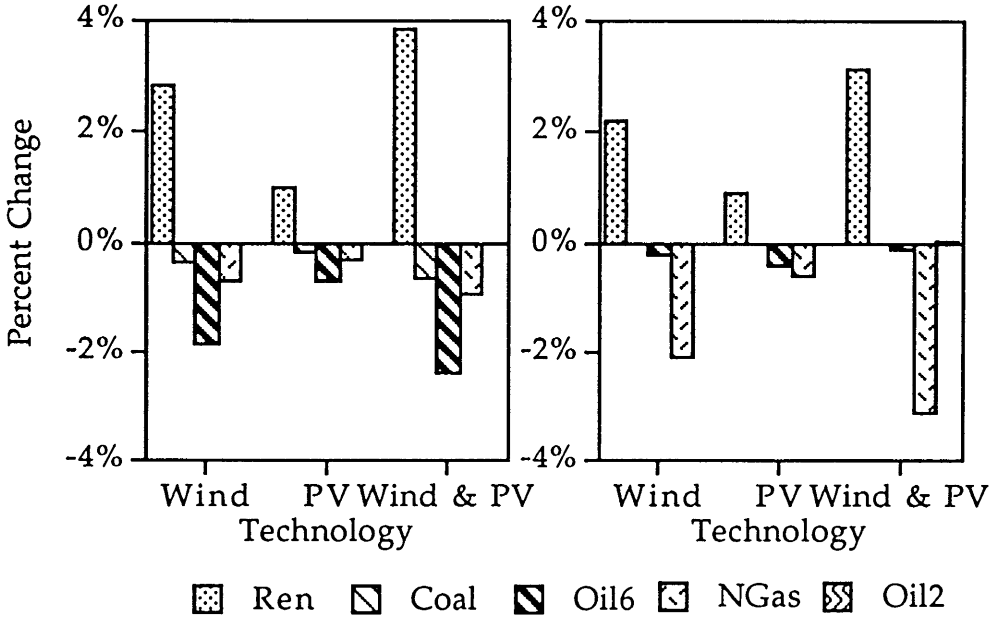


Figure 10: Decrease in Fuel Use in 2007 and 2011 for Triple Conservation



Pollutant Emissions Reductions

The inclusion of RETs, which are non-polluting technologies, results in system wide emissions reductions. Emissions reductions due to utilizing any of the Gas/Oil & RET technology mixes instead of the Gas/Oil alone mix, are affected by the increasing DSM levels, increasing repowering, and increasing NO_x controls due to CAAA compliance. Emissions reductions and the influence of the other attributes on these reductions are shown in figures 11 through 16. Figures 11, 12 and 13 graph the SO_2, NO_x and CO_2 reductions due to including wind power and photovoltaic generation, for both reference DSM and triple conservation programs. All these graphs show that over the final eight years of the twenty year study[1], the emissions from the three technology mixes converge. This occurs because as the existing, base system becomes cleaner due to both the addition of emissions controls and from newer (cleaner) technologies coming on line, the possibility for emissions reductions from RET generation decreases. The comparison of reference to triple DSM is interesting in that it shows that the potential for emissions reduction and the deplacement of dirty fossil

---

[1] Only the final eight years are shown since these are the years for which the 1500 MW_p of RETs are fully installed.

fuel generation (see figures 8, 9 and 10) from RETs *increases* as DSM increases. This occurs because as DSM increases, less new capacity needs to be built. Less new capacity means the system as a whole remains older and dirtier, so that RET generation displaces this older, dirtier generation rather than new, clean generation.

Figure 11: SO_2 Reductions with Reference and Triple DSM

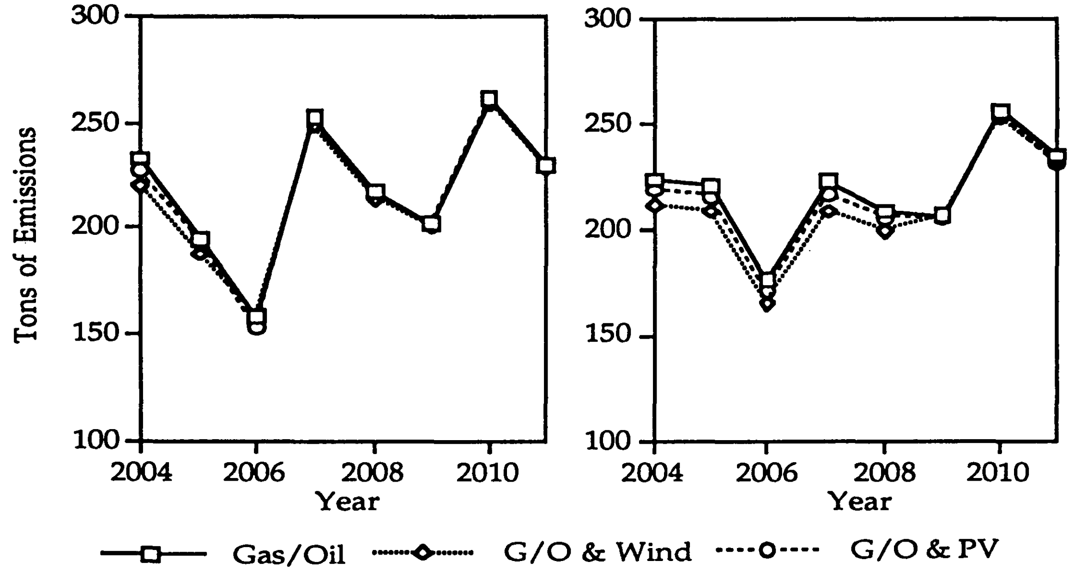


Figure 12: NO_x Reductions with Reference and Triple DSM

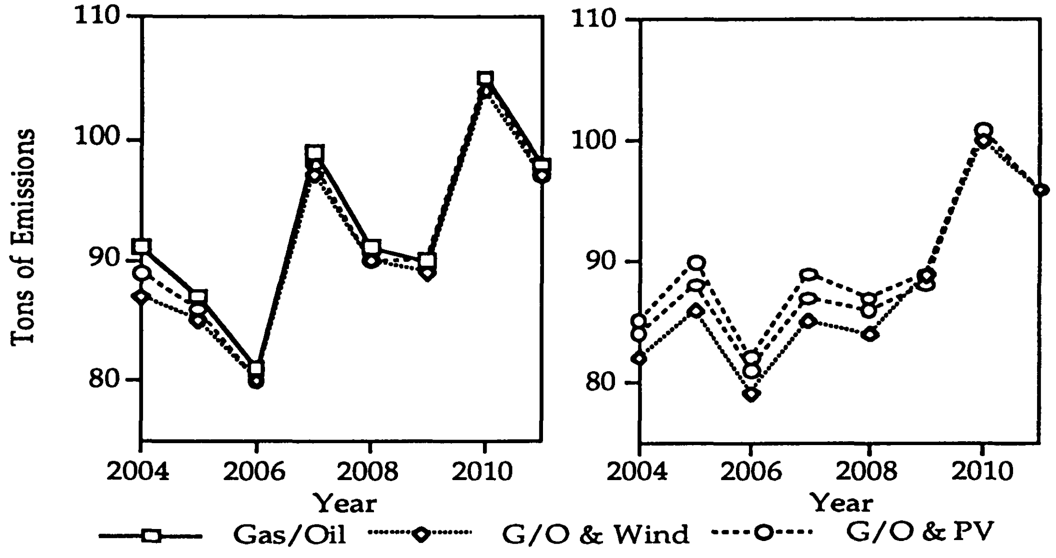
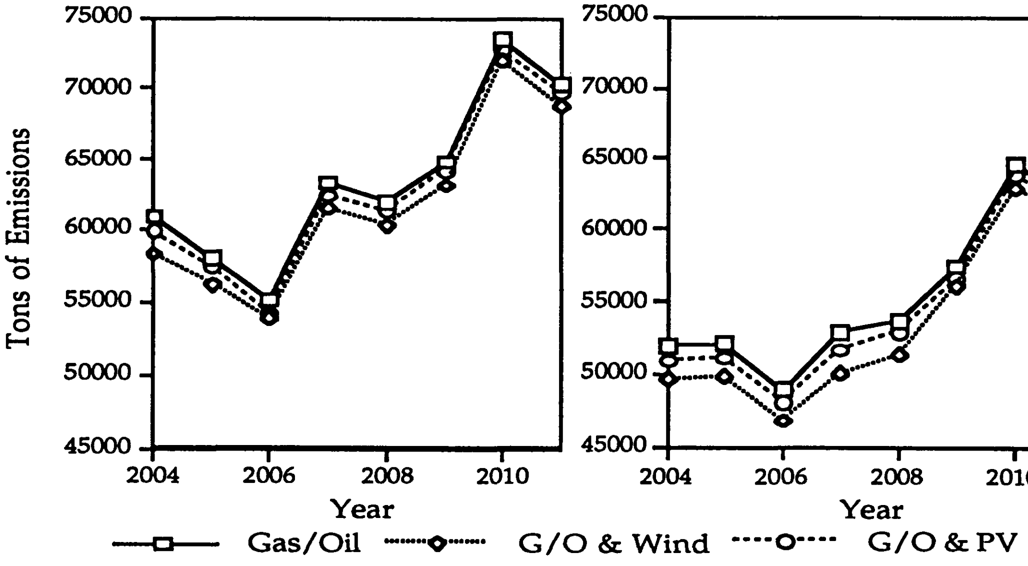


Figure 13: CO_2 Reductions with Reference and Triple DSM



The histograms in figures 14, 15 and 16 show the *percent reductions* in pollutant emissions for increasing DSM levels, for the single years of 2007 and 2011. The RET options of Wind, PV and Wind & PV together are compared to the Gas/Oil option in determining the percent reductions. These graphs show explicitly the decreasing impacts in emissions reductions in 2007 and 2011 as the existing system becomes cleaner. They also show the increasing impacts as DSM levels increase.

Figure 14: Emissions Reductions in 2007 and 2011 for Reference DSM

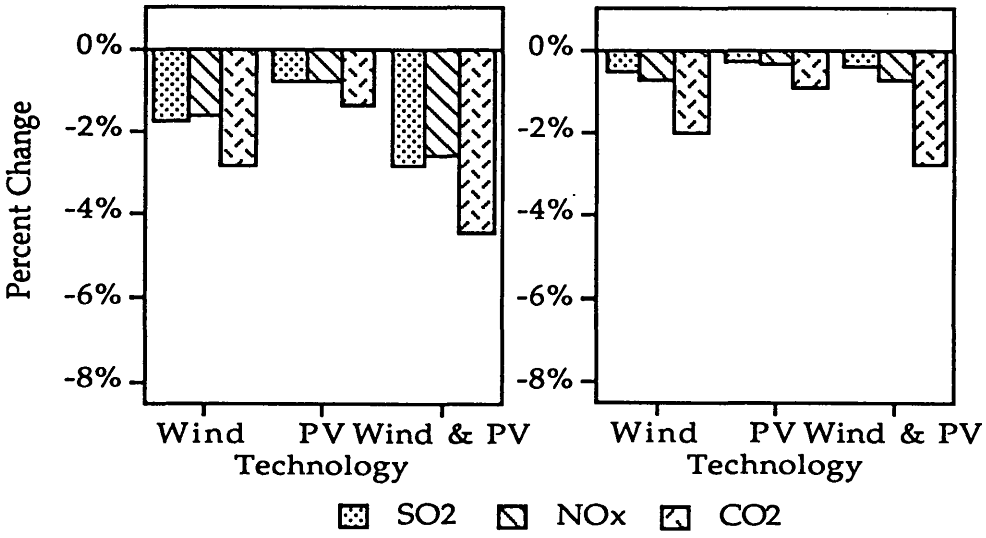


Figure 15: Emissions Reductions in 2007 and 2011 for Double DSM

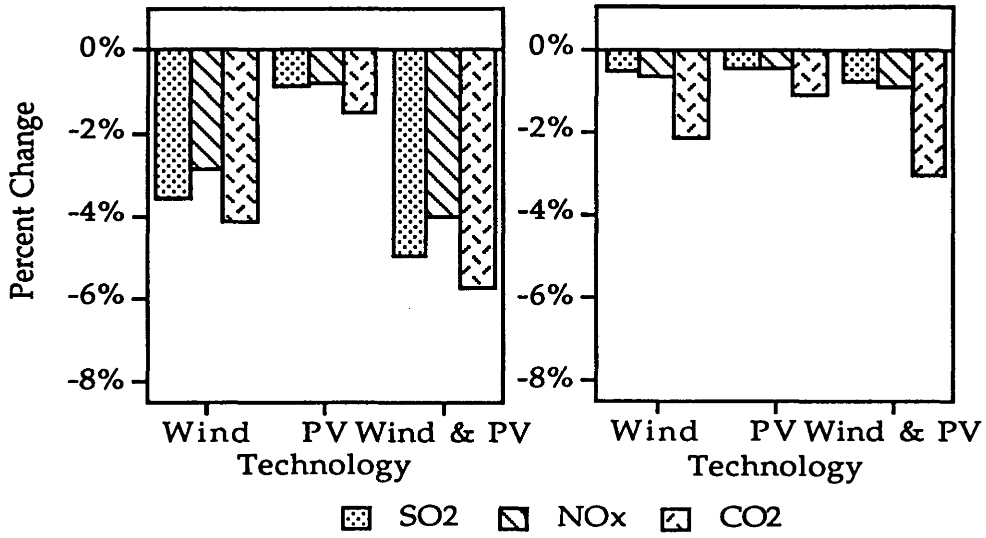
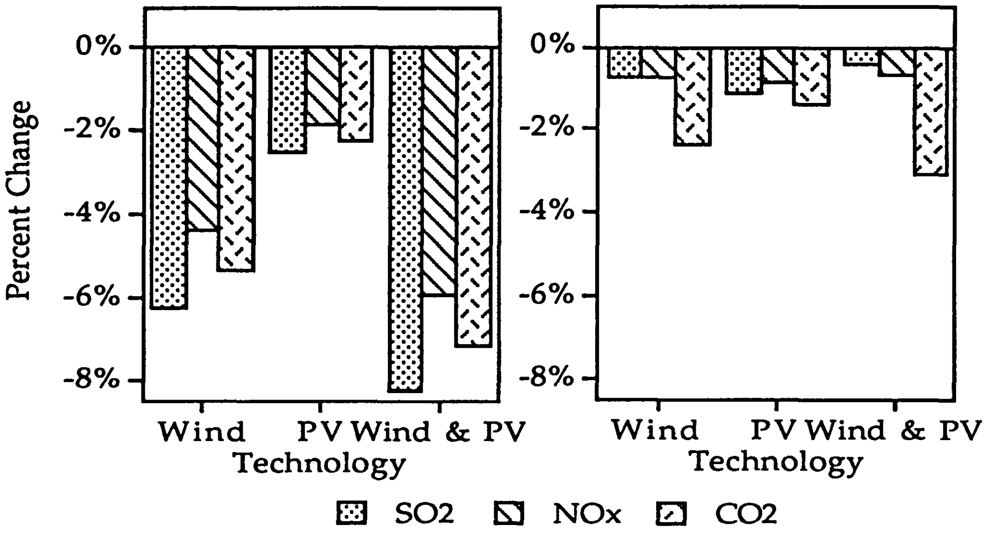


Figure 16: Emissions Reductions in 2007 and 2011 for Triple DSM



The potential for reductions in pollutant emissions from the inclusion of RETs in the generation supply mix is quite significant in the near term. An additional conclusion from these results might be that RETs are not an option for achieving long term emissions reductions. However, a different conclusion is also possible. The results clearly show that if the existing power system is dirty (defining the 1992 system as dirty) then the inclusion of RETs has a noticeable emissions reduction. Pursuing this result further, if the system remains dirty, as it does with triple, and to some extent with double DSM, then again RET generation significantly reduces emissions. Thus RET generation together with conservation programs will decrease emissions and save energy.

The potential for emissions reductions from RETs decreases when the power system is cleaned up through other means. When this is the situation, targeting RETs for emissions reductions becomes redundant. These results suggest that the combination of the options of building new (clean) conventional capacity, installing emissions controls on existing capacity or relying on RETs for emissions reductions is redundant, while options such as increased DSM with RET generation are complementary.

Cost of RET Generated Electricity

The cost of the electricity (COE) generated by wind power and by photovoltaics is graphed in figures 17 and 18. These COE trajectories are based on the capital cost assumptions presented in the previous chapter. The COE from wind power, in figure 17, decreases significantly over time for two reasons: i) capital and O&M costs are assumed to decrease over time, ii) no new turbines are installed after 2004. Also, the cost for a Maine transmission line spur is added all in the first year of construction, making the early ¢/kWh higher than the COE from the wind turbines alone. The current federal production tax credit for windpower generation of 1.5¢/kWh is assumed here to end in 2002 (expiring after the current ten year time period for the federal production credit, voted into law as part of the federal energy bill on October 8, 1992). Given that wind turbines are assumed to have a twenty year life time, turbine retirement would begin in 2015, adding new capital costs to the expenditure stream at the time. The PV COE in figure 18 also includes new capital costs only for the years 1995 to 2004.

Figure 17: Cost of Electricity from Wind Power Generation

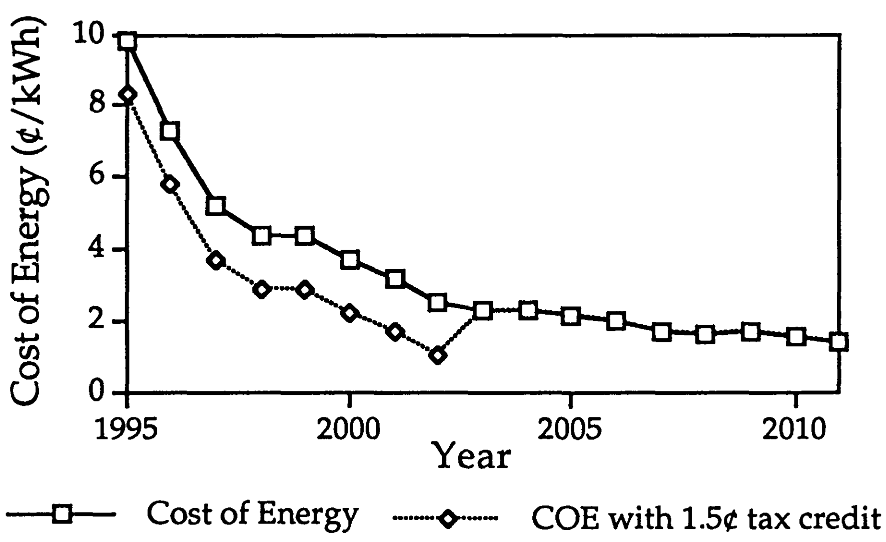
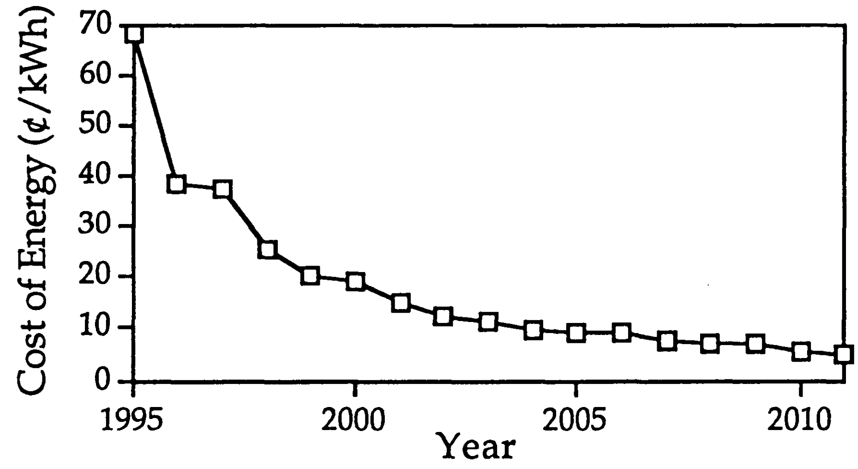


Figure 18: Cost of Electricity from Photovoltaic Generation



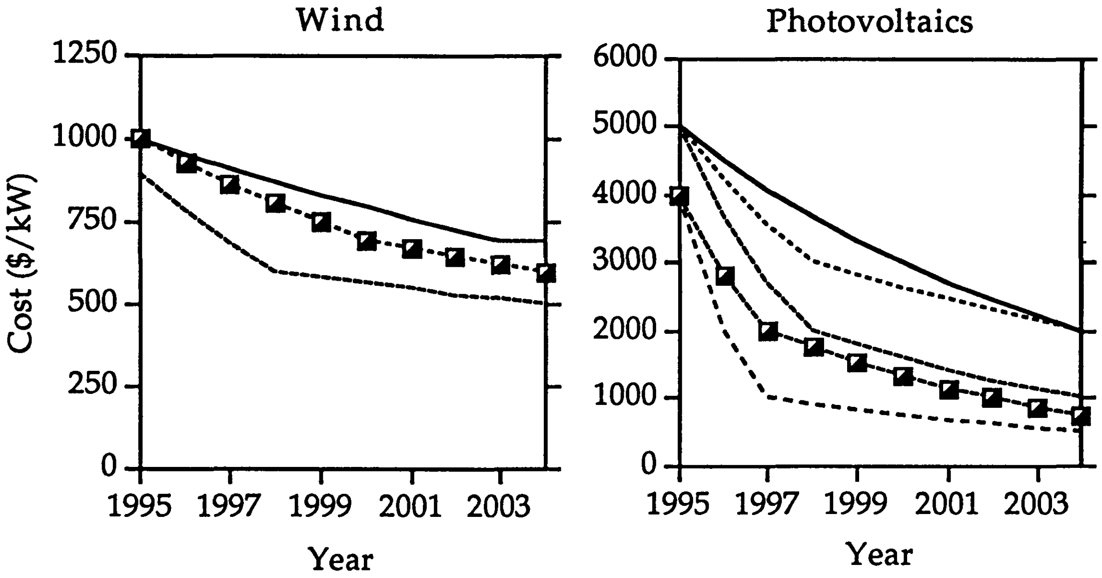
SENSITIVITY STUDIES ON COST AND EFFICIENCY

Capital Cost Sensitivity Studies

The sensitivity studies on system cost include changes to the assumed capital cost trajectories for both wind turbines and photovoltaics. Two discount rates are also used to bound the resulting net present value of the power system through the year 2011.

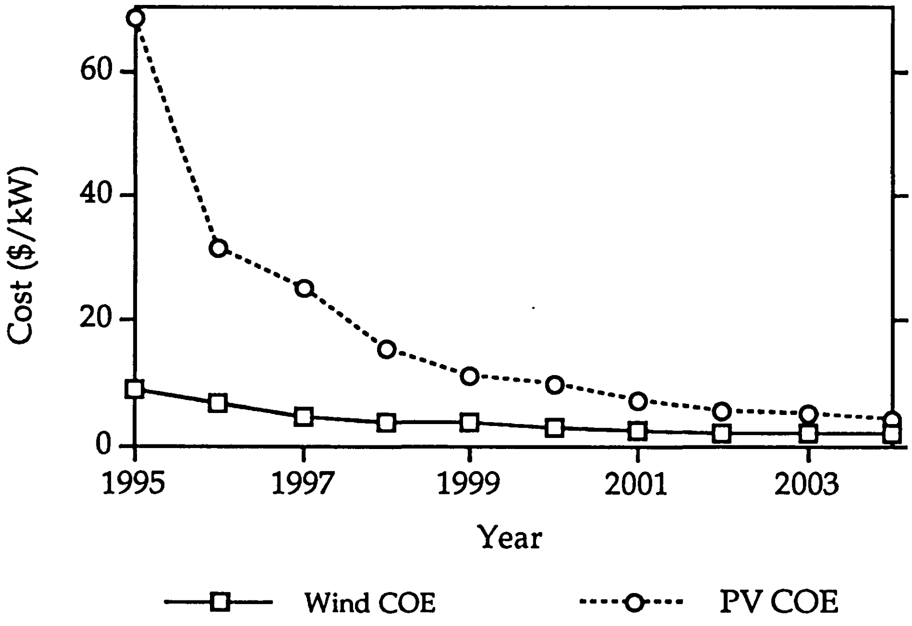
The capital cost trajectories that were tested are shown below in figure 19.

Figure 19: Capital Cost Trajectories



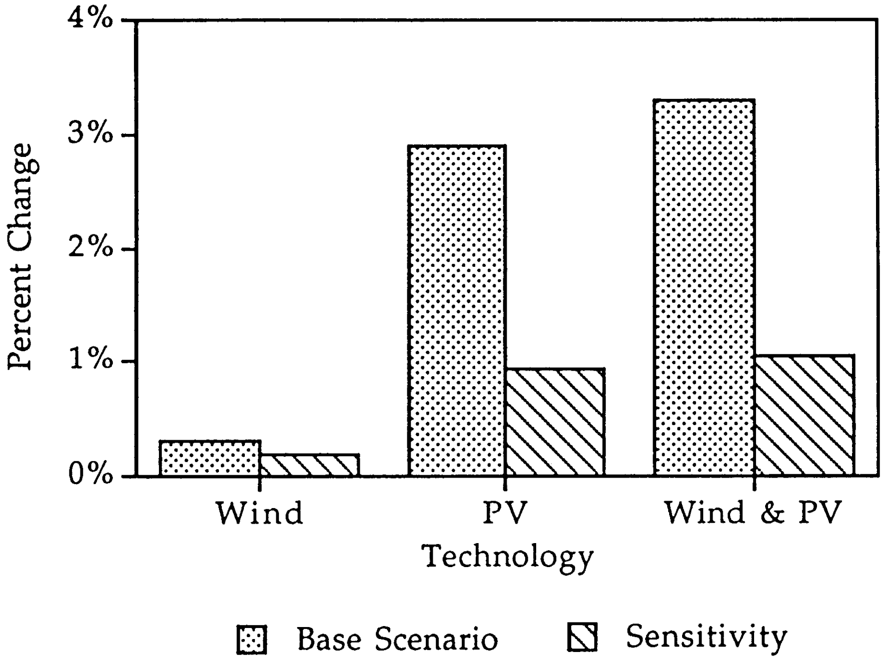
Trajectory 2 for wind turbines and trajectory 4 for photovoltaics are focused on for the remainder of this section. These trajectories result in the cost of electricity generated by wind and PVs as shown in figure 20.

Figure 20: Sensitivity on Cost of Electricity from RET Generation



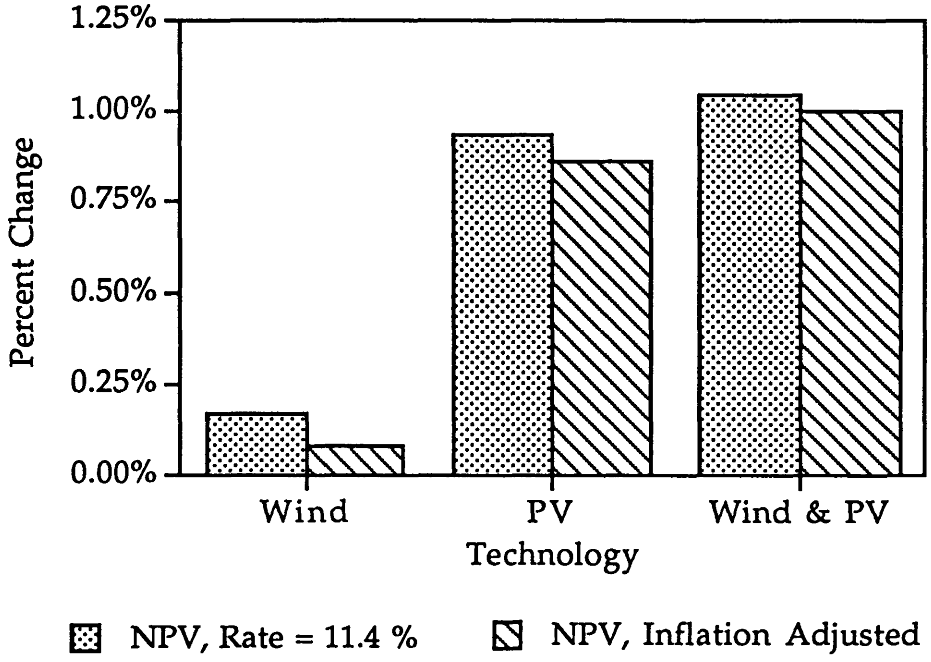
Originally, the COE from wind decreased from about 10 ¢/kWh to 2 ¢/kWh. For the sensitivity study, wind COE decreases from about 9 ¢/kWh to 1.5 ¢/kWh. The change for PVs is from an original derease from about 70 ¢/kWh to 5 ¢/kWh. For the sensitivity study, PV COE decreases from about 67 ¢/kWh to 2.5 ¢/kWh. The change in percent increase in system cost due to changes in assumed RET capital costs are shown in table 5.

Table 5: Sensitivity on Percent System Cost Increase from RETs



One further sensitivity, on the results of the net present value (NPV) of system cost, comes from the discount rate used to compute the NPV. The rate used for all previous cost values is the standard utility rate of 11.4 %, which is assumed to be an upper bound. For a lower bound on the discount rate, an assumed inflation rate of 3 % is used. Figure 21 shows the effect on system cost increase from including RETs, for the two different discount rates. For wind turbines, the change in percent system cost increase is almost 50 %. Although the changes for PVs are not as large, this graph does show that the discount rate could effect the overall cost competitiveness of supply side options.

Figure 21: Sensitivity of System Costs with Discount Rate

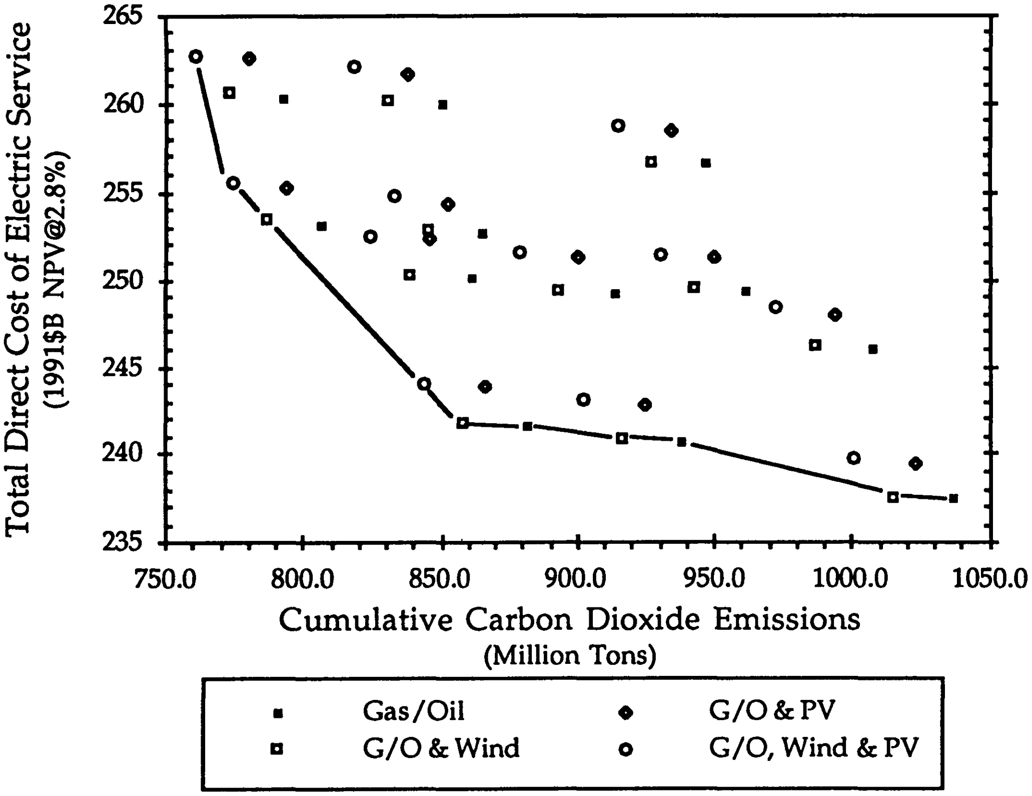


Conversion Efficiency Sensitivity Studies

The sensitivity analyses on the RET conversion efficiencies were performed by changing the wind turbine power curve, and altering the tile angle of the PV arrays. Due to the coarseness of the wind speed data used, the effect from using a different wind turbine power curve was not significant. Changing the tilt angle of the PV arrays, however, lead to a 50 % increase in the energy capture which resulted in greater reductions in emissions of 50 % for CO_2, 100 % for NO_x and 35 % for SO_2. Figure 22 shows a trade-off graph of cost (using the assumed inflation rate of 3 % for discounting) versus CO_2, keyed for supply side technology mix. For this graph, the sensitivity capital cost trajectories and PV tilt angle are used.

Comparing this graph to figure 4 shows that the Gas/Oil & Wind technology mix remains noticeably superior in terms of emissions reductions to the Gas/Oil alone mix, and is now almost equivalent in terms of cost. The Gas/Oil & PV mix has moved very clost to the trade-off curve,

Figure 22: Sensitivity of System Cost versus CO_2



and at higher cost/lower emissions region of the trade-off curve, the Gas/Oil, Wind and PV mix is the optimum. The groupings in terms of DSM level and treatment of existing plant follow the same patterns as those shown previously in figures 5 and 6. Thus, different assumptions about capital costs, the placement of the PV arrays and the discount rate lead to the result that the use of both wind turbines and photovoltaics for power generation can significantly reduce emissions with only a small increase in cost.

CHAPTER 6

CONCLUSIONS

INTRODUCTION

Many factors are required to achieve an increase in the use of renewable energy technologies such as wind turbines and photovoltaics for electric power generation, with a significant increase possible if they were more widely used by utilities. This thesis has dealt with developing and demonstrating analysis tools to be used in conjunction with an existing utility standard production-costing model, and with increasing the familiarity of the characteristics and behavior of these technologies.

The results of performing the analysis of the impact of including 1500 MW_p each of wind power and photovoltaics in New England are shown in table 1 below. These results show that with 2.7 % of the total regional energy generation (1500 MW_p installed) coming from wind power, a small increase in system cost (0.08 %) leads to system wide emissions reductions for NO_x of 2.9 %, SO_2 of 3.6 %, and CO_2 of 4.2 %. Reductions in oil6 (residual) use are about 1.1 % and in coal use are 0.3 %. For the same installed capacity as wind, PVs contribute 0.9 % of the total regional energy generation. Including PVs results in a 0.9 % increase in total system costs, and emissions reductions for NO_x of 1.6 %, SO_2 of 1.2 %, and CO_2 of 2.3 %. Fuel use is reduced by 0.3 % for oil6 and 0.1 % for coal.

Table 1: Impacts of 1500 MW_p of PV and Wind Power

Parameter	Wind Power	Photovoltaics °
Installed Capacity	1500 MWp	1500 MWp
Average Energy Capture	3000 GWh	1500 GWh
(% of 1992 Demand)	3 %	1.5 %
Average Capacity Credit	350 MW	450 MW
Average Capacity Factor	24 %	15 %
* Cost of Energy, 1995	9.8 ¢/kWh	68.4 ¢/kWh
2004	2.3 ¢/kWh	4.4 ¢/kWh
Capacity Displacement	Peak & Intermediate	
** % System Cost Increase	0.08 %	0.86 %
*** % CO2 Decrease	4.2 %	2.3 %
% SO2 Decrease	3.6 %	1.2 %
% NOx Decrease	2.9 %	1.6 %
% GWh from RET	2.7 %	0.9 %
% GWh from Oil6 Decrease	1.1 %	0.3 %
% GWh from Coal Decrease	0.3 %	0.1 %

° Sensitivity analysis data used.

* Cost of Energy: 1995 is the first year of installation, 2004 is the final year of installation, and thus the last year that capatal costs are included in the COE calculation.

** The system cost increase is for 2011, inflation (3 %) adjusted only.

*** The emissions and fuel use reductions numbers are for 2007, double DSM.

As important as the numerical results is the interaction between the different planning options (supply-side technologies, DSM level and repowering) and the time evolution of the impacts analyzed in chapter 5.

The potential for reductions in fossil fuel consumption and pollutant emissions from the inclusion of RETs in the generation supply mix is quite significant in the near term. The results from this research show that over time, as the existing, base system becomes cleaner due to both the addition of emissions controls and from newer (cleaner) technologies coming on line, the possibility for emissions reductions from RET generation decreases. Conversely, the potential for emissions reduction and the displacement of dirty fossil fuel generation due to RET generation *increases* as the level DSM increases. This occurs because as DSM increases, less new capacity is required, leaving an older and dirtier system. The RET generation then displaces this older, dirtier generation rather than new, clean generation.

These results suggest that the combination of the options of building new (clean) conventional capacity, installing emissions controls on existing capacity and relying on RETs for emissions reductions is redundant, while options such as increased DSM with RET generation are complementary. The results reinforce the importance of interactions within the system in determining the relative benefits of RETs. They also serve to emphasize the fact that the benefits of using RETs may change over time as the power system as a whole evolves.

BARRIERS TO INCREASED USE OF RETS

Regardless of the potential for positive results in emissions and fuel use reductions, wind power to a degree, and photovoltaics much more so, continue to be viewed as marginal technologies, not seriously considered for large scale power generation. This is not an inherent property of these technologies however, but more a reflection of the existing institutional and political institutions which favor large, centrally located and controlled, fossil fuel power plants over distributed renewable energy generation.

Financial Barriers

Technologies such as wind turbines and PVs face two types of financing barriers. First, these technologies often are not considered dependable or appropriate for electric power generation due to the intermittent nature of their resource and the fact that they are viewed as "emerging" rather than established technologies. These factors result in financing difficulties since the technologies are thus perceived to be risky.

Second, the methods used for discounting expected cost streams for comparing projects favors fossil fuel plants. RETs tend to appear more expensive due to the fact that the majority of their expenses (capital costs) are incurred in the initial years of their life time. Capital costs for fossil fuel plants are lower initially, yet significant additional costs are incurred each year for fuel purchases. With discounting however, these projects are compared as though their cost streams had the same pattern, with the result that fossil fuel plants appear less expensive overall after discounting.

RETs however, have *lower* financial risk due to not facing uncertain fuel and construction costs. The standard utility practice of using the "weighted average cost of capital," WACC, as the discount rate for *individual* projects distorts the comparison of proposed projects in favor of fossil fuel plants. An analogous example would be to use a financial portfolio's average 10 % rate of return as the discount rate for comparing the expected yield from a low risk U.S. Treasury bond with a 7.0 % yield and a high risk "junk bond" with a 16 % yield (Awerbuch, 1993).

Public Perception

Although in general, public opinion often supports renewable energy, people do resist large construction projects in their own local area. Conventional power plants have a slight advantage over RETs due to the fact that the visual and environmental impacts from RETs[1] are strictly local while controversy over impacts from fossil fuel use are more dispersed to the regional and global levels[2].

Experience with Renewable Energy Power Generation

Previous use and promotion of wind power and photovoltaics has not been all positive. As mentioned in chapter 1, tax credits for these technologies in the 1970s were often abused. In addition, the format of power purchasing

---

[1] This is true especially for wind turbines which require significant land area, and have killed many birds in California. Roof mounted PVs do not encounter the same siting or environmental resistance.

[2] All power plants do tend to encounter siting resistance. The growing controversy over fossil fuel use comes from the serious global and regional environmental impacts though, not from local air pollution or local siting controversies.

contracts between utilities and independent power producers (IPPs) were not standardized initially, requiring that new contracts be negotiated for every IPP. This results in unnecessary loss of time and money, and often negative relationships between utilities and IPPs (Kozloff, 1992). This lead the state of California to mandate "standard offers" for IPPs, as discussed in chapter 1. However, even these standard offers did not always stabilize the rates in the contracts since they were tied to the utilities' avoided cost, which itself was tied to the fluctuating cost of natural gas. Investment tax credit abuses were unaffected by power purchase contracts.

Tendency for Continued Fossil Fuel Use

The barriers listed above address direct drawbacks to the use of RETs. A second type are those impediments resulting from the benefits of using conventional power generators and the negative aspects of *change,* whatever that change might be. Both the lobbying power of industries relying on the use of conventional fuels and the inertia of the existing infrastructure block innovation in the energy supply. There is a widespread distrust of small, decentralized, intermittent and non-fossil technologies in utilities (Sachs, 1992). Industry inertia is made apparent in the time frame required historically for shifts in fuel use in the commercial energy system during peacetime (previously moving from wood to coal to oil). These shifts tend to occur very gradually over approximately fifty year time periods (Starr, 1992).

Overcoming the Barriers

A significant yet intangible barrier, is simply a lack of familiarity with and understanding of "small, decentralized and intermittent" renewable energy technologies. One goal of the research presented in this thesis was to demonstrate that intermittent resources *can* be predicted, modeled and analyzed in conjunction with existing utility computer models. Chapter 2 presented methods for modeling the resources. Chapter 4 discussed a method for analyzing wind turbine and PV technologies as part of electric utilities, and chapter 5 presented the results of applying these methodologies to the New England electric power sector. A second goal of this research, in interacting with regional stakeholders in the New England electric power sector, was to begin to find methods to address the issue of familiarity. Chapter 3 addressed the issue of familiarity by discussing the operation and performance of these technologies along with related issues.

BENEFITS FROM USING RETS

If the situation were that RETs simply had not received the same opportunities to mature as have conventional plants but had no unique benefits to offer society, there would be no cause for actively promoting their use. However the use of RETs for power generation does offer many benefits to society and to the utilities which use them, as discussed at the end of chapter 3, and demonstrated by the results presented in chapter 5. These benefits include:

- monetary savings from decreased fossil fuel consumption
- system wide pollutant emissions reductions
- long term price stability
- decreased long term capital costs due to:
  - capacity credit
  - capacity displacement

In particular, wind power and PVs are well known as having very beneficial environmental properties. Political concern over acid rain, ozone depletion and global warming is growing as revealed domestically with the 1990 Clean Air Act Amendment, and internationally in Agenda 21 from the UN Conference on Environment and Development in Rio de Janeiro in 1992[3]. It is also clear from the fact that the Gulf war *occurred* that our nation is very insecure over its dependence on foreign owned fuel. The use of renewable energy not only does not require the military to secure its continued supply, but also protects consumers from the cycle of fluctuating fuel prices.

---

[3] The Clean Air Act was discussed in chapter 5. Chapter 9 of Agenda 21 from the Rio Summit calls for international protection of the atmosphere, and the implementation of sustainable energy programs with emphasis on "promoting, distributing and developing renewable sources of energy to encourage environmentally safe and sound energy systems."

Value in terms of decreased environmental destruction and energy insecurity are some of the benefits. Other advantages come from the modular and distributed nature of these technologies[4]. Small, decentralized technologies such as PVs (and fuel cells), are coming to be seen as desirable for these very properties. They can be installed modularly saving expenditures on interest payments. And being decentralized they can reduce the load on transmission and distribution systems.

POLICIES TO PROMOTE THE USE OF RETS BY UTILITIES

Many policy proposals dealing with renewable energy are currently made in response to environmental concerns. One common example, the carbon tax, would focus on carbon emitting (fossil fuel) power generation, favoring RETs. The concept of "allowance reserves" would allow utilities which build RETs to delay meeting CAAA emissions reduction mandates. Alternatively, "pollution allowances" could be given to utilities which use renewable energy (Sklar, 1990). Proposed amendments to PURPA (see chapter 1) would raise the current limit on fossil fuel co-firing of qualifying facilities from 25 % to 50 %, allowing wind turbines and PVs to be dispatchable. As these proposals reveal though, the desire to compete according to the economic rule of cost competitiveness may compromise the environmental advantages of renewable energy power generation.

In addressing the financing difficulties facing many RET projects, it is important to offer utilities the same incentives as IPP. Utilities, which have easier access to financing than IPPs, could then act as a group or individually in accepting proposals for RET projects. One such initiative came from New England Power. In December of 1991, NEP issued a "Green RFP" (request for proposals) as part of long term goals of continued environmental improvement and maintaining a diverse and reliable energy supply along with competitive and stable rates (Hachey, 1992).

---

[4] PVs can be used to support a distribution system. Modular construction renders the pattern of building too much capacity unnecessary, as well as not requiring large, long term loans and interest payments for the construction.

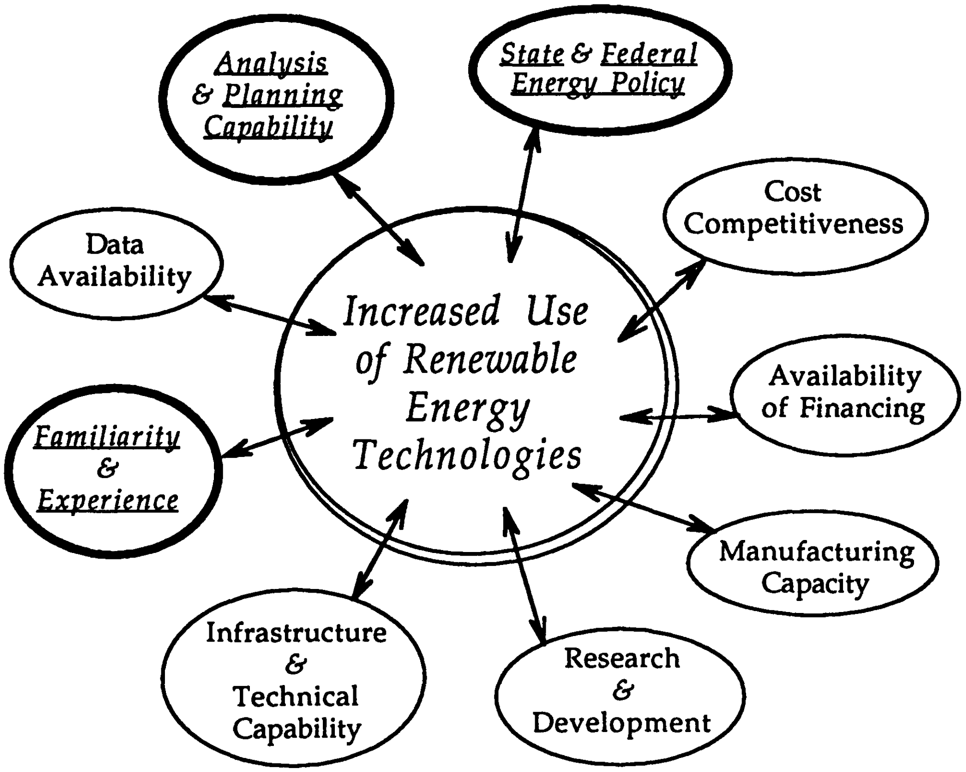
In order to avoid the abuses as occurred with the investment tax credit of the 1980s (see chapter 1), policies should focus on production, or output, rather than input subsidies. An output subsidy is visible, as it is relatively easy to determine if a plant is generating electricity or not. It also encourages development of and investment in those technologies which generate electricity the most cost-effectively. In contrast, input subsidies such as investment tax credits, do nothing to encourage cost-effective energy *generation*. In line with these ideas, in October 1992, the federal energy bill was passed, which included a ten year 1.5 ¢/kWh production tax credit for wind power. As more of a continuation of previous policy however, the bill included a permanent extension of a 10 % investment tax credit for firms which install solar energy equipment.

Federal energy policy, as presented in the Energy Policy Act of 1992, unfortunately goes no further than acknowledging the existence of RETs, placing no emphasis on possible benefits of using these technologies within the United States. Title XII of the Energy Policy Act focuses on the commercialization of renewable energy technologies, specifically calling for proposals for demonstration and commercial application projects. Title XII does acknowledge that commercial barriers to RET use exist which favor conventional plants. However, it makes no mention of any need for *domestic* use of these technologies, emphasizing instead their export potential. Encouraging domestic use seems to be left to state governments and regulators who do actively promote RETs, often in response to the public's concern over the environment.

CONCLUSIONS

Efforts to address all the areas shown below in figure 1, repeated from chapter 1, are required before technologies such as wind turbines and PVs are utilized for electric power generation more widely. The overall results from this research were summarized in table 1.

Figure 1: Avenues to Increased Use of Renewable Energy Technologies



Costs, especially for PVs, must continue to decrease. Perhaps more important though is the realization that these costs must decrease *relative to* conventional generators, and this requires the removal of the institutional and political biases which favor the use of fossil fuel over intermittent renewable energy resources. The sensitivity studies on the capital costs reveal the importance of favorable government policies access to financing opportunities. Although the costs used in this analysis are assumed to be strictly capital costs of the technologies, they could also represent the equivalent capital costs seen by potential owners (utilities or IPPs) after accounting for different possibilities in financing costs or government subsidies. Thus, these sensitivity studies reveal the importance of favorable policies and financing terms if renewable energy power generation is to become "cost-effective."

An interesting outcome of this thesis, resulting from the dynamics of the power system, is that the potential benefits gained from utilizing renewable energy power generation are dependent upon interactions with other planning options, such as pollution controls, demand side management programs, and the expansion or retirement of conventional capacity. As the system evolves over time, the collective planning decisions impact whether RETs will or will not make a significant contribution to emissions reductions and decreased fossil fuel use.

The research performed for this thesis further reveals that the lack of intermittent renewable energy resource data is a major obstacle to performing analyses on renewable energy technologies for power generation. If rigorous analyses of renewable energy technologies are to be possible, the policy of funding the collection of intermittent renewable energy resource data must be pursued once again. Analyses relying on this data will then increasingly facilitate the inclusion of renewable energy technologies in electric power sector decision making.

The results from this research demonstrate many concrete benefits to be gained from RET power generation, such as reduced pollutant emissions, decreased fossil fuel use, and a firm capacity contribution. In this era of growing concern over greenhouse gases and sustainability, the potential offered by renewable energy power generation of reducing both emissions and our dependence on fossil fuel must not be overlooked.

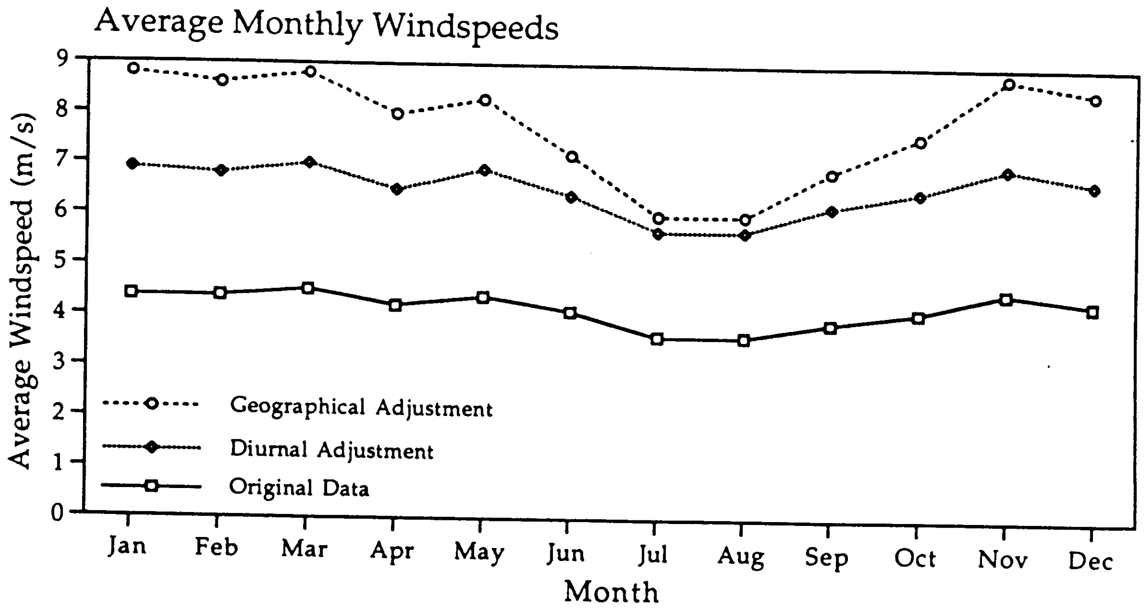
APPENDICES

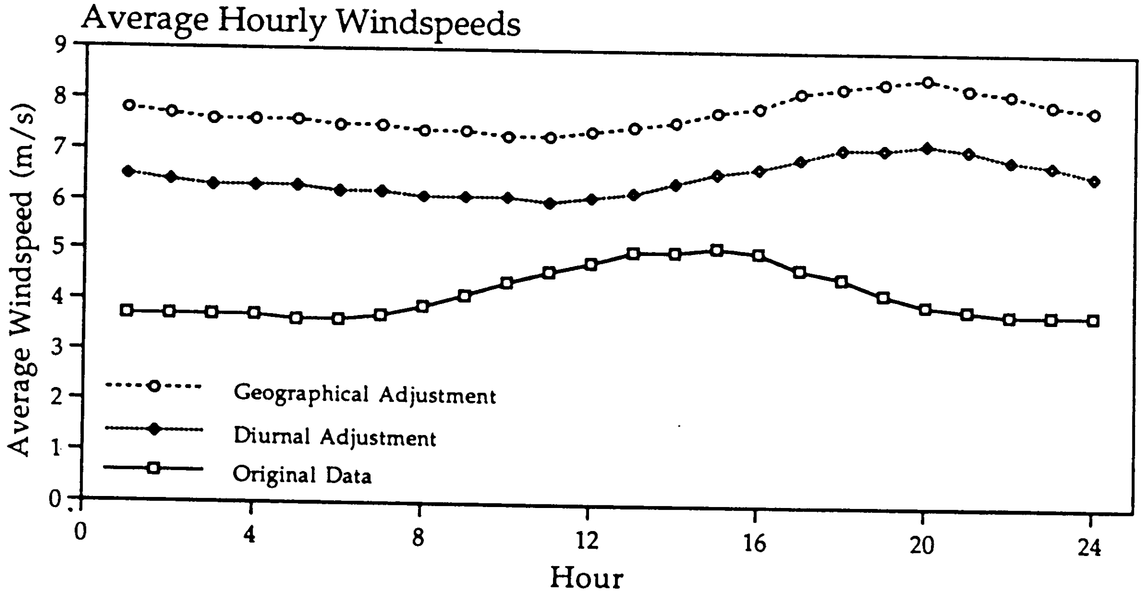
APPENDIX A: PRELIMINARY ANALYSIS OF HOURLY WIND SPEED DATA

This appendix contains complete sets of graphs of the hourly wind speed data for the two hypothetical wind turbine sites in this analysis. The first set of graphs is for Caribou ME, with the data adjusted to represent the wind regime of the Longfellow Mountains. The data is adjusted from a site with an average wind speed of 4.9 m/s (11.0 mph) to one with an average of 7.8 m/s (17.4 mph).

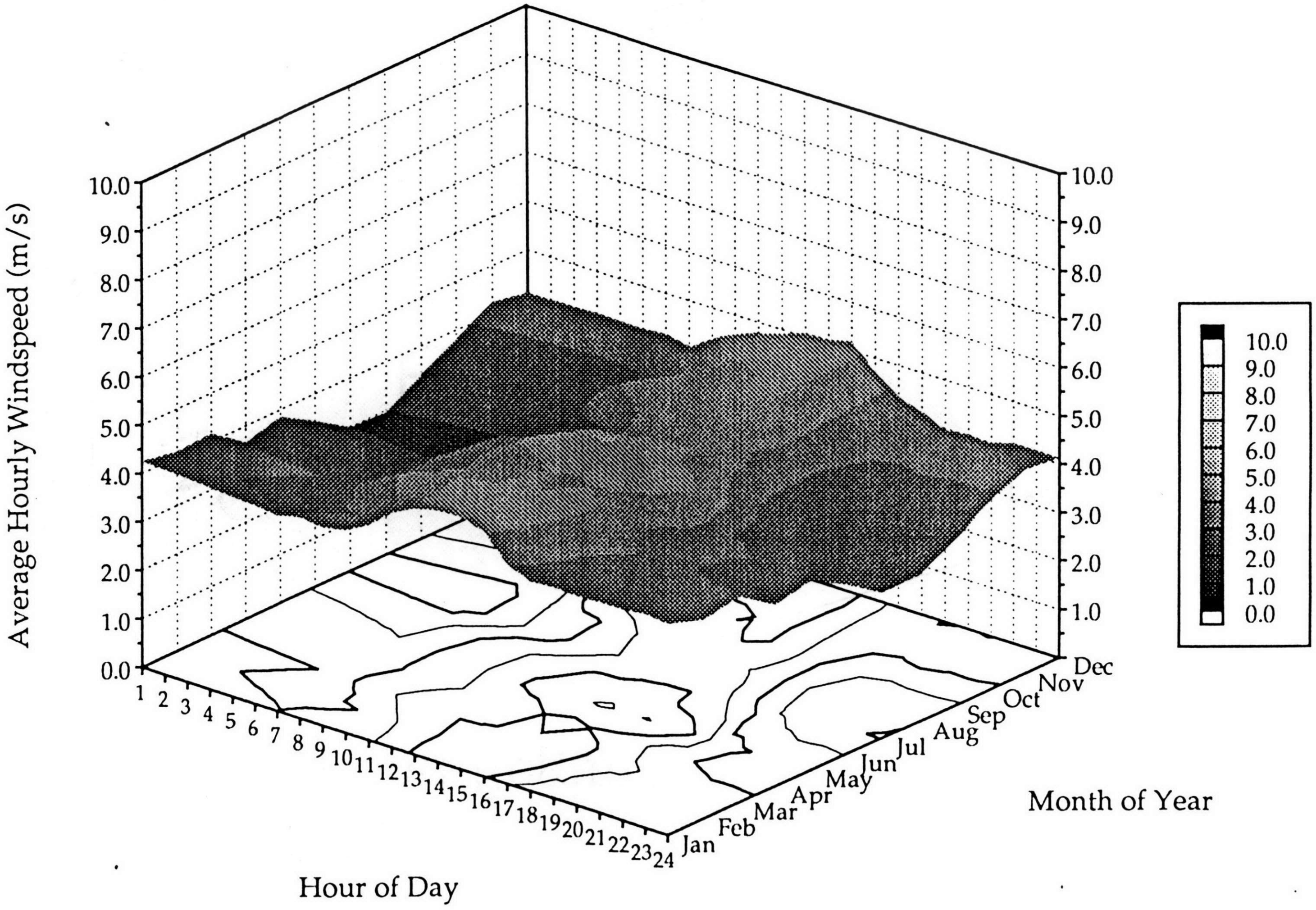
Mt. Tom is a very good wind turbine site in terms of wind resource yet has very little acreage. Therefore the second set of graphs represents a hypothetical site close to Mt. Tom with more acreage. For these graphs, the data was adjusted from an average wind speed of 6.4 m/s (14.3 mph) to one with an average of 6.9 m/s (15.4 mph).

Caribou ME, Average Wind speeds

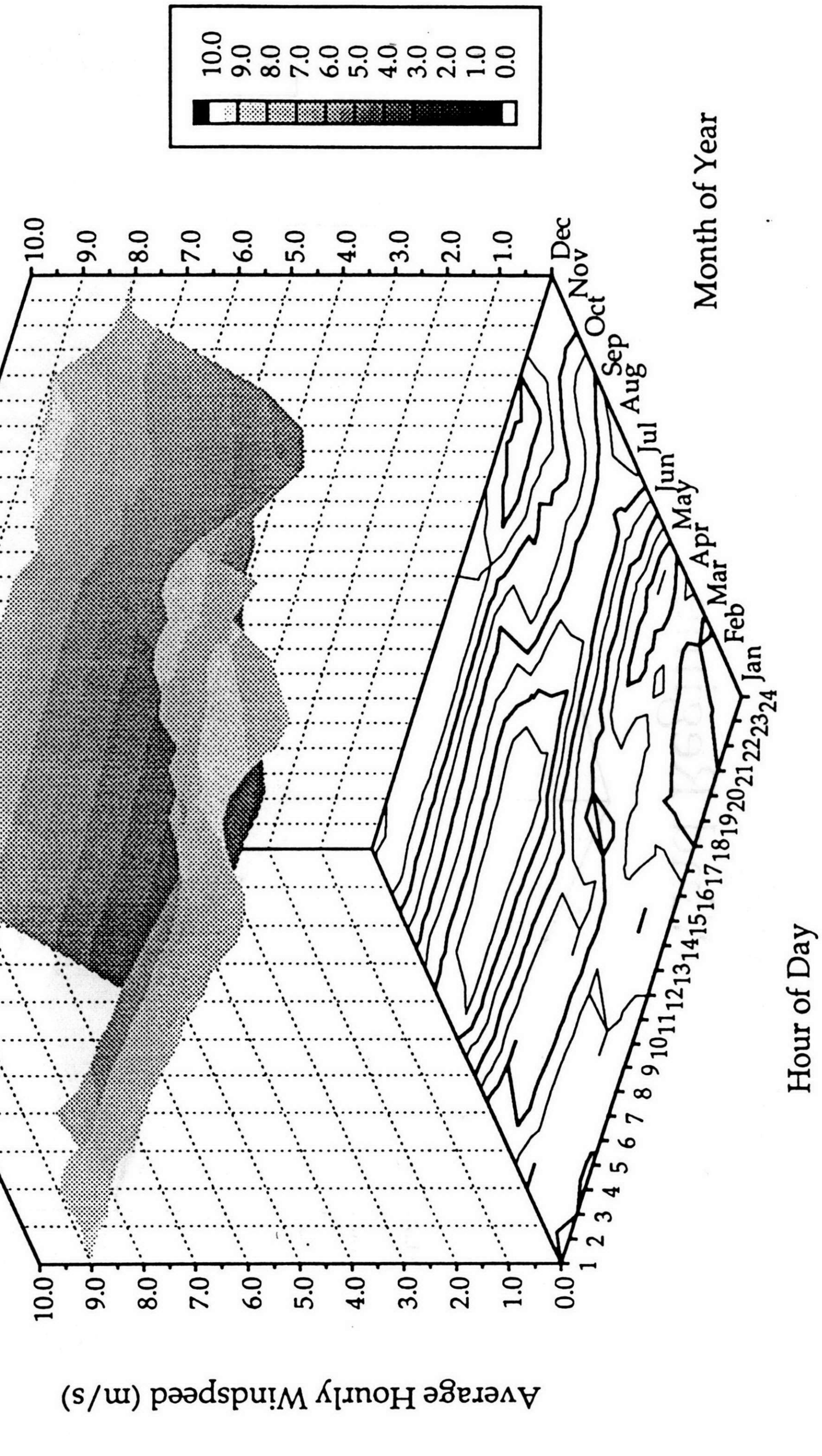




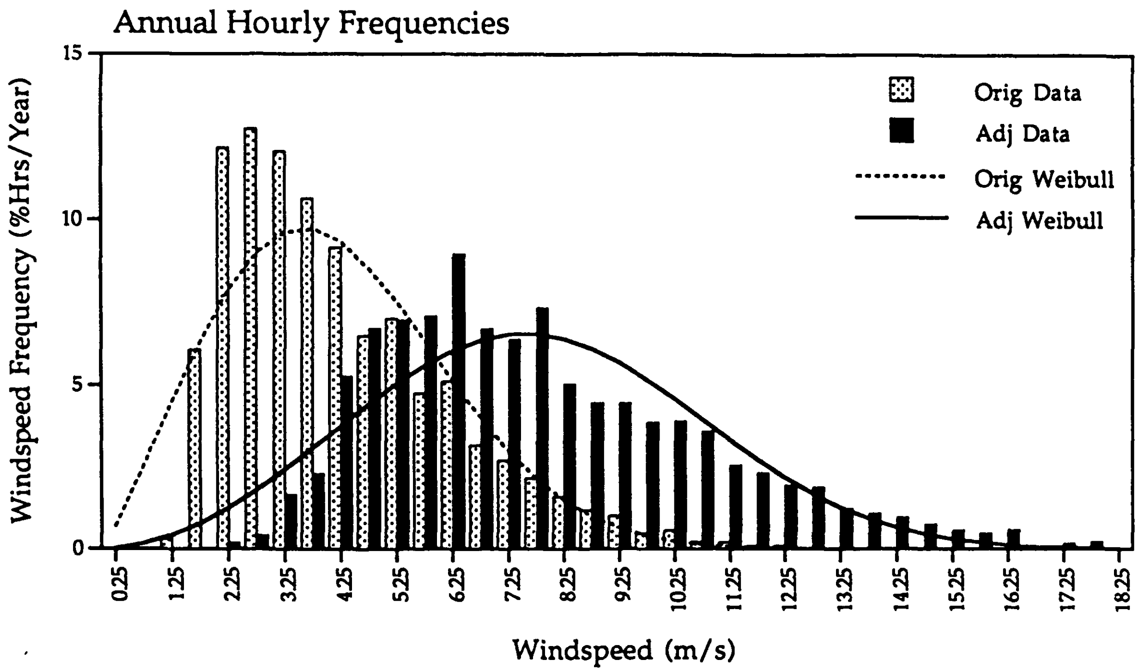
Caribou ME, Original Wind Regime

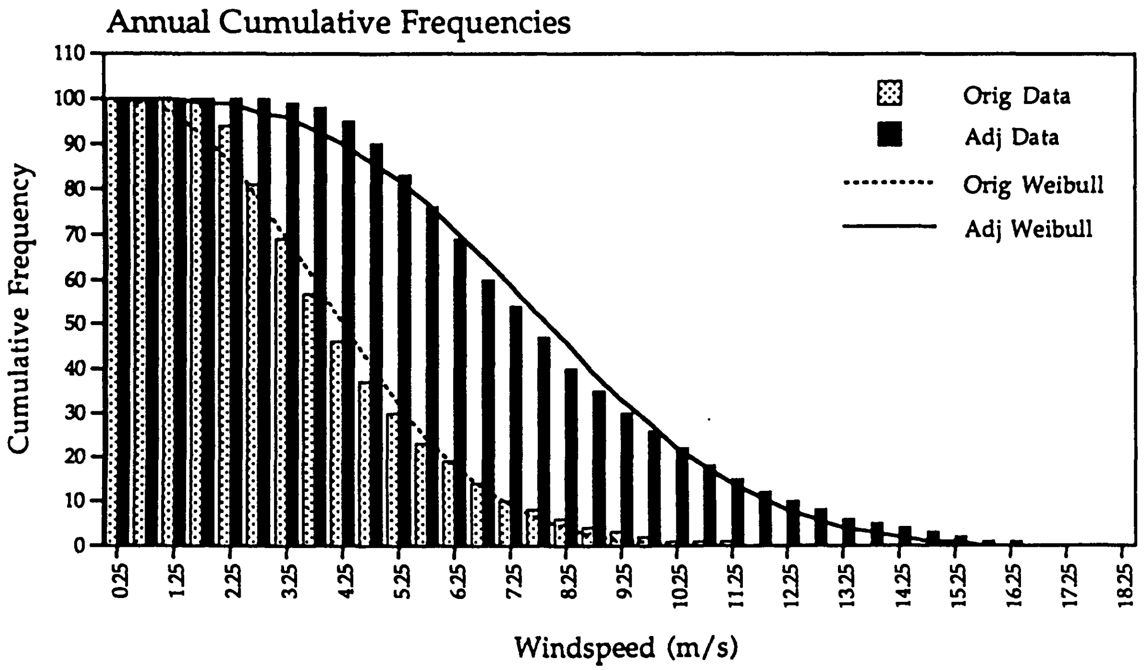


Caribou ME,
Adjusted Wind Regime

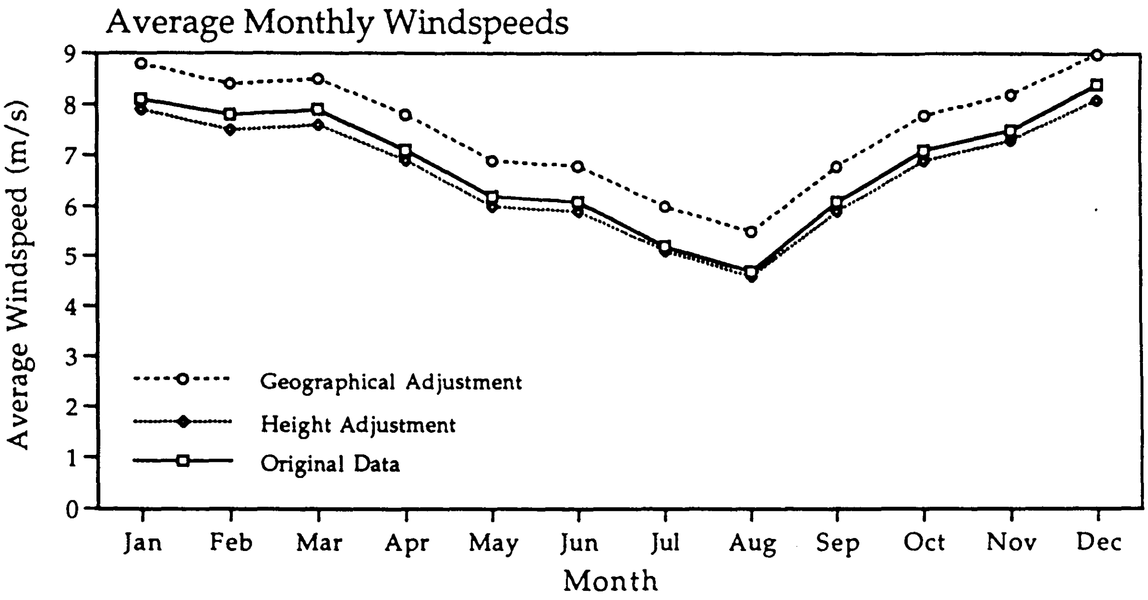


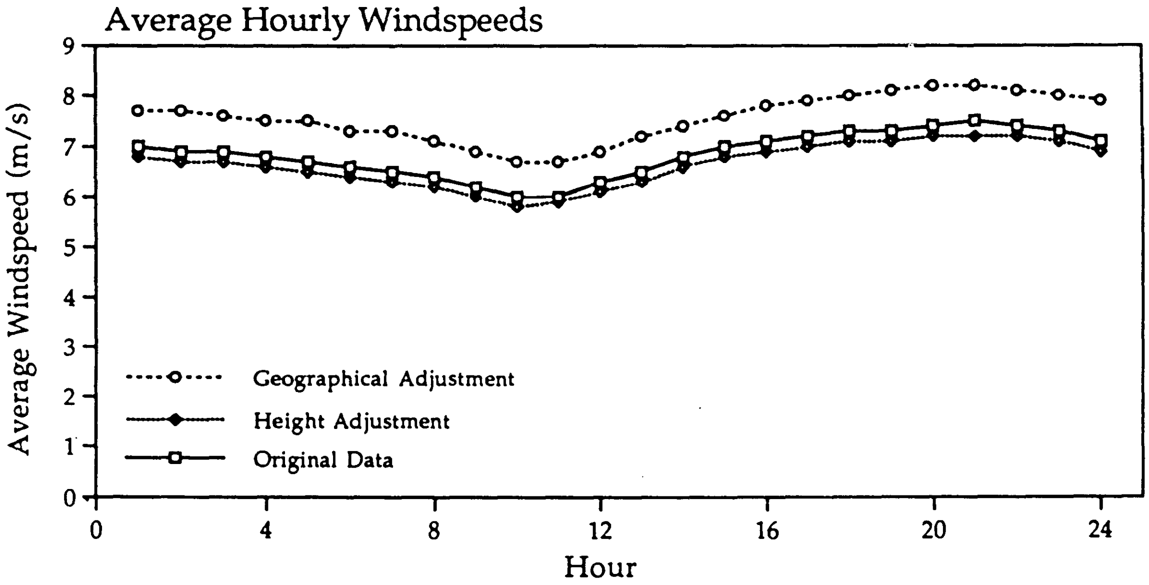
Caribou ME, Weibull Distributions



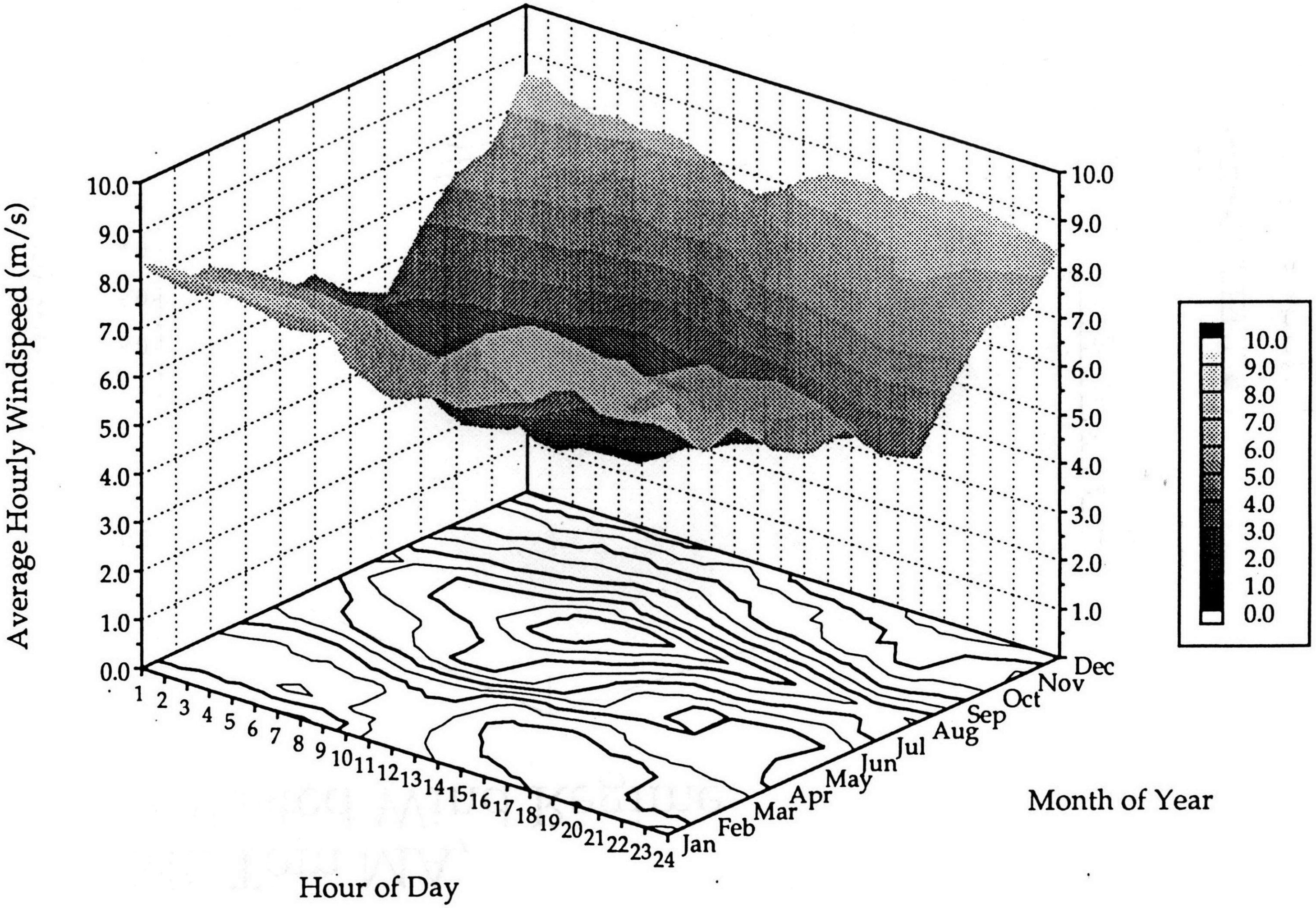


Mt. Tom MA, Average Wind speeds

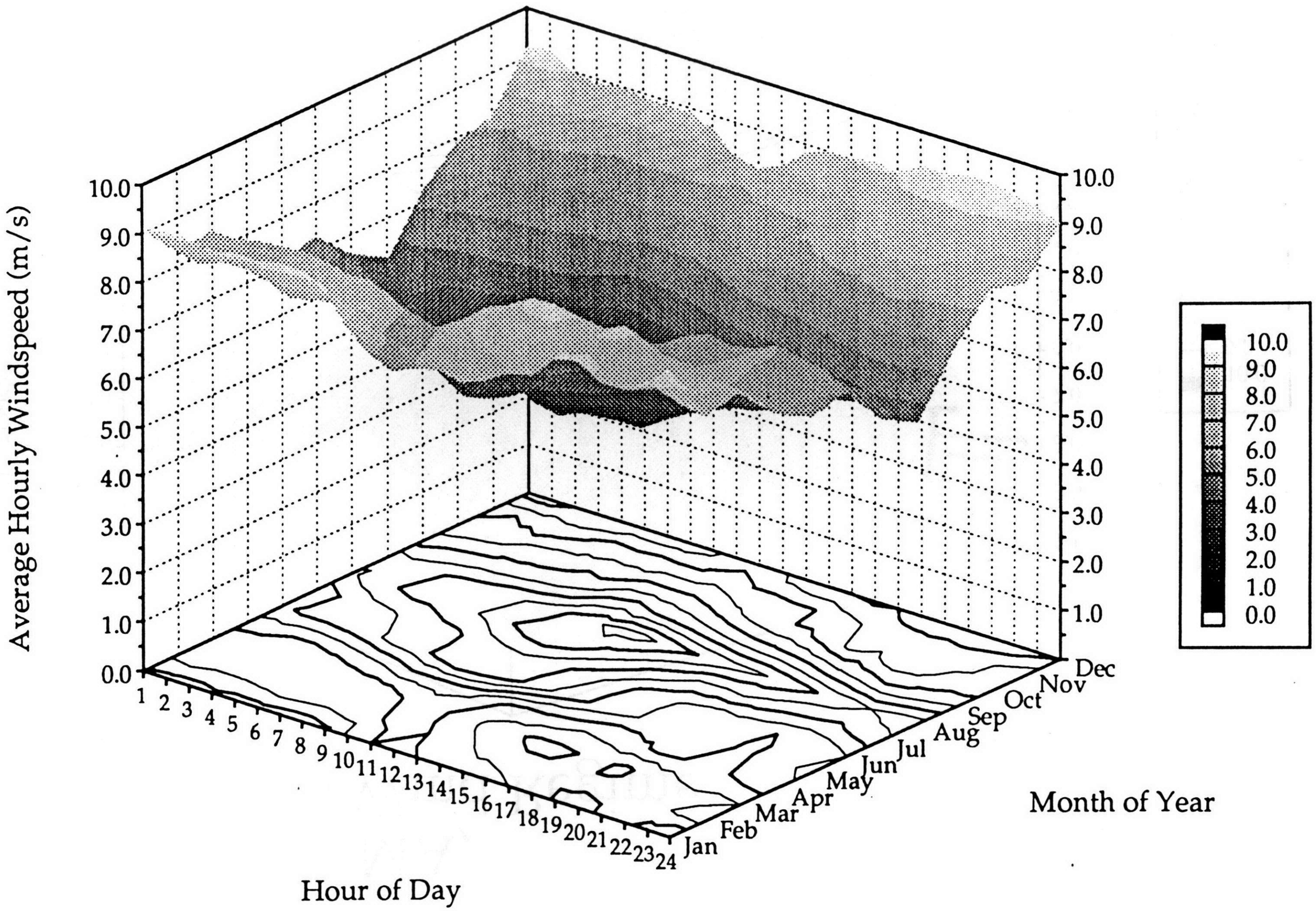




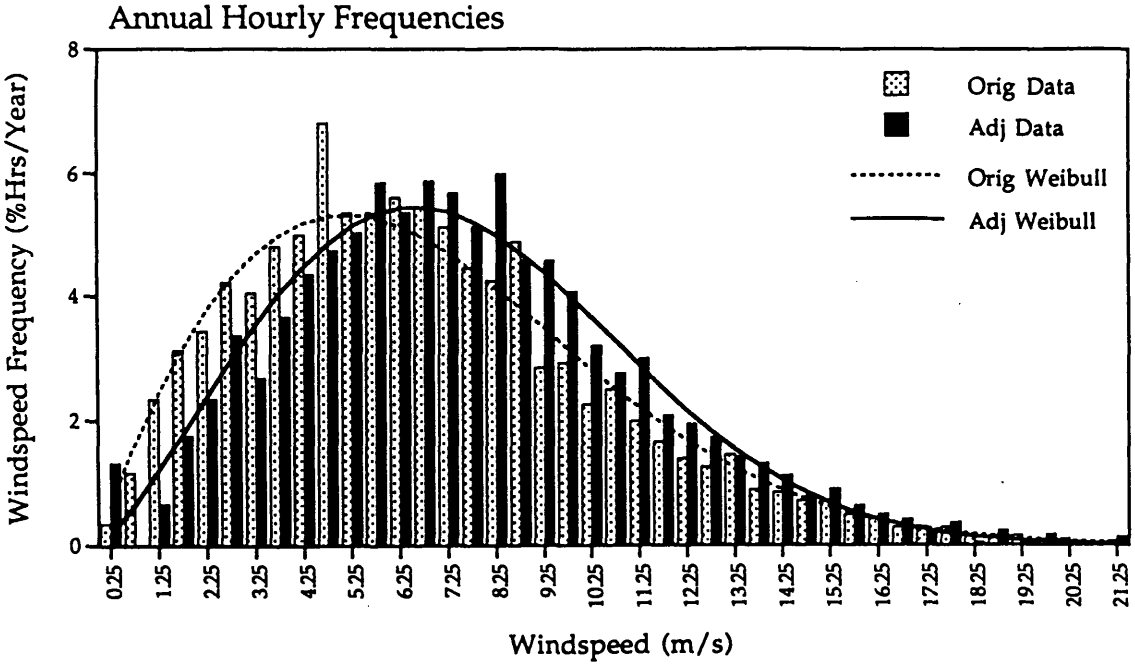
Mt. Tom MA,
Original Wind Regime

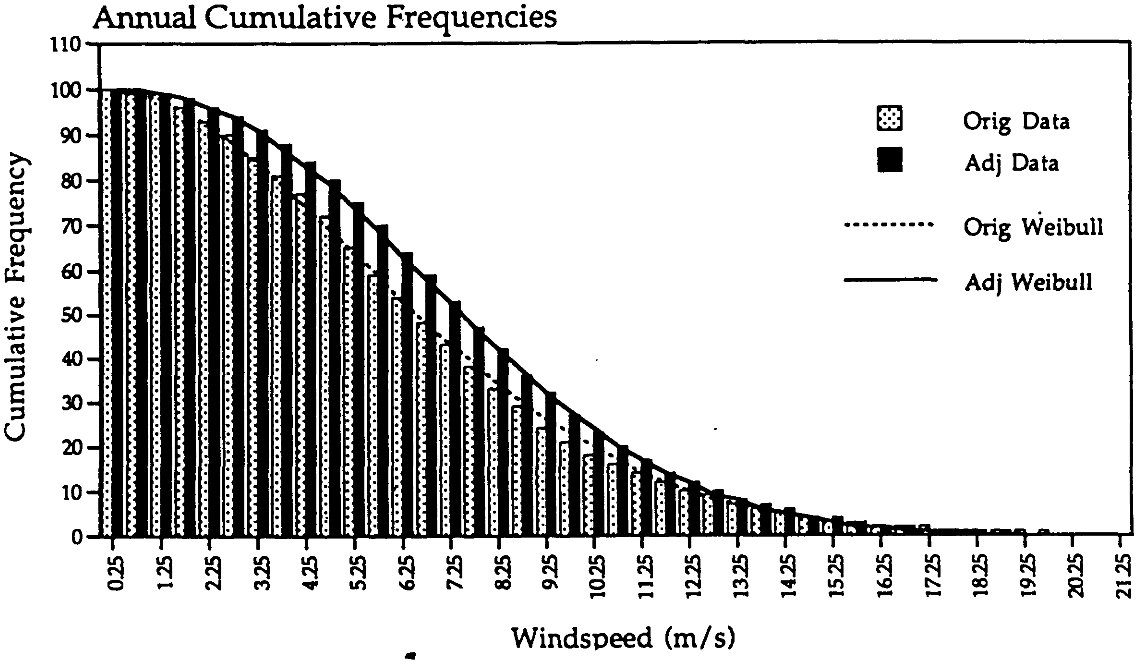


Mt. Tom MA,
Adjusted Wind Regime



Mt. Tom MA, Weibull Distributions





APPENDIX B: MODELING ASSUMPTIONS FOR AGREA STUDY

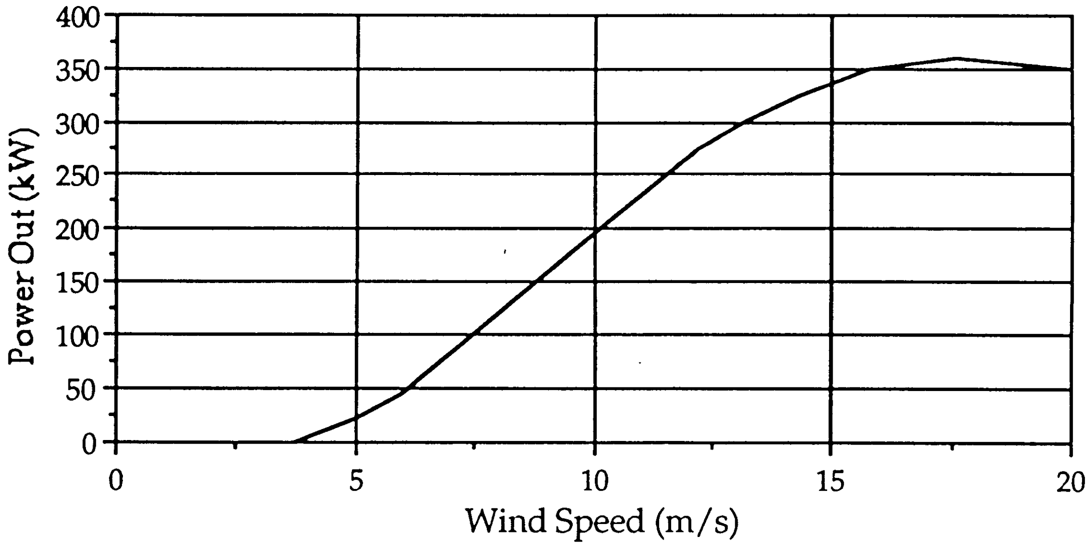
WIND POWER MODELING ASSUMPTIONS

Wind Turbine Characteristics

The turbine used for the modeling is Atlantic Orient Corporation's AOC 33/350 350 kW turbine (NREL 1992); the power curve is shown in Figure 1 below. This turbine is modeled with a 50 meter (160 ft) hub height and a 30 meter (100 ft) rotor diameter. It is expected to be commercially available in 1995.

A second power curve to be analyzed would be that for a variable speed turbine. In actual practice though, it is expected that the constant speed–variable pitch turbine will be the most widely used in New England since its performance is not as seriously degraded by icing as that of the stall controlled turbine, and it is a more proven technology than the newer variable speed turbine (Ralph 1992).

Figure 1: AOC 33/350 Turbine Power Curve



Cost and Performance Assumptions

Table 1 below lists the cost (presented in base year, 1991, dollars) and performance values to be used in the analysis (Chapman 1992; Ralph 1992). The system costs cited reflect the cost of the system as well as installation and interconnection. Due to its distant location from most of the NEPOOL service area[1], the Maine site includes a dedicated transmission line spur as well as a loss factor. The transmission line and associated loss as shown in the table are applied to the Maine site only since the Massachusetts site is located within the NEPOOL service area, and thus does not incur any loss beyond that automatically accounted for by EGEAS. The cost of the additional transmission line is assumed to be incurred in the first year of construction (1995) rather than being spread over the study period[2], the effect of which is reflected in the resultant trajectory of the cost of electricity from wind power (discussed in chapter 5).

The Variable O&M column in the table includes a small annual charge for the "wind lease," or rights to the land where the wind farms are located, in addition to normal operational O&M costs. The forced outage and additional loss factors, from turbine icing and wind farm turbulence, are included in the analysis as a constant 15% subtracted from the energy generated from the wind farms.

Table 1: Wind Power Cost and Performance Assumptions

---

[1] NEPOOL is the New England power pool, which coordinates the dispatching of New England's generating units.

[2] The transmission line cost is estimated as follows: [(150 miles of 230kV transmission line at \$360k/mile) x (25000 acre right-of-way x \$10000/acre) / 1250MW wind farm capacity] =>
= \$54M x \$25M / 1250k = \$65/kW in 1991\$.

Category	*Value*	*Year*
System Costs ($/kW)	1000	1995
	900	2001
	700	2004
Variable O&M (¢/kWh)	1.50	1995
	0.75	2004
Transmission Line Spur ($/kW)	65	1995
Forced Outage	5%	1995-2011
Additional loss from icing, & wake effects ...	15%	1995-2011
Transmission Line Spur Loss	10%	1995-2011

Wind Farm Land Requirements

The wind farms that will be modeled are a 1250 MW$_P$ farm in the Longfellow Mountains in Maine, and a smaller farm of 250 MW$_P$ in western Massachusetts. The Massachusetts site is smaller since less land is available in that state. Table 2 below estimates the land usage in each state, based on a standard rotor diameter, D, of 100 feet. The values in the table represent the total area encompassed by the wind farm; approximately 1% to 10% of this land would actually be occupied by turbines or access roads and related equipment, with the rest remaining essentially undisturbed.

Table 2: Estimated Land Required for the Wind Farms

State	Maine	Massachusetts	
Wind Farm Rating	1250	250	(MW)
Turbine Rating	350	350	(kW)
Turbine Hub Height	50	50	(m)
Rotor Diameter	33	33	(m)
Average Tree Height	12	12	(m)
Number of Turbines	3571	714	
Area/Turbine	1.25	0.75	(acre)
Turbine Spacing	5D x 10D	3D x 10D	
Total Land Required	4.50	0.40	(k acre)
% of State's Total Area	0.02%	0.01%	

(D = diameter)

PHOTOVOLTAIC MODELING ASSUMPTIONS

Photovoltaic System Characteristics

The AGREA analysis assumes all PV arrays are roof mounted, making fixed axis, flat-plate PV systems appropriate for the analysis. The arrays are assumed to have 12% conversion efficiency at 45°C, with a 0.5% efficiency temperature coefficient[1]. They face South, and have a 10° tilt angle, as discussed at the end of chapter 3.

Sensitivity studies for the PV analysis will involve decreasing the cost only, and not increasing array efficiency. This is because the modeling uses 1500 MW_p of PV capacity. If the PV cells become more efficient, then fewer cells will be needed, but the analysis will be for 1500 MW_p regardless. The effect of increased efficiency therefore translates into the possibility of overall decreased cost, since *fewer* arrays are required.

Cost and Performance Assumptions

Table 3 presents cost and performance assumptions for the photovoltaic analysis, in 1991$ (Basso, 1991; Kern, 1993). Power output from the PV cells

---

[1] A 0.5% efficiency temperature coefficient means that for every degree of PV array temperature above 45°C, the conversion efficiency decreases 0.5%.

alone is assumed to be decreased by approximately 10% due to the inclusion of interconnections for arrays, modules and balance-of-system. This loss is calculated directly in PVSim. There is also an assumed 2% additional decrease in power generation due to the distribution system. Since the PV arrays are modeled as distributed generation rather than centralized power generation as with the wind power analysis though, no losses for the transmission system are included.

Table 3: Photovoltaic Cost and Performance Assumptions

Category	*Value*	*Year*
System Costs ($/kW)	5000.00 2000.00	1995 2005
Variable O&M (¢/kWh)	1.40 0.40	1995 2005
System Losses	10%	1995-2001
Distribution Losses	2%	1995-2011

Photovoltaic Array Area Requirements

The photovoltaic panels are assumed to be installed on new commercial rooftops in the Southern New England states of Connecticut, Massachusetts and Rhode Island. Based on NEPOOL estimates of new commercial construction in these states between 1995 and 2004, there will be 31 million square meters of new roof area available. If half of this area is covered with PV arrays, and on average PV power generation is 50 W_p/m^2, 1540 MW_p could be generated. In actuality, some PV installation could also be retrofitted to existing rooftops.

References listed by chapter:

CHAPTER 1 INTRODUCTION:

Charo, R. Alta, Lisa R. Stearns, Karen L. Mallory, "Alternative Energy Power Production: The Impact of the Public Utility Regulatory Policy Act," Columbia Journal of Environmental Law, Vol. 11:477, 1986.

(EIA) "Overview of the Renewable Fuels Module of the National Energy Modeling System," Prepared by: Coal, Uranium and Renewable Fuels Analysis Branch, Energy Supply and Conversion Division, Office of Integrated Analysis and Forecasting, Energy Information Administration, DRAFT - July 2, 1992.

Flavin, Chris, Nicholas Lenssen, "Policies for a Solar Economy," Energy Policy, March 1992.

Hamrin, Jan, "Renewable Resource Policies on the State Level," NARUC-DOE Fourth Annual IRP Conference, September 1992.

Kozloff, Keith Lee, "Renewable Energy Policies: A Blueprint for Regulatory Action," NARUC-DOE Fourth Annual IRP Conference, September 1992.

Narum, David, "A Troublesome Legacy: The Reagan Administration's Conservation and Renewable Energy Policy," Energy Policy, January 1992.

National Energy Strategy: Powerful Ideas for America, One Year Later, Washington DC, February 1992.

Nola, Sebastian J., Fereidoon P. Sioshansi, "The Role of the US Electric Industry in the Commercialization of Renewable Energy Technologies for Power Generation," Annual Review of Energy, Vol. 15, 1990.

Rader, Nancy, Jan Hamrin, "The Role of Renewable Energy in Global Warming Mitigation – A Critique of Trusted Assessments," The Electricity Journal, Vol. 5, No. 6., July 1992.

Wald, Matthew L., "U. S. Finds Energy Industry Subsidies are Small," New York Times, Dec. 19, 1992.

CHAPTER 2 WIND REFERENCES:

PERSONAL CORRESPONDENCE:

Chapman, Jamie, (president, OEM Corporation), Spring 1992.

McGowan, Jon, Professor of Mechanical Engineering, University of Massachusetts, 1992 – 1993.

Ralph, William, (Green Mountain Power Corp.), Spring 1992.

BOOKS:

Coty, U.A., United States Wind Speed and Wind Power Duration Table by Months, US DOE contract, 1975.

Hunt, V.Daniel, Windpower, Litton Educational Publishing, Inc., New York, 1981.

Elliott, D.L., L.L. Wendall, G.L. Gower, An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States, Battelle Pacific Northwest Laboratory (for DOE), 1991.

Elliott, D.L., C.G. Holladay, W.R. Barchet, H.P. Foote, W. F. Sandusky, Wind Energy Resource Atlas of the United States, Battelle Pacific Northwest Laboratory (for DOE) [PNL], 1987.

Freris, L.L., Wind Energy Conversion Systems, Prentice Hall, New York, 1990.

Rookwood, M.J.M., Going With the Wind: A Socially Viable Alternative for Generating Electricity in the UK, Masters Thesis for Technology and Policy, MIT, June 1992.

Lysen, E. H., Introduction to Wind Energy, Steering Committee Wind Energy Developing Countries, SWD c/o DHV Consulting Engineers B. V., P.O. Box 85, 3800 AB Amersfoort, The Netherlands, 1982.

New Electric Power Technologies, Problems and Prospects for the 1990s, Office of Technology Assessment, Congress of the United States, [OTA], 1985.

ARTICLES:

Douglas, John, "Renewables On the Rise", EPRI Journal, June 1991.

Jespersen, K. Dyre, "First Offshore Windfarm Starts Up," Modern Power Systems, October 1991.

Larke, C., A. Woodbridge, M. Hayes, "Towards Equitable Solutions to Siting and Noise Problems in Windfarms," Wind Energy Conversion Proceedings of the 1991 Thirteenth AWEA Wind Energy Conference.

Pitcher, K., R. Wade-smith, F. Fawcett, "Environmental, Planning, and Communication Strategies and Experience for Windfarm Developments in Yorkshire," Wind Energy Conversion Proceedings of the 1991 Thirteenth AWEA Wind Energy Conference.

Wald, Matthew L., "Putting Windmills Where its Windy," The New York Times, November 11, 1991.

The Potential of Renewable Energy: An Interlaboratory White Paper, March 1990, SERI/TP-260-3674.

Utility Wind Interest Group brochures, with SERI and EPRI, November 1990, August 1991, February 1992.

CHAPTER 2 PV REFERENCES

PERSONAL CORRESPONDENCE:

Kern, Edward, president Ascension Technology, Inc., Spring 1993.

BOOKS:

Cook, Gary, Lynn Billman, Rick Adcock, Photovoltaic Fundamentals, SERI/TP-220-3957; DOE/CH10093-117, 1991.

Duffie, John A., William A. Beckman, Solar Engineering of Thermal Processes, John Wiley & Sons, New York, 1980.

National Renewable Energy Lab, National Solar Radiation Data Base (1961-1990) User's Manual Volume 1, distributed by the National Climatic Data Center, Ashville NC, 1992.

SOLMET User's Guides, TD-9724, National Climatic Data Center, 1988.

ARTICLES:

Chalmers, Bruce, "The Photovoltaic Generation of Electricity," Scientific American, p. 34, 1976.

Fan, C. C. John, "Solar Cells: Plugging into the Sun," Technology Review, August/September, p. 14, 1978.

Kern, Edward C., Miles C. Russell, "Rotating Shadow Band Pyranometer Irradiance Monitoring for Photovoltaic Generation Estimation," 22nd IEEE Photovoltaic Specialists Conference, Las Vegas, NV, 1991.

CHAPTER 3 WIND REFERENCES:

PERSONAL CORRESPONDENCE:

Chapman, Jamie, president OEM Corporation, Spring 1992.

Ralph, William, Green Mountain Power, August 1992.

BOOKS:

Cox, Alan J., Susan Finger, Richard D. Tabors, "The Economics of the Photovoltaic-Utility Interaction," chapter 3 in Economic and Market Analysis of the Photovoltaic Technology: Final Report, MIT Energy Laboratory, 1982.

Elliott, D.L., L.L. Wendall, G.L. Gower, An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States, Battelle Pacific Northwest Laboratory (for DOE), 1991.

Elliott, D.L., C.G. Holladay, W.R. Barchet, H.P. Foote, W. F. Sandusky, Wind Energy Resource Atlas of the United States, Battelle Pacific Northwest Laboratory (for DOE) [PNL], 1987.

Eggleston, D. M., F. S. Stoddard, Wind Turbine Engineering Design, Van Nostrand Reinhold, New York, 1987.

Freris, L.L., Wind Energy Conversion Systems, Prentice Hall, New York, 1990.

Golding, E. W., The Generation of Electricity by Wind Power, E &FN Spon, London, 1977.

Hunt, V.Daniel, Windpower, Litton Educational Publishing, Inc., New York, 1981.

Johnson, G. L., Wind Energy Systems, Prentice Hall, Englewood Cliffs, NJ, 1985.

Lysen, E. H., Introduction to Wind Energy, Steering Committee Wind Energy Developing Countries, SWD c/o DHV Consulting Engineers B. V., P.O. Box 85, 3800 AB Amersfoort, The Netherlands, 1982.

Rookwood, M.J.M., Going With the Wind: A Socially Viable Alternative for Generating Electricity in the UK, Masters Thesis for Technology and Policy, MIT, June 1992.

New Electric Power Technologies, Problems and Prospects for the 1990s, Office of Technology Assessment, Congress of the United States, [OTA], 1985.

Twidell, J., Renewable Energy Resources, Spon, London, 1986.

ARTICLES:

van Beek, A., "Wind Turbine Noise," Wind Energy Conversion Proceedings of the 1991 Thirteenth AWEA Wind Energy Conference.

Bosley, P.B., K.W.Bosley, "Risks and Benefits of Wind Generated Electricity: Facts and Perceptions," Energy Sources, Vol.14, pp. 1-9, 1992.

Bosley, P.B., K.W.Bosley, "A Study of American Utilities Attitudes and Behaviours Towards Wind Energy," Wind Engineering, vol. 15, no. 3, pp. 163-172, 1991.

Dodd, Henry M., Susan M. Hock, Robert W. Thresher, "The Sensitivity of Wind Technology Utilization to Cost and Market Parameters," SERI/TP-257-3986, November 1990.

Douglas, John, "Renewables On the Rise", EPRI Journal, June 1991.

Hock, Susan M., Robert W. Thresher, Joseph M. Cohen, "Performance and Cost Projections for Advanced Wind Turbines," SERI/TP-257-3795, August 1990.

Jespersen, K. Dyre, "First Offshore Windfarm Starts Up," Modern Power Systems, October 1991.

Larke, C., A. Woodbridge, M. Hayes, "Towards Equitable Solutions to Siting and Noise Problems in Windfarms," Wind Energy Conversion Proceedings of the 1991 Thirteenth AWEA Wind Energy Conference.

Manwell, J. F., J. G. McGowan, B. H. Bailey, "Electrical/Mechanical Options for Variable Speed Wind Turbines," Solar Energy, vol. 46, mo. 1, pp. 41-51, 1991.

Moore, Taylor, "On-Site Utility Applications for Photovoltaics", EPRI Journal, March 1991.

Nahas, M. N., A. S. Mohamad, M. Akyurt, A. K. El-Kalay, "Wind Energy: An Engineering Survey," Energy Sources, vol. 9, no. 3, pp. 137-148, 1987.

Pitcher, K., R. Wade-smith, F. Fawcett, "Environmental, Planning, and Communication Strategies and Experience for Windfarm Developments in Yorkshire," Wind Energy Conversion Proceedings of the 1991 Thirteenth AWEA Wind Energy Conference.

Smith, D.R., M.A. Llyin, "Wind and Solar Energy, Costs and Value," 10th ASME Wind Energy Symposium, SED-Vol. 11, 1991.

Tangler, J.L., P.K.C.Tu, "Peak Power and Blade Loads on Stall-Regulated Rotors as Influenced by Different Airfoil Families," SERI/TP-217-3334, August 1988.

Tangler, J., B. Smith, D. Jager, T. Olsen, "Atmospheric Performance of the Special-Purpose SERI Thin-Airfoil Family: Final Results," SERI/TP-257-3939, September 1990.

Wald, Matthew L., "Putting Windmills Where its Windy," The New York Times, November 11, 1991.

The Potential of Renewable Energy: An Interlaboratory White Paper, March 1990, SERI/TP-260-3674.

Utility Wind Interest Group brochures, with SERI and EPRI, November 1990, August 1991, February 1992.

CHAPTER 3 PV REFERENCES

PERSONAL CORRESPONDENCE:

Kern, Edward, president Ascension Technology, Inc., Spring 1993.

BOOKS:

Ankrum, Paul D., Semiconductor Electronics, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1971.

Cook, Gary, Lynn Billman, Rick Adcock, Photovoltaic Fundamentals, SERI/TP-220-3957; DOE/CH10093-117, 1991.

Katzman, R. T., Katzman, A. C., Economic and Financial Analysis of Residential Photovoltaic Systems: The Impact of Solar Photovoltaics on Utilities: Final Report, MIT Lincoln Laboratory, US DOE Contract No. DE-AC02-76ET20279, February 1982.

Kern, Edward C., Marvin D. Pope, Development and Evaluation of Solar Photovoltaic Systems: Final Report, MIT Lincoln Laboratory, US DOE Contract No. DE-AC02-76ET20279, June 1983.

Tabors, Richard D., Economic and Market Analysis of the Photovoltaic Technology: Final Report, MIT Energy Laboratory, US DOE Contract No. EX-76-A-01-2295, August 1982.

ARTICLES:

Basso, Thomas S., Thomas Surek, John Thornton, "Photovoltaics: From the Laboratory to the Marketplace," Solar Engineering, 1991.

Beyer, U., B. Dietrich, R. Pottbrock, A. Lotfi, "Solar Modules Tested at Kobern-Gondorf," Modern Power Systems, December 1990.

Brown, Linda R., "Sunrise for White Pine," Solar Today, March/April 1992.

Bzura, John J., "The New England Electric Photovoltaic Systems Research and Demonstration Project," IEEE Transactions on Energy Conversion, Vol. 5, No. 2, June 1990.

Carlson, D. E., "Photovoltaic Technologies for Commercial Power Generation," Annual Review of Energy , Vol. 15, 1990.

Chalmers, Bruce, "The Photovoltaic Generation of Electricity," Scientific American, October, 1976.

Conover, Karen, "Photovoltaic Operation and Maintenance Evaluation," IEEE Transactions on Energy Conversion, Vol. 5, No. 2, June 1990.

Cook, Gary, "Photovoltaics," in Howes, R., A. Fainberg, eds., The Energy Source Book: A Guide to Technology Resources and Policy, American Institute of Physics, NY, NY, 1991.

Douglas, John, "Renewables On the Rise", EPRI Journal, June 1991.

Fan, John C. C., "Solar Cells: Plugging into the Sun," Technology Review, August/September 1978.

Hester, S. L., C. M. Whitaker, "PVUSA: Results and Experience," Solar Engineering, Vol. 1, American Society of Mechanical Engineers, 1992.

Kazmerski, L. L., K. A. Emery, "Photovoltaic Technologies: From Atoms to Arrays," in Renewable Energy, Technology and the Environment, 2nd World Renewable Energy Congress, Vol. 1, Pergamon Press, 1992.

Kelly, Henry, "Photovoltaic Power Systems: A Tour Through the Alternatives," Science, Vol. 199, 10 February 1978.

Kimura, Kenjiro, "Further Cost Reductions Needed in PV Systems," Modern Power Systems, December 1990.

Levine, Jules D., Gregory B. Hotchkiss, Milfred D. Hammerbacher, "Basic Properties of the Spheral Solar Cell," Solar Today, January/February 1992.

Matlin, Ronald, Richard Lenskold, "PVUSA Programme Pushes Photovoltaics into the 1990s," Modern Power Systems, November 1989.

Moore, Taylor, "On-Site Utility Applications for Photovoltaics", EPRI Journal, March 1991.

Ryan, John, Richard Sellers, "Overcoming Institutional Barriers," Solar Today, March/April 1992.

Russell, Miles C., Edward C. Kern, "Lessons Learned with Residential Photovoltaic Systems," 21st IEEE PV Specialists Conference, vol. 2, 1990.

Slusarczuk, Marko M. G., "The Environmental Implications of an Emerging Energy Technology: Photovoltaic Solar Cells - A Study of the Toxic Aspects," Boston College Environmental Affairs Review, Vol. 9, Fall 1981.

Stoloff, Jonathan D., Karen L. Mallory, Lisa R. Stearns, "Legal Issues Raised by the Environmental Impacts of Photovoltaic Energy and Wind Energy Conservation Systems," Columbia Journal of Environmental Law, Vol. 11, 1986.

Wilson, Alex, "Solar Electricity in the '90s," Independent Energy, January 1991.

Zweibel, Ken. "Thin-Film Photovoltaic Cells," American Scientist, Vol. 81, July-August, 1993.

CHAPTER 4 REFERENCES:

ARTICLES:

Caramanis, Michael C., Richard D. Tabors, Kumar S. Nochur, Fred C. Schweppe "The Introduction of Non-Dispatchable Technologies as Decision Variables in Long-Term Generation Expansion Models," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 8, August 1982, pp. 2758-2667.

Caramanis, Michael C., "Analysis of Non-Dispatchable Options in the Generation Expansion Plan," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 7, July 1983, pp. 2098-2103.

Milligan, M. R., A. H. Miller, "The Value of Windpower: An Investigation Using a Qualified Production Cost Model," Prepared for *Windpower '93*, NREL/TP-441-5730, July 1993.

Milligan, Michael, "WInd Power Simulator (WIPS) User's Guide Draft," National Renewable Energy Laboratory, July 1993.

National Renewable Energy Laboratory [NREL], "Advanced Wind Turbines: Electricity for the 1990s and Beyond," 1992.

Thurber, Mark C. "Photovoltaics and CO_2 Emissions: A Study and Simulation of Utility System Operation," Undergraduate Thesis under Clinton J. Andrews, Princeton University, 1992.

CHAPTER 5 REFERENCES:

PERSONAL COMMUNICATION:

Meetings at the National Renewable Energy Laboratory in Golden CO, July 1993.

ARTICLES:

Garver, L. L., "Effective Load Carrying Capability of Generating Units," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-85, No. 8, August, 1966.

Finger, Susan, "Electric Power System Production Costing and Reliability Analysis Including Hydro-Electric, Storage, and Time Dependent Power Plants," MIT Energy Laboratory Technical Report #MIT-EL-79-006, February 1979.

CHAPTER 6 REFERENCES:

BOOKS:

Brower, Michael, Cool Energy, MIT Press, Cambridge, MA, 1992.

"Energy Policy Act of 1992," Public Law 102-486, 42 USC 13201, Title XII - Renewable Energy, Oct. 24, 1992.

Lee, Thomas H., Ben C. Ball, Jr., Richard D. Tabors, Energy Aftermath, Harvard Business School Press, Boston, MA,

ARTICLES:

Awerbuch, Shimon, "The Surprising Role of Risk in Utility Integrated Resource Planning," The Electricity Journal, Vol. 6, No. 3, April 1993.

Boshier, John F., "Can We Save Energy by Taxing It?," Technology Review, August/September, 1978.

Cox, Alan J., Carl J. Blumstein, Richard J. Gilbert, "Wind Power in California: A Case Study of Targeted Tax Subsidies," Regulatory Choices, A Perspective on Developments in Energy Policy, University of California Press, Berkeley, CA, 1991.

Hachey, Michael E., Stephen D. Makowka, "The NEP Renewable Energy Initiative: Objectives and Experiences," NARUC-DOE 4th Annual IRP Conference, September 1992.

Jackson, Tim, "Renewable Energy: Summary Paper for the Renewable Series," Energy Policy, September 1992.

Rich, Daniel, J. David Roessner, "Tax Credits and US Solar Commercialization Policy," Energy Policy, March 1990.

Phillips, Julie Ann, "Wind Power's Coming of Age," The Electricity Journal, Vol. 5, No. 3, April 1992.

Sachs, H. M., F. G. Muller, "Technology Policy and Wind Power in the U. S. Utility Sector," Wind Power '92 Proceedings, October 19-23, 1992.

Schmalensee, Richard, "Appropriate Government Policy Toward Commercialization of New Energy Supply Technologies," Energy Journal, Vol. 1, No. 2, April 1980.

Sklar, Scott, "The Role of the Federal Government in the Commercialization of Renewable Energy Technologies," Annual Review of Energy, Vol. 15, 1990.

Starr, Chauncey, Milton F. Searl, Sy Alpert, "Energy Sources: A Realistic Outlook," Science, Vol. 256, May 15, 1992.

Thornton, John, Linda Brown, "Photovoltaics: The Present Presages the Future," The Electricity Journal, Vol. 5, No. 3, April 1992.

Weinberg, Carl J., "Adding Renewables to the Portfolio," The Electricity Journal, Vol. 5, No. 3, April 1992.

2574-0