ECONOMIC ANALYSIS AND MONTE CARLO SIMULATION OF COMMUNITY WIND GENERATION IN RURAL WESTERN KANSAS

by

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Abstract

Energy costs are rising, supplies of fossil fuels are diminishing, and environmental concerns surrounding power generation in the United States are at an all-time high. The United States is continuing to push all states for energy reform and where better for Kansas to look than wind energy? Kansas is second among all states in wind generation potential; however, the best wind generation sites are located predominantly in sparsely populated areas, creating energy transportation problems. Due to these issues interest in community wind projects has been increasing. To determine the economic potential of community wind generation a distribution system in rural western Kansas where interest in community wind exists was examined and a feasibility study based on historical data, economic factors, and current grid constraints was performed. Since the majority of the load in this area is from pivot-point irrigation systems, load distributions were created based on temperature ranges instead of a linear progression of concurrent days. To test the economic viability three rate structures were examined: flat energy rate, demand rate, and critical peak pricing. A Monte Carlo simulation was designed and run to simulate twenty-year periods based on the available historical data; twenty-year net present worth calculations were performed to ensure economic viability. A sensitivity analysis was then performed to examine the effects of change in turbine size and energy rate scale. Finally, an energy storage analysis was performed to examine the economic viability of various sizes of battery storage systems.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to thank everyone who helped me or had a part in my Master's Thesis and graduate program. I would especially like to thank Dr. Anil Pahwa for being an amazing advisor and for the guidance he provided throughout the course of my research, Dr. Ruth Douglas Miller and Mary Knapp from Kansas State University and Al Tamimi from Sunflower Electric Power Corporation for providing data necessary to complete this project, the Department of Energy for financial support for the project, and finally the Department of Electrical and Computer Engineering for providing me with this excellent opportunity.

Dedication

To my amazing wife and parents; without your combined love and support I would have never made it this far.

Chapter 1 - Introduction

Energy costs are rising, supplies of fossil fuels are diminishing, and environmental concerns surrounding power generation in the United States are at an all-time high. The United States is continuing to push all states for energy reform and where better for Kansas to look than wind energy? Kansas is second among all states in wind generation potential; however, the best wind generation sites are located predominantly in sparsely populated areas creating energy transportation problems. Due to these issues interest in community wind projects has been increasing.

Community wind generation, especially in rural western Kansas, could be the solution to some Kansas energy problems. This thesis will examine the economic potential for community wind generation for a power cooperative in southwest Kansas. The goal of this research is to determine whether or not community wind generation is a profitable endeavor with high potential for Kansas.

Before doing a detailed analysis, one has to have a basic understanding of wind turbines and the surrounding technologies. This chapter provides a base level of information about wind turbines, their benefits and drawbacks, as well as some issues with wind farms and a possible solution that will be examined in later chapters.

Wind Turbine Description

The most efficient way to harness wind energy is with a wind turbine. Wind turbines come in many different sizes, from 10 kilowatt or smaller personal machines to 6 megawatt or larger off-shore machines. Regardless of the size, all have the same general characteristics. Figure 1.1 below shows an overview of the components in a wind turbine.

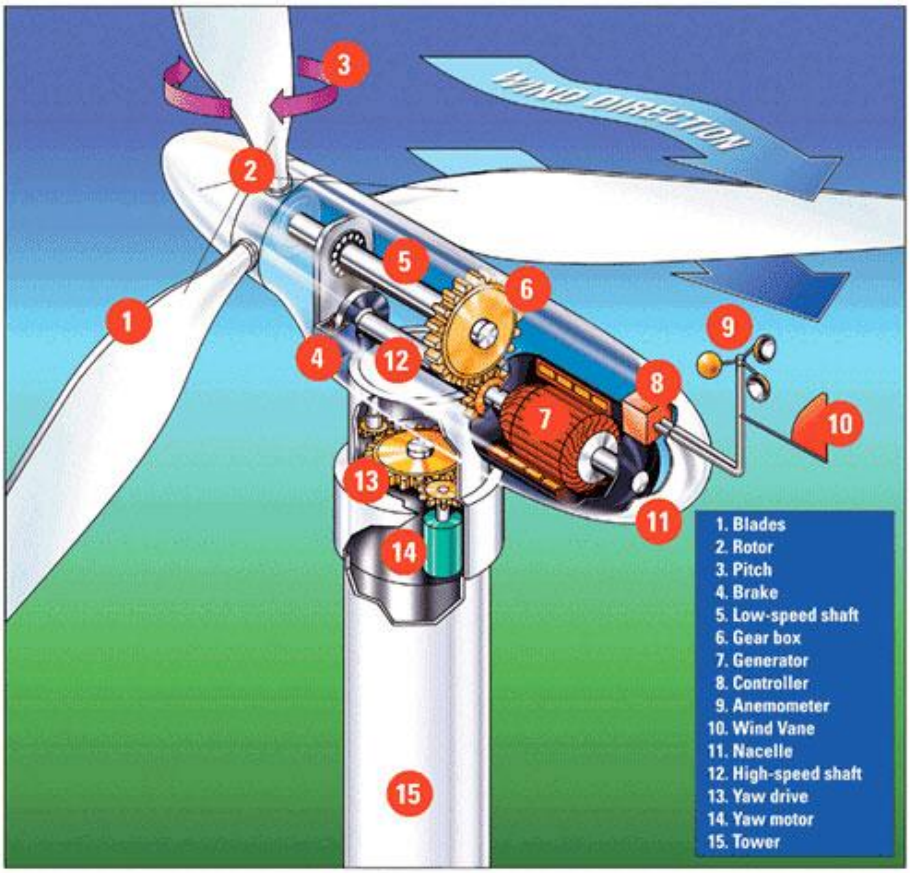

Figure 1.1: Diagram of the Mechanical Components of a Wind Turbine [1]

As shown in Figure 1.1, the four main physical features of the wind turbine are the blades, rotor, nacelle, and tower. The three blades of the wind turbine (circle 1 in Figure 1.1) are responsible for catching the wind and turning the rotor (circle 2 in Figure 1.1). As the wind turbine gets bigger so do the blades; on large turbines they are over 150 feet long. The blades also have a pitch control (circle 3 in Figure 1.1). The pitch control changes the amount of surface area of the blade that is able to catch the wind. This feature allows the wind turbine to operate at its preferred velocity as long as the wind speed is between eight and fifty miles per hour [2]. The next key component is the rotor. The rotor is made up of the blades and the point around which they rotate. The rotor area determines the power output of the wind turbine; wind turbines are rated by their rotor area [2]. The rotor is attached to the nacelle (circle 11 in Figure 1.1). The nacelle houses all the equipment necessary to change the relatively slow movement of the rotor into electrical energy we can transport and consume. The final physical component of a wind turbine is the tower (circle 15 in Figure 1.1). The tower supports the blades and on large turbines can be over 300 feet tall. The main reason the tower is so tall is that wind blows faster farther off

the ground due to lower drag from the ground. The tower is usually two to three times the blade length; this provides a balance between material cost and the benefit of faster wind speeds at higher heights [2].

Wind Farm Layouts

Wind generators are most commonly grouped together to form wind farms. Wind farms have two main layouts which are dictated by the geography of the area the wind farm is in. If the entire wind farm is going to be placed on level ground the wind turbines will typically form a grid. Grids are used whenever possible as they are aesthetically pleasing. If, however, the land under the wind farm is hilly the layout process becomes more difficult. When designing a wind farm in hills, or around other vertical structures, turbulence has to be avoided. Turbulence reduces performance and can shorten the life of a wind turbine [3]. To avoid turbulence, the following rules should be followed:

- The wind turbine should be placed on a site that is free from all minor obstructions (e.g. trees, buildings) in all directions for 350 feet [3].
- The wind turbine should be placed on a site that is free from all major obstructions (e.g. abrupt landforms) in all directions for 700 feet [3].
- If it is not possible to obey the above rules, the tower height should be increased to 30 feet higher than the obstructions within 350 feet [3].
- In general, a turbine should be at a minimum height of three times the tallest upwind obstruction [3].

Wind Farm Connection and Control

After wind farms are laid out, they are connected together and to the power grid. Figure 1.2 shows how wind turbines are connected to the power grid and how they are controlled. First, the wind turbines are connected together and taken to the secondary of a transformer. At the transformer a computer retrieves data from the wind turbines through an analog to digital converter. The power from the wind turbines is then stepped up to high voltage through the transformer and connected to the power grid [4]. Once in the power grid, the energy is taken to households and businesses in the surrounding area.

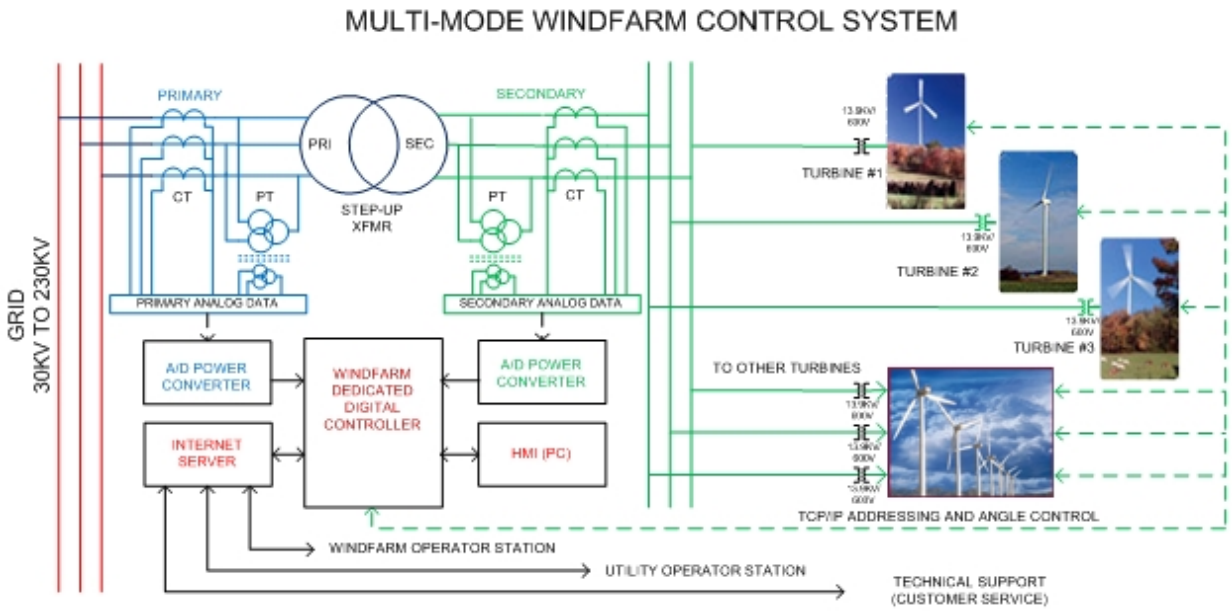

Figure 1.2: Multi-mode Wind Farm Control System [5]

Benefits

Through the course of this research it was found that the commonly agreed upon benefits of wind energy fall in the following two categories:

- Economic
- Environmental

Economic

Wind energy has numerous positive effects on the economy. Wind farms can play a key role in revitalizing rural economies and provide steady income to land owners through leasing agreements. Also, unlike coal and gas, the cost of wind energy does not fluctuate with inflation or the stock market [6]. Furthermore, wind farms have a small footprint, allowing farmers to farm almost right up to the base of the wind turbines. This allows farmers to farm the air and the ground on the same piece of land [7]. Wind turbines that are put in appropriate locations are very profitable. A wind turbine in a favorable wind area will pay for itself in just over half of its estimated lifetime. This characteristic, combined with low operation and maintenance costs, makes wind farms have a substantial long term economic benefit [6].

Environmental

Wind energy is also extremely environmentally friendly. Figures 1.3 and 1.4 below show wind energy is essentially pollution free. Wind energy produces no carbon dioxide, sulfur dioxide, or nitrogen oxides. One could argue that wind energy actually prevents pollution. In 2006 wind energy prevented over 15 million tons of pollutants from being expelled into the atmosphere. Also, because wind energy is pollution-free, using wind energy helps reduce and prevent global climate change [8].

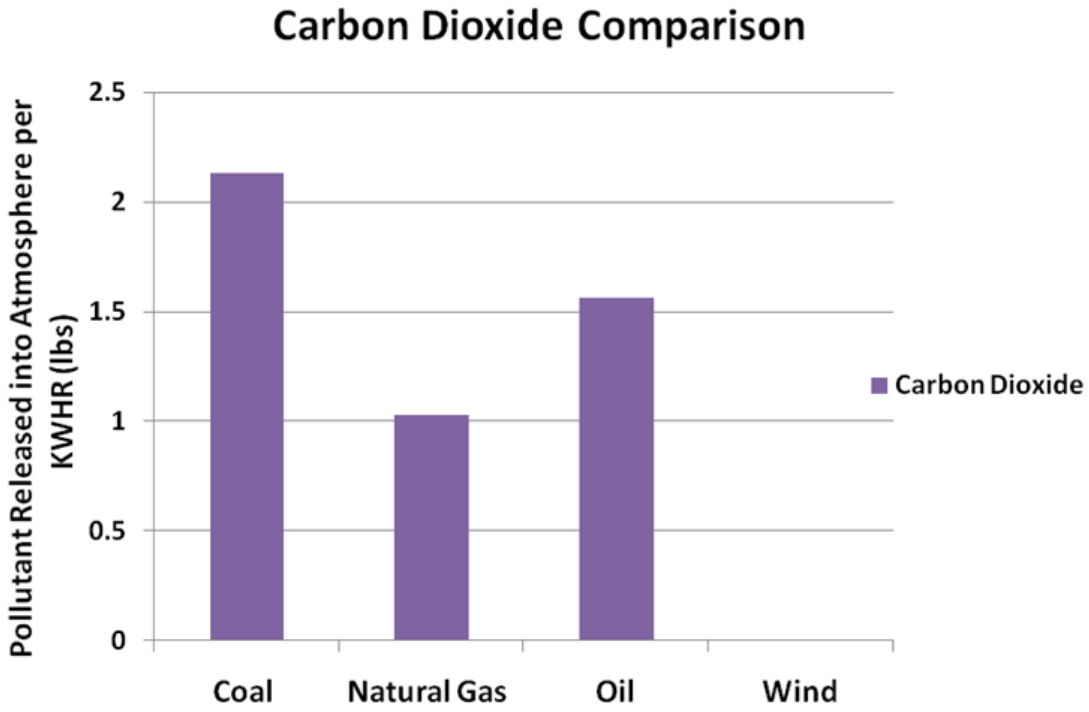

Figure 1.3: Bar Graph Comparison of Carbon Dioxide Emissions in Energy Generation [8]

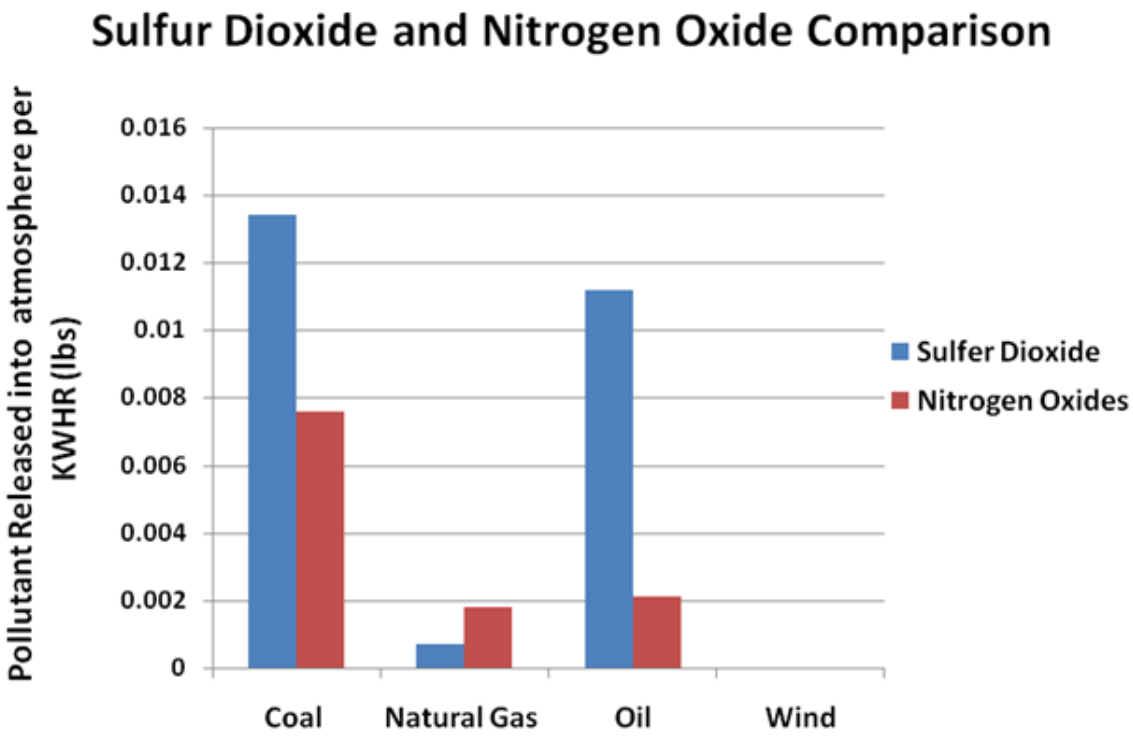

Figure 1.4: Bar Graph Comparison of Sulfur Dioxide and Nitrogen Oxides in Energy Generation [8]

Drawbacks

Through the course of this research the following three drawbacks were identified:

- Initial Cost
- Bird Fatalities
- Aesthetics

Initial Cost

The biggest drawback with wind energy is the large upfront cost. The startup cost of a wind farm is approximately two million dollars per megawatt [9]. This causes wind farm implementation to be incredibly costly. With the average wind farm producing over 100 megawatts, this requires over 200 million dollars up front. Especially with the current financial situation, finding financing for the development and construction of a wind farm is difficult [6].

Bird Fatalities

Another drawback with wind energy is bird fatalities. Environmental activist groups use bird deaths as the main reason why wind farms should not be developed. However, it was found that bird fatalities from wind turbines are extremely low. Figure 1.5 shows that less than 0.001% of bird deaths are caused by wind turbines. In comparison with numerous other structures, there is no reason why wind turbines should be singled out as bird killers [8].

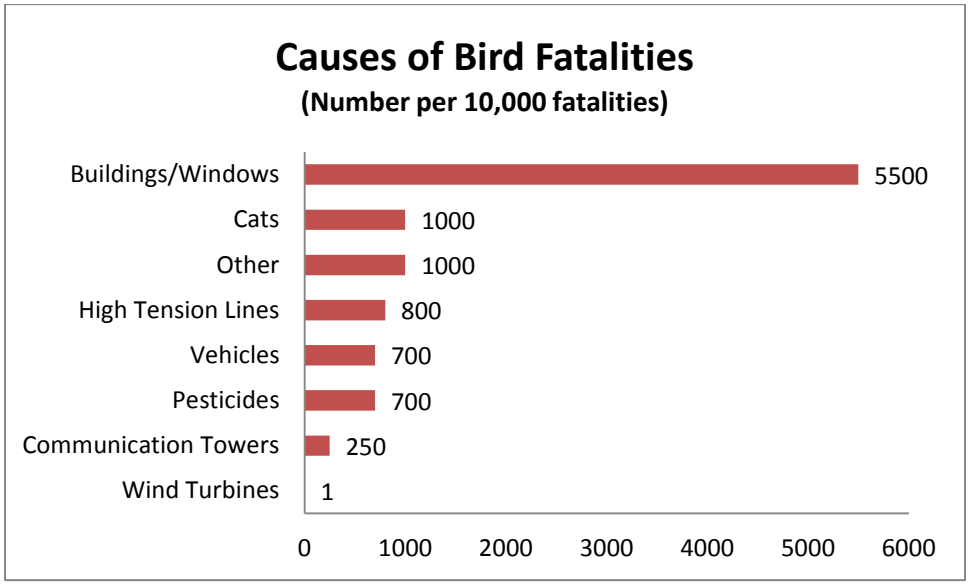

Figure 1.5: Bar Graph Comparison of Causes of Bird Fatalities [8]

Aesthetics

Another complaint with wind farms is aesthetics. Common complaints include disruption of scenery, shadow flicker, and noise. At a potential height of over 400 feet, wind turbines have a large effect on the surrounding areas [10]. Most of the aesthetic issues with wind farms can be partially resolved with good planning. For example, disruption of scenery can be improved with quality layout designs. The effect of shadow flicker can also be eliminated by keeping wind turbines away from existing houses. The noise given off from wind turbines has been almost eliminated with improved generator technology [8]. Aesthetics will always be an issue for some, but steps are being taken to improve the situation.

Wind Farm Issues

Wind farms face some other issues that single wind turbines do not. The majority of quality sites for wind farms are not close to areas with a large demand for energy. This creates the problem of what to do with the energy after it is produced. The key aspects of this problem will be examined through the following sections on energy transmission, energy storage, and distributed generation.

Transmission of Energy

Transmission of energy produced by wind farms can be a big problem. The current transmission systems in the United States are not designed to efficiently move energy from rural areas in one part of the country to populated areas sometimes hundreds of miles away. A solution to this problem would be to build new transmission lines; however, this is very expensive and time-consuming. While it can take a year to build a wind farm, it could take five or more years to build the necessary transmission lines to get the energy where it needs to go [11]. At the same time wind power developers want the transmission lines in place before they sign onto a project while utilities want wind turbines under construction before they pay to create new transmission lines [11]. This has prompted states like Texas to pass legislation regarding transmission line creation to allow wind power developers to move forward without having to worry about whether transmission lines will be built or not [11]. This may work on a state scale, but in other areas where transmission lines would have to be built across multiple state lines it could be difficult to get all the different state governments to agree on a regional transmission network plan. This is an area that needs further research; hopefully someone, or the federal government, can come up with a plan to solve the transmission problem. Some states have started transmission upgrades, but without nationwide cooperation and collaboration it will be difficult for individual states to accomplish much.

Energy Storage

Another problem with wind farms is that there are very few efficient ways to store the energy produced. This means that energy is only being produced when the wind is blowing and the utility has to be prepared with enough flexible generation in order to compensate for a sudden loss of wind. There have been many suggestions of possible ways to store energy; no suggestion

is without faults. The main problem with the energy storage options is that they are site-specific and quite expensive. Some of the most popular options are compressed air, pumped hydro, flywheel, and electrochemical battery technologies.

Compressed Air

Compressed air would work at a wind farm built on or near underground caverns. Air is pumped into chambers underground and stored until energy demand increases. It is then released into a turbine where it is used to create energy. The size of the underground cavern must be large, such as an abandoned mine or underground cave [12].

Pumped Hydro

Another option is pumped hydro. This uses wind turbines to drive pumps which pump water from a lower reservoir to a higher reservoir; the change in height needs to be over 400 feet. When energy demand increases water is released from the higher reservoir turning a turbine and producing energy. Energy potential is determined by the size of the reservoirs [12].

Flywheel

Flywheels are another possible option for energy storage. Flywheels are mechanical devices that use inertia to store energy. Energy capacity can be increased by increasing the flywheel's rotation or by adding additional flywheels. This is still in developmental stages and is currently used for small-scale operations needing short time storage to smooth out transients [12].

Electrochemical Batteries

Electrochemical batteries offer another solution to the energy storage problem. Electrochemical batteries consist of multiple electrochemical cells which use chemical reactions to create a flow of electrons. Extra energy from the wind farm would be stored in the batteries and released at a later time when demand was increased. The main issues with this method are poor battery efficiency and battery replacement costs [13].

Distributed Generation

A possible solution that would partially negate the need for massive storage or transmission and an option that will be examined in later chapters is distributed generation. This

is a system where instead of energy being produced at a large central plant, or in our case wind farm, the generation is divided up into smaller units and scattered about the system [14].This reduces the need for large transmission lines and storage devices, at least on the local level. This wouldn't solve the issue of moving energy across state lines or across the nation, but it would allow for cities and municipalities in good wind areas to build the amount of generation they need and not have to worry about having the transmission systems necessary to send the extra generation anywhere [15].

Community Wind

Community wind is a facet of distributed generation on a larger scale than the individual. In community wind a power cooperative, city, or municipality would decide to put up large scale wind generation to meet some or all of their power needs. Power cooperatives exist primarily in rural areas and are member owned; every member has an equal say in the cooperative's operation. The profits gained by the cooperative are reinvested in the cooperative's infrastructure or paid out to the members through patronage checks. Power cooperatives generally do not own generation and instead negotiate rates to buy power from generation owners to then resell to the cooperatives members [23]. This allows for lower rates for the cooperative than the individual members could get on their own. A power cooperative, city, or municipality putting up large wind generation allows for communities that would not be able to afford renewable energy generation individually to pool their money together to be able to afford clean energy; at the same time the community does not have to worry about the reliability of the energy source as it is being backed up by other generation sources.

Related Work

Through the course of the literature review a number of papers were found that dealt with topics similar, or relating, to those examined in this research. Concepts from some of these papers were used in the research presented in this document and will be discussed in detail later, other topics were examined and left out of this research upon the determination that nothing of note could be done in the area based off of the data and system being examined in this work. A few papers that could be helpful in obtaining a broader knowledge base about the subject area examined in this research are briefly examined in the following sections.

Economic Evaluation of Wind Generation Projects in Electricity Markets [26]

"Economic Evaluation of Wind Generation Projects in Electricity Markets," by A. Pereira and J. Saraiva, provides a suggested approach of how to conduct economic analysis of new renewable energy generation. The steps outlined in this paper somewhat correspond to the steps preformed in this research [26].

Economic Evaluation of Small Wind Generation Ownership under Different Electricity Pricing Scenarios [24]

"Economic Evaluation of Small Wind Generation Ownership under Different Electricity Pricing Scenarios," by A. Jose, examines how different utility rate structures affect the economic viability of owning a small wind generator. The research outlined in A. Jose's paper provides an economic analysis of smaller sizes of wind generation than those examined in this paper; however, the steps taken in the economic analysis are similar [24].

Intelligent Dispatch for Distributed Renewable Resources [22]

"Intelligent Dispatch for Distributed Renewable Resources," by M. Hopkins, examines how energy storage systems affect the economic viability of owning small solar or wind generation. M. Hopkins' work also creates an algorithm to optimize the dispatching of energy storage systems. The research provided by M. Hopkins examines energy storage systems and their benefits through several case studies and provides a foundation to build off of for future studies [22].

The Economic Analysis of Wind Solar Hybrid Power Generation System in Villa [27]

"The Economic Analysis of Wind Solar Hybrid Power Generation System in Villa," by W. Jinggang, G. Xiaoxia, and D. Hongbiao, provides economic analysis for a hybrid wind-solar power generation system in China. A different system and different methods are used in their research, but the conclusions are similar to those found in the research conducted for this Thesis [27].

Conclusion

Based on the information compiled through this literature review, one can conclude that while wind energy is currently not the perfect energy solution, it has great promise. The

transmission or storage of the energy produced by wind farms is currently one of the biggest issues; however, there are multiple ideas and possible solutions to these problems. One of the more promising solutions is distributed energy generation which is a focus of this research.

Now that a base level of information has been established an economic analysis examining multiple rate structures will be conducted to determine which rate structure would create the most profitable outcome. A Monte Carlo simulation will then be created and run to simulate the future based on historical data. Following this, a sensitivity analysis will be performed to examine changes in rate and turbine size. Finally, an energy storage analysis will be performed to examine the economic viability of various sizes of battery storage systems.

Throughout the course of these studies the profitability of community wind generation will be thoroughly examined and a conclusion will be made determining whether or not community wind generation could be successful in rural western Kansas.

Chapter 2 - Data Acquisition and Organization

One of the first steps in determining the economic viability of wind generation is acquiring and organizing massive amounts of data. The data need to be organized in a thoughtful manner so they can be effectively used in economic and Monte Carlo simulations. The types of information needed to complete this study are the following:

- Temperature Data
- Load Data
- Wind Speed Data
- Wind Turbine Data

Each of these will be examined in this chapter following a description of the organizational method used.

Data Organization Method

Two different methods were considered to be used as the overriding organization for all the data sets; the options considered were organization by calendar year and organization by temperature range. Since plans for a Monte Carlo simulation were already in place, the data needed to be organized in a way that had relatively little variation. Looking at the data sets it was evident that the least variation would exist if the data were grouped into temperature ranges. This is partially because the bulk of the load in the location under examination is from pivot-point irrigation systems. As temperatures increase more irrigation is required, causing the load to be higher. As temperatures decrease less irrigation is required, especially over the winter months when crops are either dormant or nonexistent. Additionally, similar wind patterns can be expected on days within a small temperature range. The data were initially divided into five degree temperature ranges from zero to over one hundred degrees. This was cut down into thirteen groups to get a large enough sampling in each group; this will be explained further in the next sections.

Temperature Data

The temperature data for the research presented in this thesis, which consisted of maximum daily temperature values for a 10 year period (June 2001 – June 2011), were provided by Mary Knapp, Associate Agronomist at Kansas State University. The temperature is used to organize the load and wind data into manageable portions with relatively small variation. The following figure is a histogram of the maximum daily temperatures.

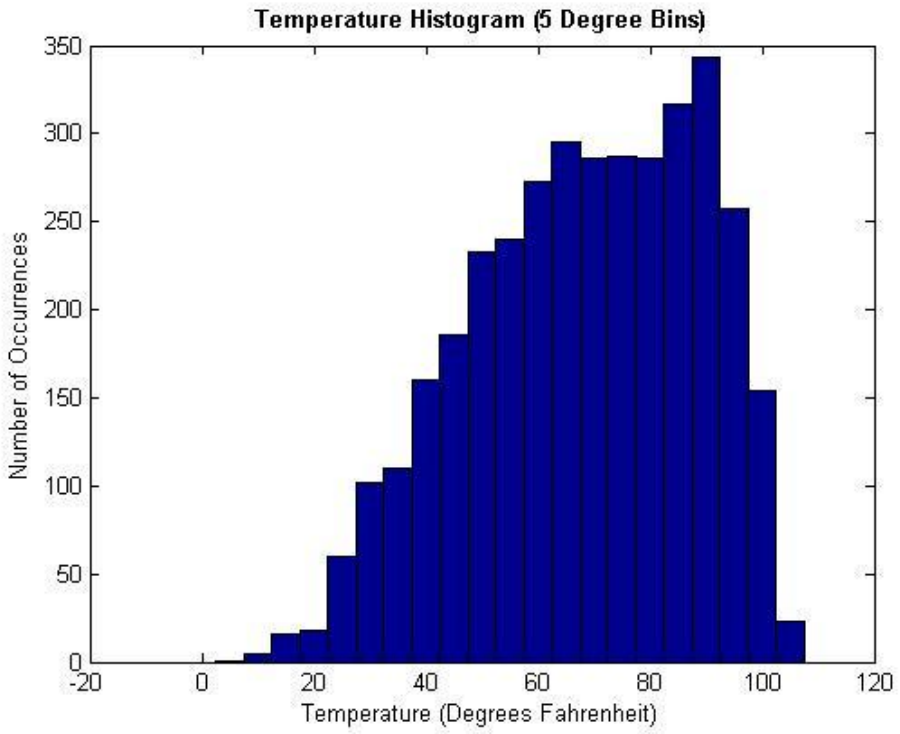

Figure 2.1: Histogram of the Maximum Daily Temperature with 5 Degree Fahrenheit Bins

Figure 2.1 shows the distribution of temperature over a ten year period. Looking at the figure it is evident that the most commonly occurring temperature is 90 – 95 degrees Fahrenheit. It is also evident that there are very few days with high temperatures lower than 25 degrees or higher than 105 degrees.

Load Data

The load data used in the research presented in this paper were supplied by Sunflower Electric Power Corporation and are from the load on a distribution system in Southwest Kansas. The load data consist of hourly readings of total three-phase kilowatts used. The period for which

data are present is from July 6, 2009 to August 14, 2011. As stated in the previous section, to minimize variation the data have been divided into the following thirteen temperature ranges:

- less than 30° Fahrenheit
- 30° - 40° Fahrenheit
- 40° - 50° Fahrenheit
- 50° - 60° Fahrenheit
- 60° - 65° Fahrenheit
- 65° - 70° Fahrenheit
- 70° - 75° Fahrenheit
- 75° - 80° Fahrenheit
- 80° - 85° Fahrenheit
- 85° - 90° Fahrenheit
- 90° - 95° Fahrenheit
- 95° - 100° Fahrenheit
- greater than 100° Fahrenheit

After the data were divided into the temperature ranges the average and standard deviation for every hour of the day in each temperature range were found. Figures 2.2 through 2.4 show examples of the average and standard deviation graphs; the complete set of graphs can be found in Appendix A.

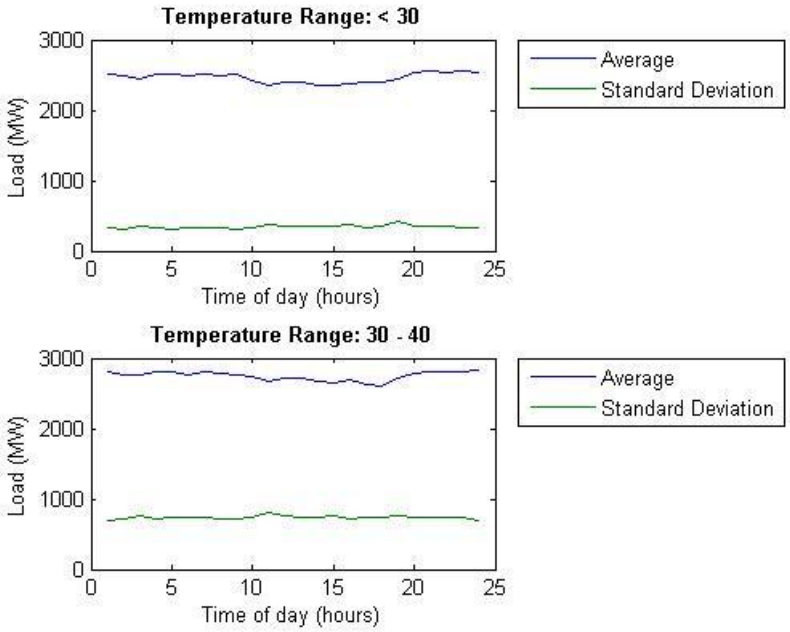

Figure 2.2: Load (MW) Average and Standard Deviation for Temperature Ranges < 30 and 30 – 40

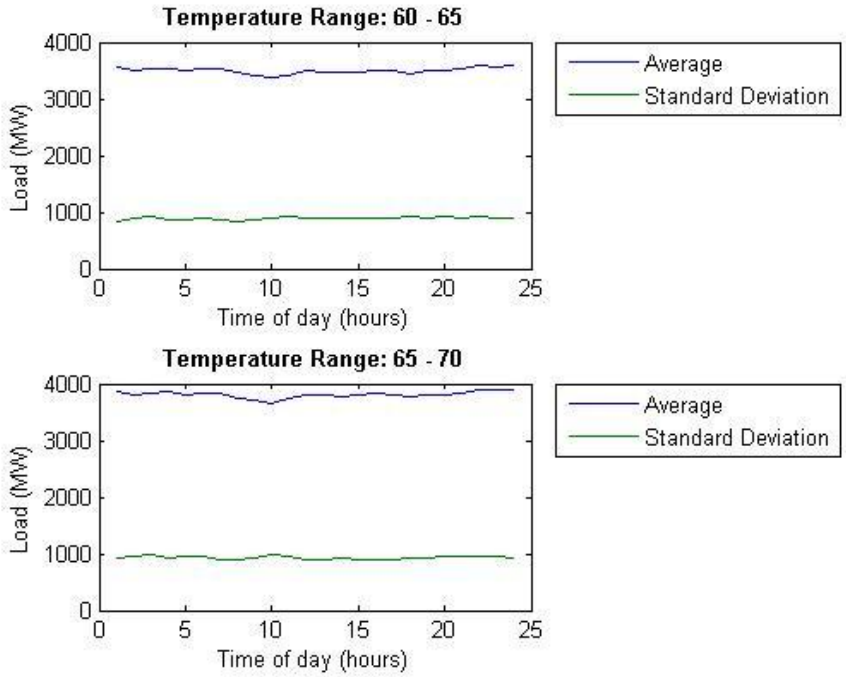

Figure 2.3: Load (MW) Average and Standard Deviation for Temperature Ranges 60 - 65 and 65 – 70

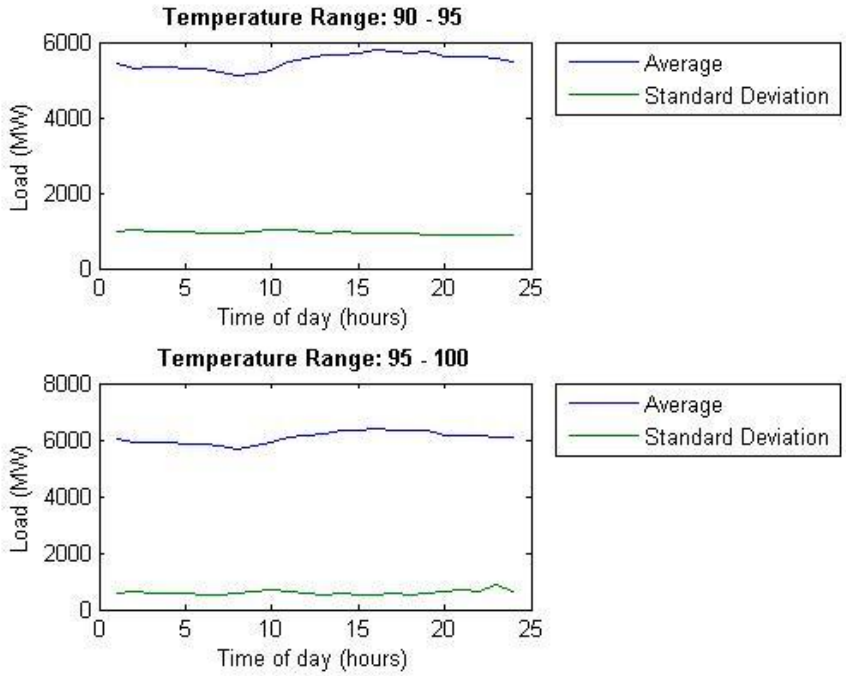

Figure 2.4: Load (MW) Average and Standard Deviation for Temperature Ranges 90 - 95 and 95 – 100

Looking at Figures 2.2 through 2.4 it is evident that as the temperature range increases the load level increases. It is also evident that while the temperature range is below 65 – 70 degrees the load level is very flat while at higher temperature ranges, for example 95 – 100 degrees, there is a noticeable increase in energy consumption from 10:00am to 8:00pm. The standard deviation levels across the temperature ranges are low, fewer than 1000 megawatts, and are very flat. This shows that the amount of variation throughout the day stays relatively constant; there is approximately the same amount of variation in the morning as in the evening.

Wind Data

The wind data for the research presented in this paper were provided by Mary Knapp, Associate Agronomist at Kansas State University, and Dr. Ruth Douglas Miller, Associate Professor in Electrical and Computer Engineering at Kansas State University. To start the research 10 meter wind data provided by Mary Knapp were used. This wind data contains hourly wind speed readings for a ten year period (June 2001 – June 2011). After examining the averages produced by this data set it was apparent that the wind readings would have to be scaled up (due to faster wind speeds at higher elevations) or data for a higher elevation would have to be found.

Dr. Ruth Douglas Miller was able to provide 80 meter data which negated any scaling of the wind data. The 80 meter data contains 10 minute readings over a 27 month period (May 2003 – August 2005). To reduce variation the wind data were also divided into the following temperature ranges:

- less than 30° Fahrenheit
- 30° - 40° Fahrenheit
- 40° - 50° Fahrenheit
- 50° - 60° Fahrenheit
- 60° - 65° Fahrenheit
- 65° - 70° Fahrenheit
- 70° - 75° Fahrenheit
- 75° - 80° Fahrenheit
- 80° - 85° Fahrenheit
- 85° - 90° Fahrenheit
- 90° - 95° Fahrenheit
- 95° - 100° Fahrenheit
- greater than 100° Fahrenheit

After being divided into these temperature ranges the hourly average and standard deviation for each temperature range were found. Figures 2.5 through 2.7 show the 10 meter and 80 meter wind speed averages and standard deviations for three of the above temperature ranges; the complete set of graphs can be found in Appendix B.

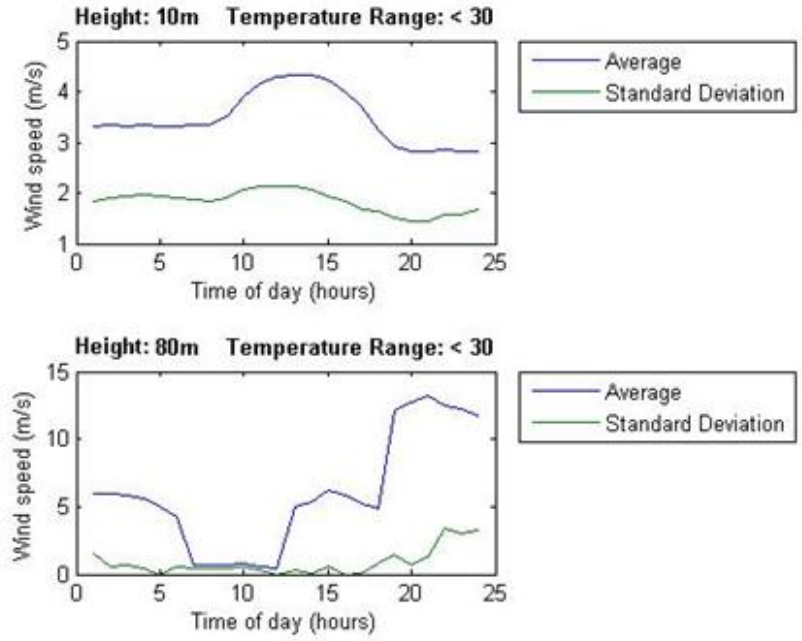

Figure 2.5: 10m and 80m Wind Speed (m/s) Average and Standard Deviation for < 30 Degree Fahrenheit Temperature Range

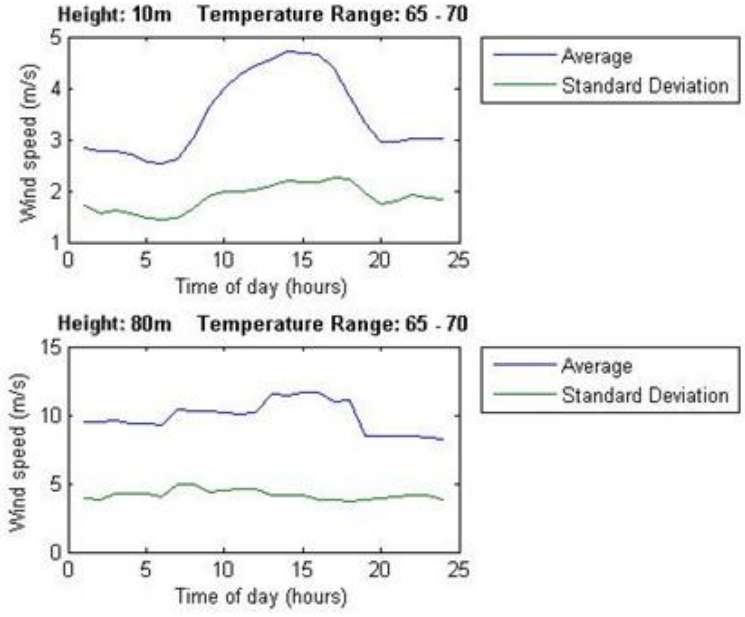

Figure 2.6: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 65 - 70 Degree Fahrenheit Temperature Range

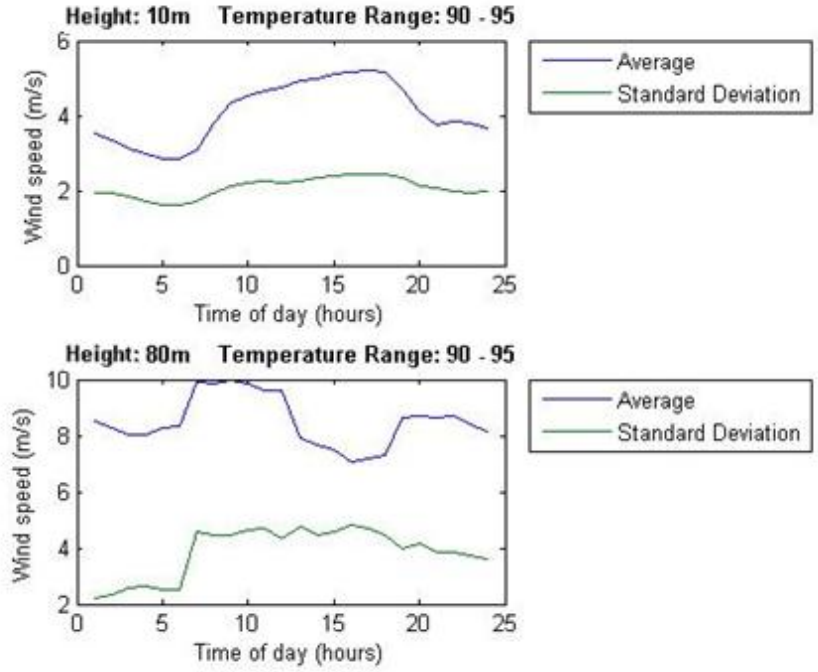

Figure 2.7: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 90 - 95 Degree Fahrenheit Temperature Range

Upon examination of the above figures it is evident that the 80 meter wind data is stronger than the 10 meter data. It is also evident that the 80 meter data graph is much more jagged than the 10 meter data graph; this is due to the fact that the 10 meter data covers a period four times as long as the 80 meter data. The wind speed graph is not level; there is a fairly consistent peak across the temperature ranges starting at 7:00am and ending at 8:00pm. This means that on an average day the wind will blow more strongly during this time; this happens to coincide with the peak load examined in the previous section. Another thing to note is that the standard deviation is not flat; it peaks with the wind speed peak. This shows that there is more variation during the wind peak which means that while some days in the temperature range are particularly windy, thus raising the average, there are still a number of days that are relatively calm.

Wind Turbine Data

The last piece of data needed is the wind turbine power curve. The acquisition of a detailed power curve was much harder than anticipated. The first step was to decide the size of the wind turbine to test. Looking at the load curves for the distribution network it was apparent

that generation close to 2.0 megawatts would be ideal; a turbine this size would never produce more energy than the network needed. After contacting multiple wind turbine manufacturers asking for power curve information the best returned by any of them was a graph of the power curve with no specific data. Figure 2.8 and Figure 2.9 are examples of the graphs provided by the manufacturing companies.

Figure 2.8: Suzlon 2.1 MW Wind Turbine Power Curve [16]

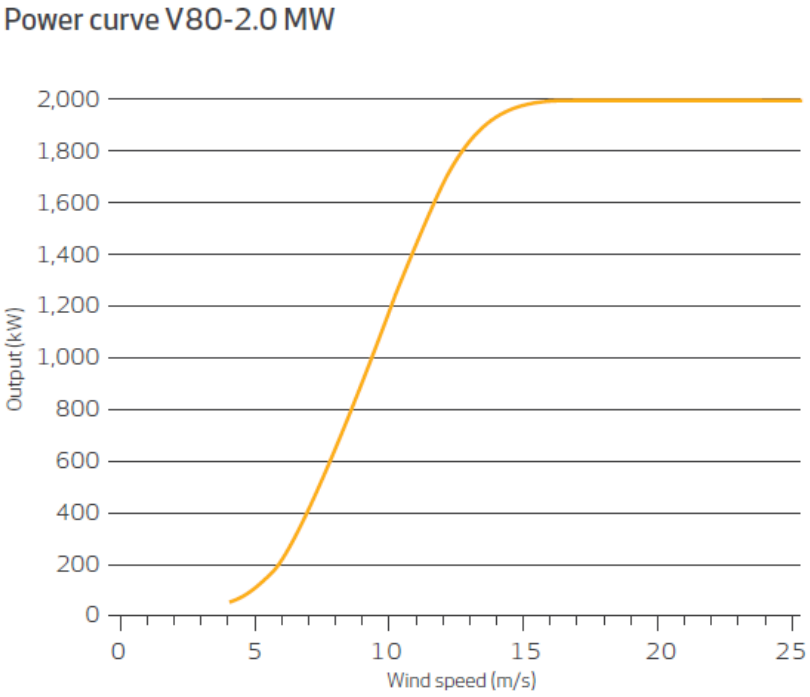

Figure 2.9: Vestas 2.0 MW Wind Turbine Power Curve [17]

Since the wind turbine manufacturers were only willing to provide graphs of power curves and power readings for every tenth of an increase in wind speed were needed, a generic power curve was created based on the power curves above. Figure 2.10 shows the generic power curve that will be used for economic analysis in future chapters.

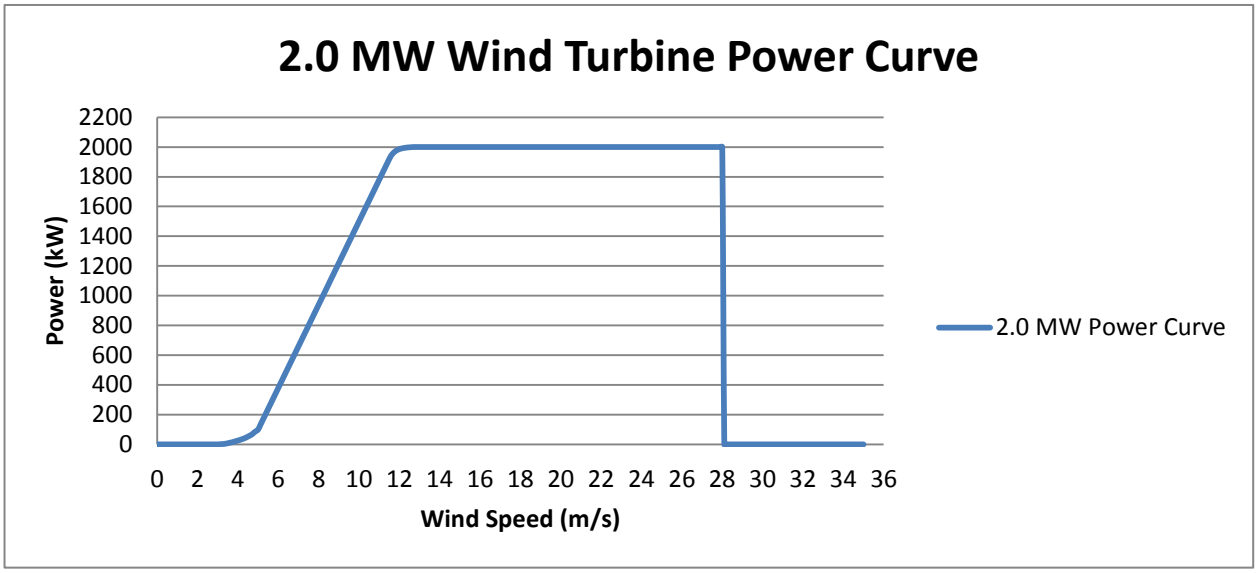

Figure 2.10: 2.0 MW Wind Turbine Power Curve

Conclusion

Data acquisition and organization is a very important step in the analysis performed in this research. Without quality data that are properly organized any sort of analysis could be potentially misleading. Data organization also allows for examination of the data to pick out trends. For example, in this research the variance in the load throughout the day is steady while the variance in the wind throughout the day fluctuates. Important information such as this can be overlooked if data is not organized and examined prior to being used.

Chapter 3 - Economic Analysis

This chapter focuses on evaluating the economics of implementing a wind generator under three pricing schemes, Flat Rate, Demand Rate, and Critical Peak Pricing (CPP). The data organization algorithm development that is common among all three rate structures will be examined first; this will be followed by a section on each of the rate structures. At the end of this analysis the best pricing scheme will be chosen for further examination in a Monte Carlo simulation.

Data Organization

The first step that is necessary in performing an economic analysis is getting the data organized into a manageable format. The algorithm for data organization is very similar across all of the rate structures and will be examined here to avoid unneeded repetitiveness in the rate structure sections.

Algorithm Development

The data organization algorithm is made up of three steps. These steps are primarily for organizational purposes. The steps used in the data organization algorithm are as follows:

1. Data input
2. Data organization
3. Data examination

Data Input

The first step in data organization is to get the raw data into MATLAB; MATLAB is the program used for the entirety of this research. The format of the raw data was an Excel spreadsheet so the MATLAB function xlsread was used to import the data directly from Excel directly into matrices in MATLAB. The four data sets that are needed for economic analysis are as follows:

1. Maximum daily temperatures for the time period in question
2. Wind speed information (ten minute previously described data was used in this research) for the time period in question

3. Load usage information (hourly data was used in this research) for the time period in question
4. Wind turbine power curve

Data Organization

The second step in data organization is to organize the data now in MATLAB into manageable matrices. During this step it is important to make sure that all the data is in the desired format. At this time all of the temperature data was converted into degrees Fahrenheit, all of the wind speed data was converted into meters per second, and all of the load data was converted into kilowatts and kilovars. This step is also used to divide the data into the temperature ranges specified in the previous chapter. At the end of this step there should be a single matrix for each of the temperature ranges containing all pertinent information for economic analysis.

Data Examination

The next step in the data organization algorithm is the examination of the data. During this step the average and standard deviation of wind speed and load for every hour of the day in each temperature range are computed. These data results act as a partial check; by looking at the standard deviation one can tell whether the data in each temperature range is a good fit. If there is a large variance then the temperature ranges used should be reevaluated or data for a longer period of time should be found.

Rate Structures

To complete the economic analysis a wind turbine simulation was designed and implemented using three different existing rate structures. The results of the rate structures were then compared to determine which was the most economically viable. The three rate structures used are the following:

- Flat Rate
- Demand Rate
- Critical Peak Pricing (CPP)

Each of the rate structures required a different algorithm. The following sections will give an overview of each individual rate structure, a description of the algorithm created for the rate structure, and the economic results obtained for the wind turbine simulation.

Flat Rate

A flat rate structure is one of the simplest and most common rate structures used. Under this system each customer pays the same flat rate for each kilowatt hour of energy used. In the area in question in this research the flat rate is 5.93 cents per kilowatt hour. This is the amount that the energy provider pays for a kilowatt-hour of energy to the supplier.

Algorithm Development

The flat rate structure algorithm was the easiest rate structure algorithm to develop. From the data organization algorithm above the wind speed and maximum daily temperature data are compiled in the same matrix. The flat rate structure algorithm then has to compare these data to the wind turbine power curve data which has already been input into MATLAB. To accomplish this a loop has been created that steps through the raw data matrix line by line and compares the wind speed at the given time interval to the power curve for the wind turbine in question to determine the total energy generated. The power generated data are stored in a matrix so it can be examined at a later time if necessary. At the end of the loop all of the days during the specified time duration will have been stepped through and the generation totals will be saved in a single matrix. It is at this point that the total generation is found by taking the sum of the power generation matrix. After the total generation has been found it is multiplied by the flat rate (5.93 cents in this case) to determine the total savings provided by the power generation of the wind turbine. The turbine simulation provides a record of energy produced each time interval, the total energy generated, and the generation savings. The time period that the analysis covers should be as large as possible and is determined by the limiting data set; in this research the limiting data set is wind speed.

Results

Running the flat rate turbine simulation on the 80 meter wind data from Kearny County, Kansas, gives the results shown in Table 3.1. The analysis ran for a 24-month period and annual data was extracted from the results by taking an average of the two years. The savings result in

the following table is for one year; present worth will be discussed and implemented immediately prior to the conclusion of this chapter.

Table 3.1: Flat Rate Turbine Simulation Results - 80m Kearny County Wind Data

Annual Turbine Generation	9,193,000 kilowatt hours
Annual Generation Savings	$545,150

Demand Rate

The demand rate structure examined in this research is a rate where there is a lower flat rate for energy but there is a once-monthly fee assessed based on peak usage of the customer that month. The rate structure for this research is based off the ratios of the rates used in a different area that is provided energy by the same company. The rates used in this simulation are a flat rate of 3.5 cents per kilowatt hour with a demand charge of 6 dollars per kilowatt of peak usage for each month.

Algorithm Development

The algorithm development for this rate structure is more complicated than that used in the flat rate structure; in fact it uses the flat rate algorithm and adds to it. The total savings in this simulation will be the total generation savings (with a flat rate of 3.5 cents per kilowatt hour) and the savings from peak reduction (the amount the peak is reduced multiplied by 6 dollars per kilowatt). The outputs of the flat rate algorithm were an hourly generation matrix, total generation, and savings from generation. The output of interest in this analysis is the hourly generation matrix. In order to find the savings gained from adding a wind turbine to the system the amount of peak reduction needs to be found. Subtracting the hourly generation matrix from the initial load data creates a new load profile. Next a loop was created that steps through the load data month by month and saves the peak monthly load to a new matrix. This loop is run for both the new and the old load profiles. The peak load matrix from the new load profiles is subtracted from the peak load matrix of the old load profiles to find a new matrix which contains the amount the peak load for each month was reduced. Each entry in this matrix is multiplied by 6 to give the demand savings from peak reduction for each month. These monthly values are then added together to find the annual peak reduction savings. The annual peak reduction savings are then added to the total savings found during the flat rate simulation to give the total generation savings using a demand rate structure. The time period that the analysis covers should

be as large as possible and is determined by the limiting data set; in this research the limiting data set is wind speed.

Results

Running the demand savings turbine simulation on the 80 meter wind data from Kearny County, Kansas, with the load data provided for the area in question gives the results shown in Table 3.2. The analysis ran for a 24 month period and annual data was extracted from the results by taking an average of the two years. The load data and wind speed data are both used in this analysis; however, they are not from the same time period. Because of this, the load data were assumed to be from the same time period as the wind data and were overlaid on the wind data's 24 month period according to the calendar year. For example, the wind speed data for June 2006 are assumed to have the load characteristic of the load data from June 2010; this results in some, but not significant, error in the calculations. The savings results in the following table are inflated; present worth will be discussed and implemented immediately prior to the conclusion of this chapter.

Table 3.2: Demand Savings Turbine Simulation Results - 80m Kearny County Wind Data

	Flat Rate Savings	**Peak Reduction Savings**	**Total Savings**
Annual Savings	$316,966.40	$9,923.60	$326,890

Critical Peak Pricing (CPP)

The CPP rate structure is based on the demand rate structure discussed previously with minor differences. CPP is a program that is designed to reduce electricity consumption during high demand periods. Customers are charged a lower than normal flat rate throughout the year except on the CPP event days; there can be up to fifteen event days each year. Event days are called on days when high energy use is expected. On an event day a high energy rate is assessed during the hours of 1:00pm to 6:00pm [18]. The simulation used for the CPP rate structure uses 3.0 cents per kilowatt hour as the flat base rate and 80 cents per kilowatt hour as the high energy rate. Table 3.3 shows the characteristics used to determine if a day was a CPP day and which days in 2004, the year examined in the analysis, were counted as CPP days [24].

Table 3.3: Critical Peak Pricing Criteria & Simulation Event Days [24]

Month	Temperature Criteria	Event Days - 2004
June	greater than 99.0 degrees Fahrenheit	6/25, 6/26
July	greater than 96.0 degrees Fahrenheit	7/3, 7/8, 7/11, 7/12, 7/13, 7/14, 7/24
August	greater than 96.0 degrees Fahrenheit	8/3, 8/7, 8/23, 8/24
September	greater than 96.0 degrees Fahrenheit	None

Algorithm Development

The algorithm for the CPP rate structure starts with the same algorithms used in the data organization and flat rate simulations. The only difference is that the flat rate being simulated is 3.0 cents per kilowatt hour. The main difference in this algorithm is that it requires more raw data as input. In addition to the wind, temperature, load, and turbine data used previously, CPP data now also needs to be used. Therefore, the data for the predetermined time interval on the CPP days was extracted from the dataset. After running the base simulation, these new data is imported into MATLAB using the same method outlined in the data organization algorithm. Once this was done, the turbine simulation was run on only the CPP data with a flat rate of 80 cents per kilowatt hour; this accounts for the increased cost of energy on CPP days. Now matrices exist stating the total flat rate generation and savings as well as the total CPP generation and savings. Add the generation matrices together to get total generation and the savings matrices together to get total savings. From these results extrapolations can be made for multiple years assuming conditions remain the same. The time period that the analysis covers should be as large as possible and is determined by the limiting data set; in this research the limiting data set is wind speed.

Results

Running the CPP turbine simulation on the 80 meter wind data from Kearny County, Kansas, gives the results shown in Table 3.4. Due to constraints on the data used in this research the analysis was only able to be run on one year of data (2004). The savings result in the following table is inflated; present worth will be discussed and implemented immediately prior to the conclusion of this chapter.

Table 3.4: Demand Savings Turbine Simulation Results - 80m Kearny County Wind Data

	Flat Rate Savings	CPP Savings	Total Savings
Annual Savings	$271,690	$39,400	$311,090

Present Worth

The results provided in the previous sections can be misleading; inflation and time value of money have not been taken into account. To account for these things a present worth calculation was performed. The equation used for present worth is the following:

$$PW(A)_N = \frac{A}{(1+d)} + \frac{A}{(1+d)^2} + \ \ldots \ + \frac{A}{(1+d)^N}$$

In the equation above A is the annual savings, N is 20 years which is the life expectancy of a wind turbine, and d is 0.08 which is the discount rate. The discount rate is related to the opportunity cost of investing money [19]. Tables 3.5 and 3.6 show the present worth of the results from the previous sections assuming that the savings every year are the same as the annual value found.

Table 3.5: Rate Structure Twenty Year Present Worth Savings Comparison

Rate Structure	Twenty Year Savings	Twenty Year Present Worth
Flat Rate	$10,090,300	$5,352,363.06
Demand Savings	$6,537,800	$3,209,404.20
Critical Peak Pricing	$6,221,800	$3,054.327.48

Table 3.6: Rate Structure Thirty Year Present Worth Savings Comparison

Rate Structure	Thirty Year Savings	Thirty Year Present Worth
Flat Rate	$16,354,500	$6,137,180.59
Demand Savings	$9,806,700	$3,680,056.80
Critical Peak Pricing	$9,332,700	$3,502.183.82

Coefficient of Power

The coefficient of power (C_p) is a measure of how much of the wind's energy is being converted into mechanical energy by the wind turbine. The formula for C_p is as follows:

$$C_P = \frac{Electricity\ Produced\ by\ Wind\ Turbine}{Wind\ Turbine\ Size}$$

The theoretical maximum C_p is 0.593 which is known as the Betz limit. Table 3.7 provides the C_p for the scenario examined in this section [25].

Table 3.7: Coefficient of Power Calculation and Result

Annual Energy Generated	Annual Electricity Produced	Wind Turbine Size	Coefficient of Power
9,193,000 kWh	1,049.429 kW	2,000 kW	0.5247

Table 3.7 shows that the C_p is 0.5247; this is a very good value that is relatively close to the theoretical maximum.

Conclusion

Based on the information shown in Tables 3.5 and 3.6 it is apparent that the best rate structure is the flat rate structure. The flat rate structure is more than two million dollars more lucrative than the other rate structure options at twenty years which is the estimated lifetime of a wind turbine. Since the flat rate structure is the obvious best choice a Monte Carlo simulation will be conducted in the next chapter using the flat rate structure based in part on the algorithm outlined in the flat rate section of this chapter.

Chapter 4 - Monte Carlo Simulation

The previous chapter examined the economics of wind generation based on historical wind and temperature data. The savings values calculated were based on the same one or two year period being replayed over and over again; however, weather patterns are constantly changing and no two years are the same. The purpose of this chapter is to explain the Monte Carlo simulation developed to predict the future based on the past instead of just repeating the past. The following sections will give an overview of the Monte Carlo simulation algorithm as well as the results found from its successful implementation.

Simulation Objective

The Monte Carlo simulation was designed to meet one main objective: to create a simulation that provides a historically accurate prediction of maximum daily temperature and sustained hourly wind speed. This is accomplished by randomly generating a maximum daily temperature and then randomly generating hourly wind speed data based on historical histograms. Success is measured by comparing the historical histograms with the predicted value histograms; the comparison should be almost identical.

Assumptions/Conditions

The simulation and the results outlined in this chapter are based on the following assumptions:

- A flat rate structure is being used with a rate of 5.93 cents per kilowatt-hour.
- The upfront cost for a 2.0 megawatt wind turbine and the equipment required to connect it to the grid is 3,000,000 dollars.
- Operation and maintenance costs are 0.7 cents per kilowatt-hour as suggested by the National Renewable Energy Laboratory (NREL) [20].

Simulation Development

The Monte Carlo simulation used in this research contains the following six steps:

1. Data Input

2. Data Organization
3. Compilation of Temperature Range Specific Wind Speed Histograms
4. Simulation of Maximum Daily Temperature
5. Simulation of Hourly Wind Speed
6. Flat Rate Wind Turbine Simulation

Steps four through six are repeated for every day in the simulation in the 20 year time frame used in this simulation. The 20 year simulation is then repeated a large number of times (500 – 2000) to determine simulation averages and upper and lower bounds.

Step 1: Data Input

There are three types of data needed for the Monte Carlo simulation. First, temperature and wind data are needed; this research uses two years of data with information for every ten minutes or 4,380 data entries (May 2003 – August 2005). A wind turbine power curve is also needed. The power curve used is for a 2.0 megawatt turbine with information for every tenth of a meter per second increase in wind speed and is shown in Figure 4.1.

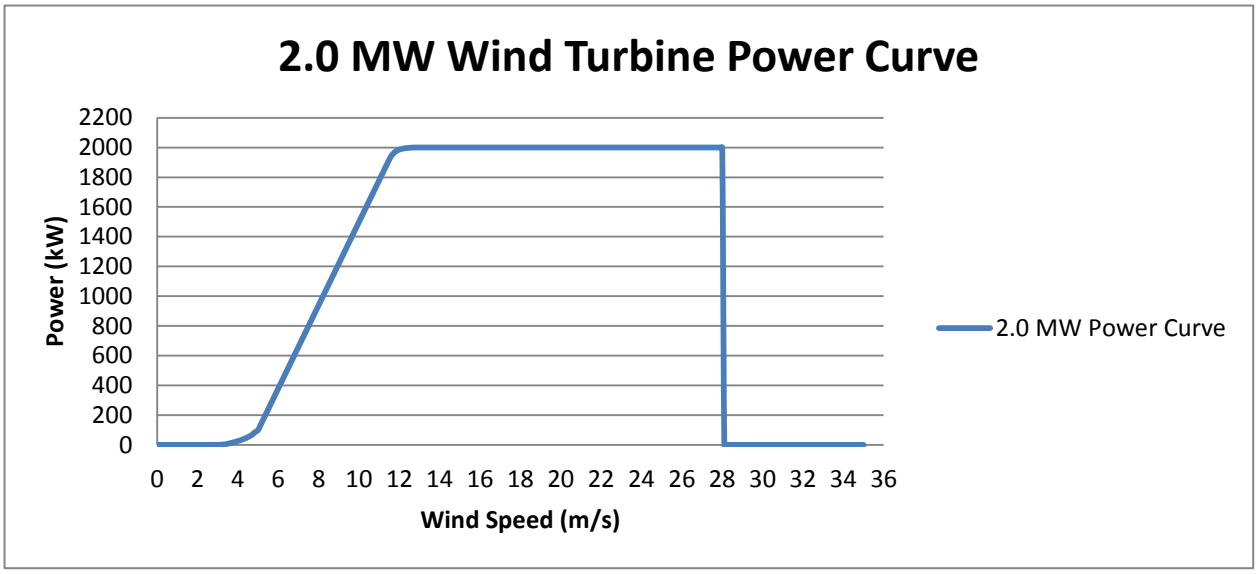

Figure 4.1: 2.0 MW Wind Turbine Power Curve

Algorithm Development

The algorithm development for this step is very simplistic. For this research data was provided in Excel spreadsheets and was moved to MATLAB for analysis using the function xlsread.

Step 2: Data Organization

The second step in the Monte Carlo simulation is to organize the data now in MATLAB into manageable matrices. During this step it is important to make sure that all the data is in the desired format. For this simulation the data are divided into maximum daily temperature ranges to minimize variance; the temperature ranges are not all equal. The temperature ranges used are the following:

- less than 30° Fahrenheit
- 30° - 40° Fahrenheit
- 40° - 50° Fahrenheit
- 50° - 60° Fahrenheit
- 60° - 65° Fahrenheit
- 65° - 70° Fahrenheit
- 70° - 75° Fahrenheit
- 75° - 80° Fahrenheit
- 80° - 85° Fahrenheit
- 85° - 90° Fahrenheit
- 90° - 95° Fahrenheit
- 95° - 100° Fahrenheit
- greater than 100° Fahrenheit

Algorithm Development

During this step MATLAB code is used to convert all of the temperature data into degrees Fahrenheit, all of the wind speed data into meters per second, and all of the load data into kilowatts and kilovars. This step is also used to divide the data into the temperature ranges shown above. At the end of this step there should be a single matrix for each of the temperature ranges containing all information needed for the Monte Carlo simulation.

Step 3: Compilation of Temperature-Range-Specific Wind Speed Histograms

This step in the Monte Carlo simulation is one of the key setup steps; without this step the Monte Carlo simulation could not work. During this step a wind speed histogram is created for every hour of the day for every temperature range; each bin in the histogram equals 0.25

meters per second. The histograms are then used to provide a wind speed value based on their distribution as described in the algorithm development section. Figure 4.2 shows an example of a temperature range specific wind speed histogram. Figure 4.2 represents the 6:00pm hour of 65 – 70 degree Fahrenheit days.

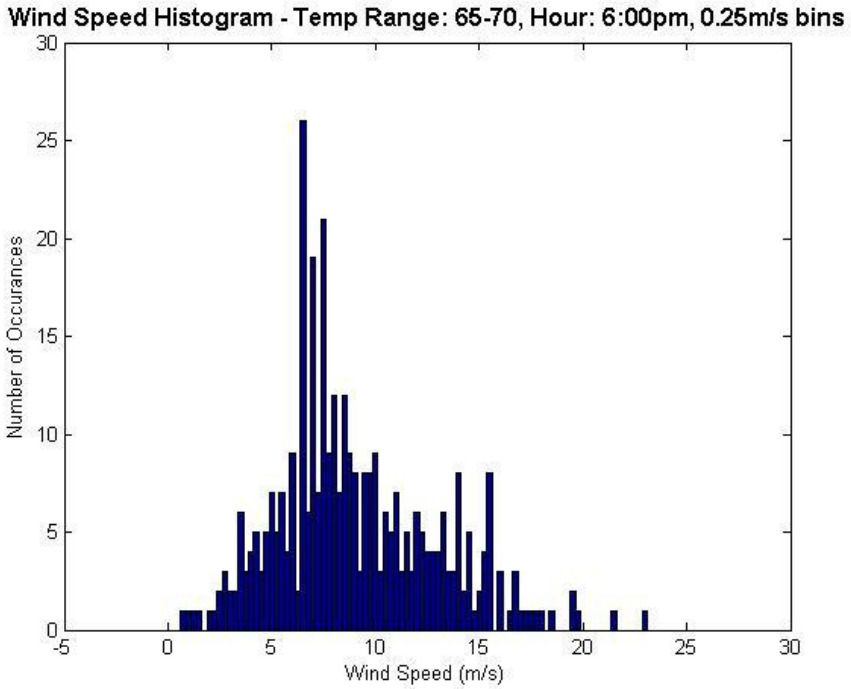

Figure 4.2: Wind Speed Histogram for 65-70 Temperature Range in the 6:00pm Hour with 0.25m/s bins

The above figure is a very jagged histogram. For this reason a cumulative distribution curve was not fit, instead the data will be used as is without any averaging or alterations.

Algorithm Development

The algorithm in this step takes in the organized matrices from the previous step, sorts the data by hour, creates hourly histograms, and then returns all the histograms in a single matrix. The bins of the histogram were set at 0.25 meters per second. A loop was created to sort the wind speed data from the data organization step into different columns based on the hour of the day the wind speed occurred. This provided a matrix with 24 columns, each containing all of that hours wind speed data. The hist function in MATLAB was then used to create histograms for each hour (column) as shown in Figure 4.2 above. Each column was then divided by the total number of data entries in the column to form a probability. Each column of probabilities was

then added together from top to bottom to form a sequence from zero to one; these new numbers show the probability that the wind is less than or equal to the corresponding wind speed. The 121st value in each of the 24 columns in each of the temperature ranges should equal one. Tables 4.1 and 4.2 show the 6:00pm column of the 65 – 70 degree temperature range in the simulation; this is the same column shown in Figure 4.2 above. Figure 4.3 shows the cumulative distribution function for the same column in the same temperature range.

Table 4.1: Cumulative Probability Distribution Example (Temp Range 65-70, Hour: 6pm, Bins 1 - 56)

Bin Number	Wind Speed (m/s)	Added Probability	Bin Number	Wind Speed (m/s)	Added Probability
1	0.25	0	29	7.25	0.3559322
2	0.5	0	30	7.5	0.37570621
3	0.75	0	31	7.75	0.43502825
4	1	0.00282486	32	8	0.46045198
5	1.25	0.00564972	33	8.25	0.49435028
6	1.5	0.00847458	34	8.5	0.51412429
7	1.75	0.01129944	35	8.75	0.5480226
8	2	0.01129944	36	9	0.57344633
9	2.25	0.01412429	37	9.25	0.5960452
10	2.5	0.01694915	38	9.5	0.60451977
11	2.75	0.02259887	39	9.75	0.62711864
12	3	0.03107345	40	10	0.64971751
13	3.25	0.03672316	41	10.25	0.67514124
14	3.5	0.04237288	42	10.5	0.68361582
15	3.75	0.05932203	43	10.75	0.70056497
16	4	0.06779661	44	11	0.71468927
17	4.25	0.07909605	45	11.25	0.73446328
18	4.5	0.09322034	46	11.5	0.74293785
19	4.75	0.10169492	47	11.75	0.75706215
20	5	0.11581921	48	12	0.76553672
21	5.25	0.13559322	49	12.25	0.78248588
22	5.5	0.14971751	50	12.5	0.79661017
23	5.75	0.16949153	51	12.75	0.8079096
24	6	0.18079096	52	13	0.81920904
25	6.25	0.20621469	53	13.25	0.83050847
26	6.5	0.21186441	54	13.5	0.84745763
27	6.75	0.28531073	55	13.75	0.8559322
28	7	0.30225989	56	14	0.86440678

Table 4.2: Cumulative Probability Distribution Example (Temp Range 65-70, Hour: 6pm, Bins 57 - 121)

Bin Number	Wind Speed (m/s)	Added Probability	Bin Number	Wind Speed (m/s)	Added Probability
57	14.25	0.88700565	90	22.5	0.99717514
58	14.5	0.89265537	91	22.75	0.99717514
59	14.75	0.90677966	92	23	0.99717514
60	15	0.90960452	93	23.25	1
61	15.25	0.91525424	94	23.5	1
62	15.5	0.92655367	95	23.75	1
63	15.75	0.94915254	96	24	1
64	16	0.94915254	97	24.25	1
65	16.25	0.95762712	98	24.5	1
66	16.5	0.95762712	99	24.75	1
67	16.75	0.96045198	100	25	1
68	17	0.96892655	101	25.25	1
69	17.25	0.97175141	102	25.5	1
70	17.5	0.97457627	103	25.75	1
71	17.75	0.97740113	104	26	1
72	18	0.98022599	105	26.25	1
73	18.25	0.98305085	106	26.5	1
74	18.5	0.98305085	107	26.75	1
75	18.75	0.98587571	108	27	1
76	19	0.98587571	109	27.25	1
77	19.25	0.98587571	110	27.5	1
78	19.5	0.98587571	111	27.75	1
79	19.75	0.99152542	112	28	1
80	20	0.99435028	113	28.25	1
81	20.25	0.99435028	114	28.5	1
82	20.5	0.99435028	115	28.75	1
83	20.75	0.99435028	116	29	1
84	21	0.99435028	117	29.25	1
85	21.25	0.99435028	118	29.5	1
86	21.5	0.99435028	119	29.75	1
87	21.75	0.99717514	120	30	1
88	22	0.99717514	121	30.25	1
89	22.25	0.99717514			

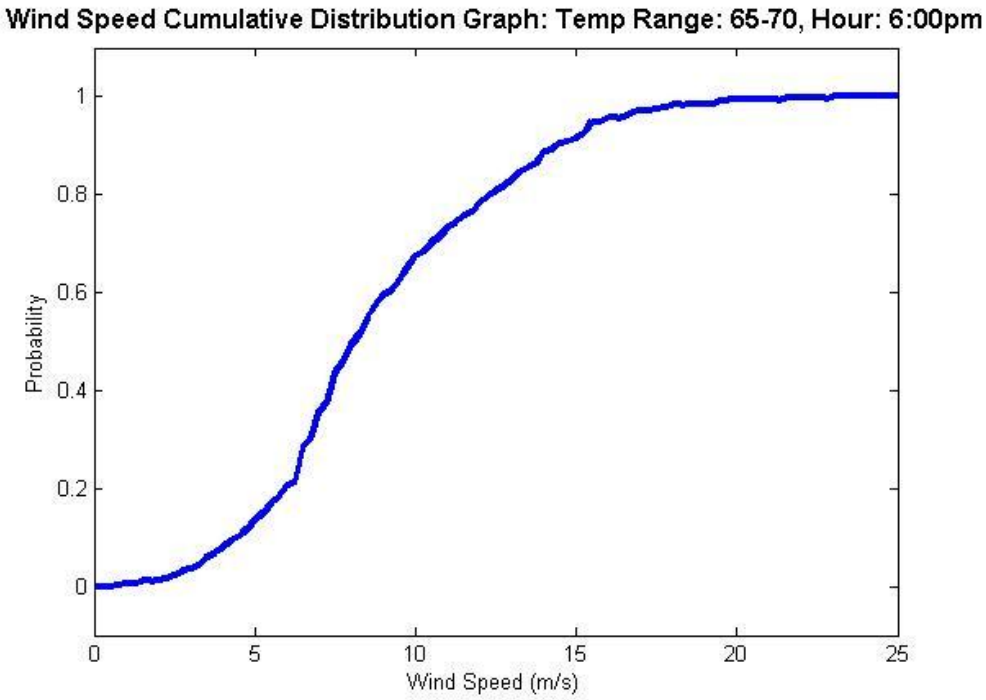

Figure 4.3: Wind Speed Cumulative Distribution Graph for the 65 - 70 Degree Temperature Range in the 6:00pm Hour

As you can see from Tables 4.1 and 4.2 and Figure 4.3, the cumulative probabilities start at zero and gradually increase to one. A table and graph like the ones shown above is created for every hour of every temperature range and will be used in simulations in future sections.

Step 4: Simulation of Maximum Daily Temperature

This step is the first step in which simulation and prediction of data takes place. The overriding organizational method of the research thus far has been temperature range so it makes sense that the first item simulated is maximum daily temperature. This temperature will be used to assign hourly wind speeds in the next section.

Algorithm Development

First, a histogram of the temperature data provided needs to be computed as shown in Figure 4.4.

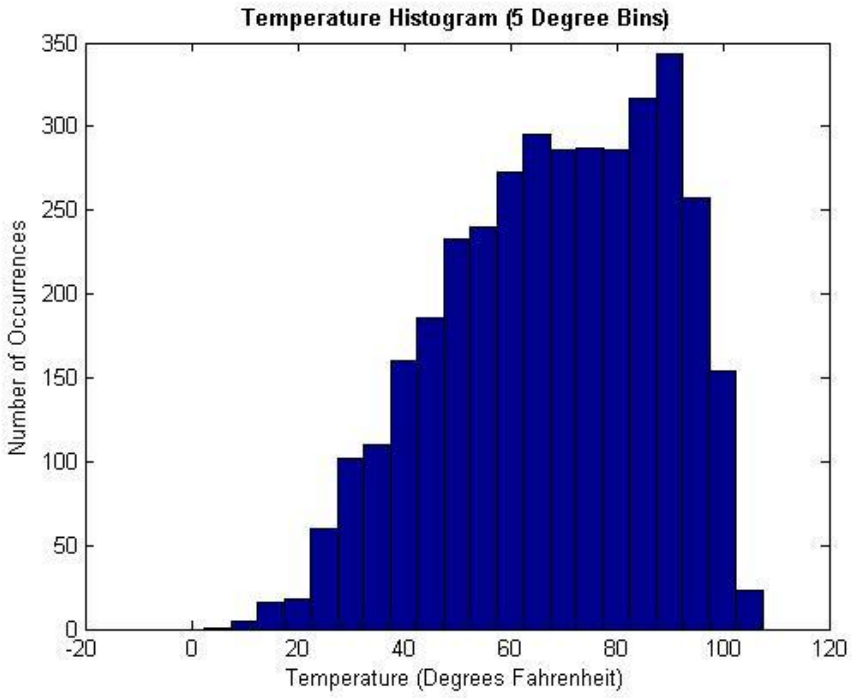

Figure 4.4: Temperature Histogram from Historical (10 year) Input Data with 5 Degree Bins

Using Figure 4.4 the probabilities of each temperature range and the cumulative probabilities need to be computed as in step 3 (see previous section of this chapter). The cumulative probabilities of the temperature ranges in this research are shown in Table 4.3 and a cumulative density function is shown in Figure 4.5.

Table 4.3: Cumulative Probability Temperature Distribution

Temperature Range	Cumulative Probability
less than 30° Fahrenheit	0.0275
30° - 40° Fahrenheit	0.0855
40° - 50° Fahrenheit	0.1802
50° - 60° Fahrenheit	0.3097
60° - 65° Fahrenheit	0.3845
65° - 70° Fahrenheit	0.4653
70° - 75° Fahrenheit	0.5436
75° - 80° Fahrenheit	0.6222
80° - 85° Fahrenheit	0.7005
85° - 90° Fahrenheit	0.7873
90° - 95° Fahrenheit	0.8812
95° - 100° Fahrenheit	0.9516
greater than 100° Fahrenheit	1.00

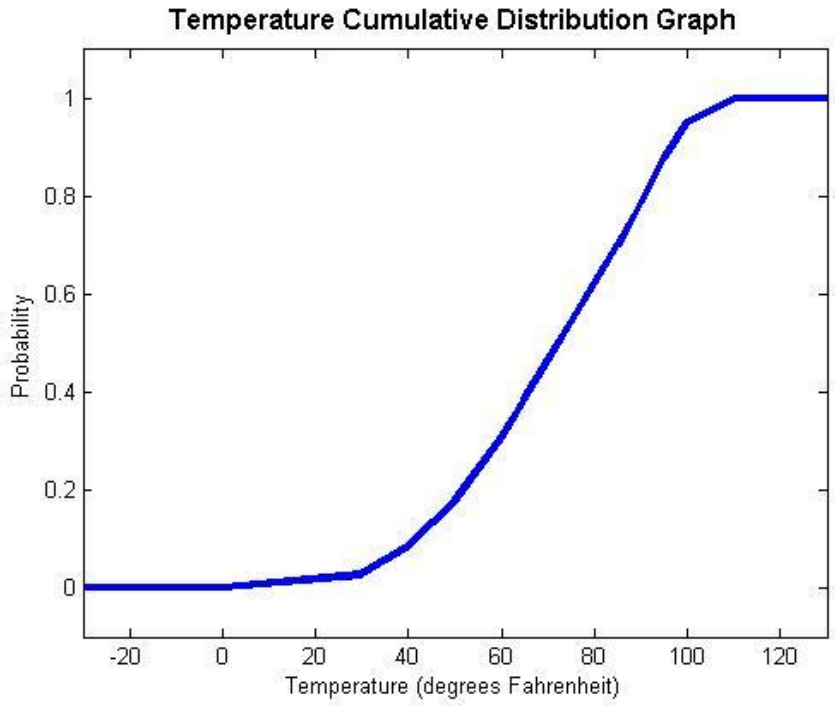

Figure 4.5: Temperature Cumulative Distribution Graph

Using the values in Table 4.3 a uniformly distributed random number is generated in MATLAB which corresponds to a temperature range. A loop steps through the temperature range cumulative probability values until it finds a value larger than the random number generated; the loop returns that temperature range. Table 4.4 shows an example of five uniformly distributed random numbers and the temperature ranges they would correspond to.

Table 4.4: Temperature Assignment from Uniformly Distributed Random Number

Generated Random Number	Temperature Range	Temperature Assigned
0.9459	95° - 100° Fahrenheit	97° Fahrenheit
0.0767	30° - 40° Fahrenheit	35° Fahrenheit
0.1714	40° - 50° Fahrenheit	45° Fahrenheit
0.4638	65° - 70° Fahrenheit	67° Fahrenheit
0.1410	40° - 50° Fahrenheit	45° Fahrenheit

As you can see from Table 4.4 temperature values were assigned near the middle of the temperate range. Every simulated day starts with this loop to determine maximum daily temperature.

Step 5: Simulation of Hourly Wind Speed

This step in the Monte Carlo simulation is very similar to step 4. This step uses uniformly distributed random numbers to determine hourly wind speeds for each simulated day. The wind speeds are then later used in the wind turbine simulation to determine savings.

Algorithm Development

The algorithm for this step is a repeated version of the algorithm in step 4. A set of 24 uniformly distributed random numbers is generated (one for each hour of the day). The maximum daily temperature found in step 4 is then used to determine the temperature range of wind histograms to use. Once the correct wind speed histograms are found a loop steps through each hour of the day and finds the first cumulative probability greater than the generated wind value and returns that bin number. The bin number is then used to determine wind speed for that hour. Table 4.5 gives an example based off of the 65 – 70 degree temperature range in the 18^{th} hour (data shown in Tables 4.1 and 4.2).

Table 4.5: Wind Speed Assignment from Uniformly Distributed Random Number (Temp Range 65-70, 18th Hour)

Generated Random Number	Wind Speed Bin Number	Simulated Wind Speed (m/s)
0.6364	40	10
0.3541	29	7.25
0.8314	54	13.5
0.9055	59	14.75
0.6058	39	9.75

Step 6: Flat Rate Wind Turbine Simulation

A flat rate structure is one of the simplest and most common rate structures used. Under this system each customer pays the same flat rate for each kilowatt hour of energy used. In the area in question in this research the flat rate is 5.93 cents per kilowatt hour. This is the amount that the energy provider pays for a kilowatt hour of energy.

Algorithm Development

The data organization algorithm above ensures that the wind speed and maximum daily temperature data are compiled in the same matrix. The flat rate structure algorithm then has to compare these data to the wind turbine power curve data which have already been input into MATLAB. To accomplish this a loop has been created that steps through the simulated data matrix line by line and compares the wind speed at the hourly time interval to the power curve for the wind turbine to determine the total energy generated. The energy-generated data are stored in a matrix so they can be examined at a later time. At the end of the loop all of the days during the specified time duration will have been stepped through and the generation totals will be saved in a single matrix. It is at this point that the total generation is found by taking the sum of the energy generation matrix. After the total generation has been found it is multiplied by the flat rate (5.93 cents in this case) to determine the total savings provided by the energy generation of the wind turbine. The turbine simulation provides a record of energy produced each time interval, the total energy generated, and the generation savings.

Results

Running the Monte Carlo simulation outlined above provides a large amount of output data. The following sections deal with organization of the results.

Present Worth

Present worth is factored into the Monte Carlo Simulation so the results provided in this section have taken into account inflation and time value of money. The equation used for present worth is the following:

$$PW(A)_N = \frac{A_1}{(1+d)} + \frac{A_2}{(1+d)^2} + \square + \frac{A_N}{(1+d)^N}$$

In the equation above A_x is the annual savings which varies every year of the simulation, N is 20 years which is the life expectancy of a wind turbine and the length of the simulation, and d is 0.08 which is the discount rate. The discount rate is related to the opportunity cost of investing money [19]. Figure 4.6 shows a histogram of 20 year present worth values for 2000 trials, Figure 4.7 shows the simulated temperature histogram for the same period, and Figure 4.8 shows the 10 year historical temperature histograms with the same bins used in the simulation.

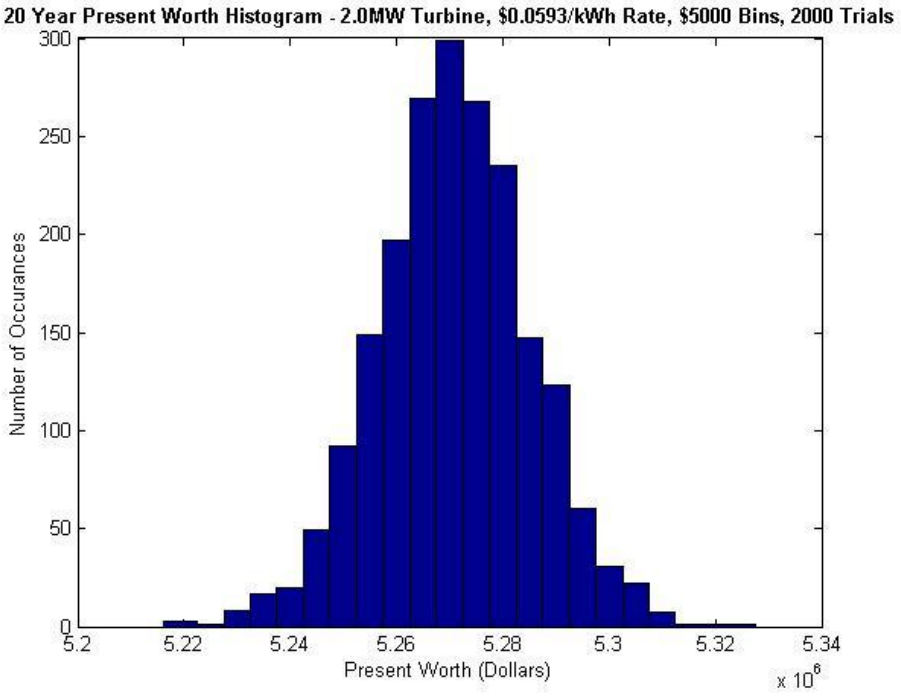

Figure 4.6: 20 Year Present Worth Histogram with 2.0MW Turbine, $0.0593/kWh Flat Rate and $5000 Bins for 2000 Trials

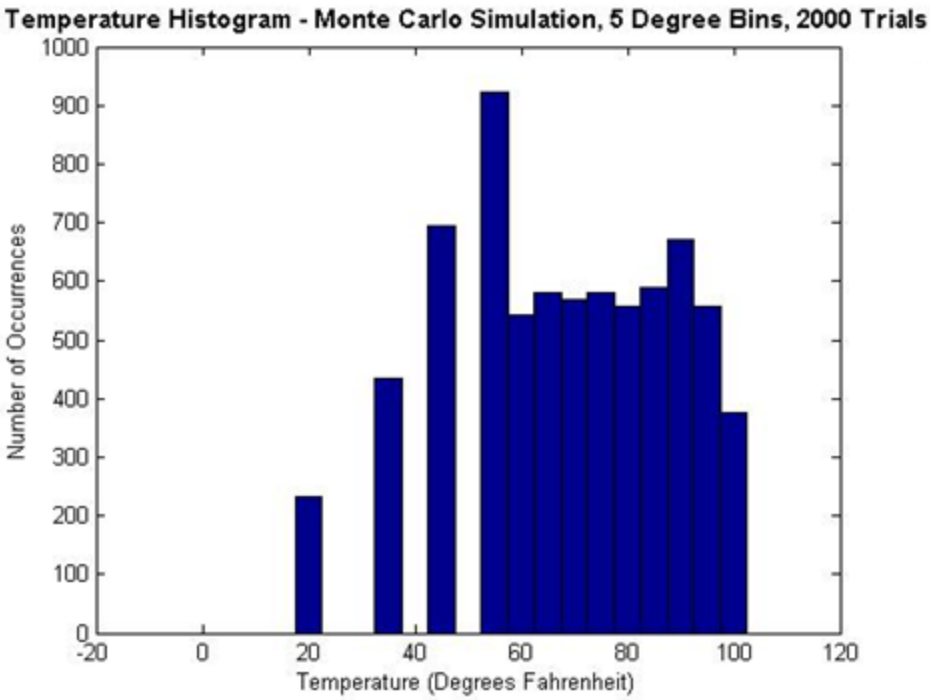

Figure 4.7: Temperature Histogram from Monte Carlo Simulation with 5 Degree Bins and 2000 Trials

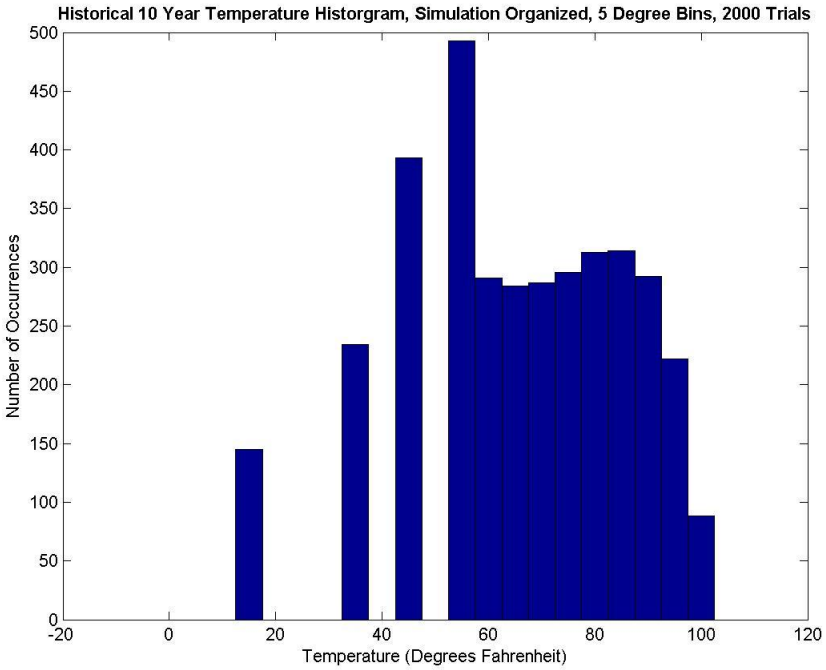

Figure 4.8: Historical 10 Year Temperature Histogram, Simulation Organized with 5 Degree Bins and 2000 Trials

The histogram in Figure 4.6 has a good distribution and a standard deviation of 14,276. This shows again that the Monte Carlo simulation is robust. The histogram in Figure 4.7 shows the simulated temperatures and closely matches the actual temperature histogram which has been organized in the same fashion as the simulation, shown in Figure 4.8. The leftmost four bars of Figures 4.7 and 4.8 have more occurrences because they cover a temperature range larger than the 5 degree bin. For information on the temperature ranges being considered refer to Chapter 2.

Break-Even Calculation

A break-even graph was created to illustrate the economic benefit of implementing a wind turbine. The break-even graph shown in Figure 4.9 includes present worth calculations, base cost of a wind turbine, and operations and maintenance costs for a 2.0 megawatt wind turbine. This graph is a representation of the averages of 2000, 20 year Monte Carlo simulations. The results from these simulations were compiled and simplified into Figure 4.9.

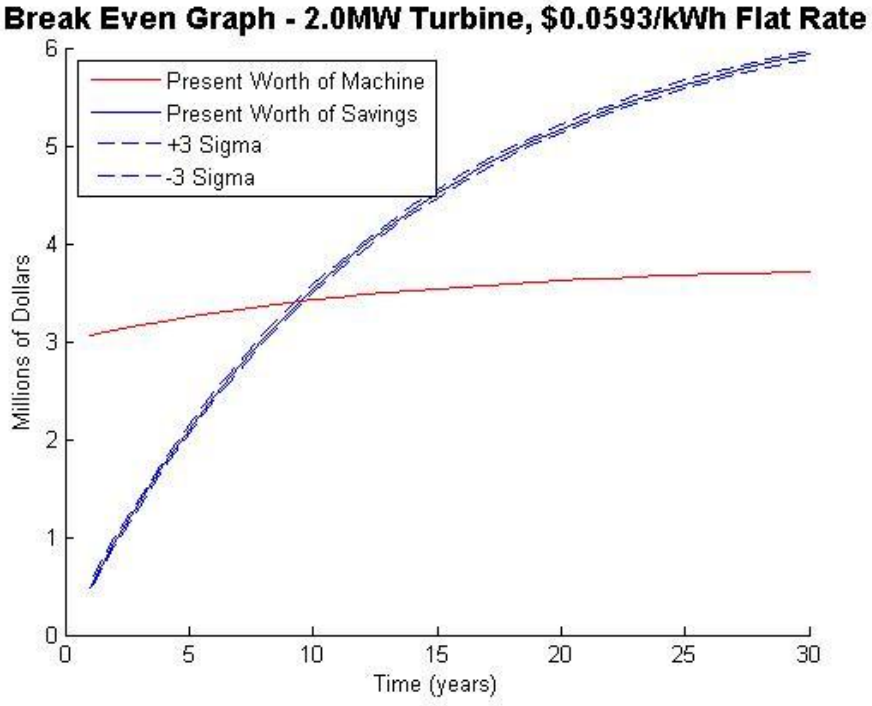

Figure 4.9: Break-Even Graph from Monte Carlo Simulation with Variance – 30 Years

Figure 4.9 shows two solid lines. The first solid line is the present worth of the machine; this line starts at 3 million dollars and ends at approximately 3.5 million dollars. This line is a representation of the present worth of the startup costs and operation and maintenance costs of the wind turbine. The second solid line represents the present worth of the savings created by the

wind turbine; this line starts at zero and ends at approximately 6 million dollars. This line is a record of the present worth of the money made from not having to purchase the amount of power generated. The two dashed lines surrounding the second solid line form a 99% confidence interval of savings from the wind turbine. The first 20 years of the graph in Figure 4.9 are based on annual averages for each year; the graph is extended out from 20 years to 30 years using the average annual value of the data found in this simulation.

Figure 4.9 shows a break-even point of approximately nine years and a maximum profit over a thirty year period of just fewer than three million dollars. Based off the Monte Carlo simulation, having a 2.0 megawatt wind turbine and a flat rate of 5.93 cents per kilowatt hour for energy generated is economically feasible with an estimated profit of 1.5 to 2 million dollars over the lifetime of the wind turbine.

Chapter 5 - Sensitivity Analysis

After verifying that the Monte Carlo simulation in Chapter 4 works as expected, a sensitivity analysis was conducted on the system. The purpose of the sensitivity analysis was to examine the effects on the system if two variables would change: turbine size or flat rate of energy. To accomplish this analysis the Monte Carlo simulation had to undergo some minor alterations. After the alterations were complete the sensitivity analysis was performed.

Assumptions/Conditions

The sensitivity analysis results examined in this chapter are based on the following assumptions and conditions:

- A flat rate structure is being used with a variable rate per kilowatt-hour.
- The upfront cost for a 2.0 megawatt wind turbine and the equipment required to connect it to the grid is 3,000,000 dollars.
- As wind turbine size increases by 1 megawatt upfront costs increase by 20% as suggested by Sunflower Electric Power Corporation.
- The wind turbine sizes used assume the necessary technology exists to design, build, install, and operate the turbine.
- Excess power produced by the wind turbine will be dumped at no cost onto the existing transmission system.
- The power dumped will be included in the operation and maintenance cost.
- Operation and maintenance costs are 0.7 cents per kilowatt-hour as suggested by the National Renewable Energy Laboratory (NREL) [20].

Monte Carlo Simulation Modification

In order to complete the sensitivity study the Monte Carlo simulation had to undergo one main change. In the original Monte Carlo simulation load was not a factor due to the fact that the wind turbine being used was smaller than the lowest load demand. In the sensitivity analysis the turbine size will be increased to sizes potentially larger than the load demand. This required the Monte Carlo simulation to provide an hourly load profile as well as an hourly energy generation

profile; records of energy sold, energy dumped onto the grid, and total energy generated need to be kept. To accomplish this a hourly load profile was developed in the same way as the hourly wind profile is created in Chapter 4. First, the two years (July 2009 through July 2011) of hourly load data were divided into matrices according to the predetermined temperature ranges. Next, histograms were created for each temperature range which allowed for probabilities for each of the bins in the histograms to be found. Finally, using these probabilities and generated random numbers the hourly load profile was created (for more detailed information see appropriate sections in Chapter 4). Figures 5.1 through 5.3 provide graphical interpretations of the load data. Figure 5.1 is a histogram of the entire load data. Figures 5.2 and 5.3 show a histogram and cumulative distribution graph for the 6:00pm hour in the 65 – 70 degree temperature range that has been used as an example in the previous chapter. For further explanation of Figures 5.1 through 5.3 please see relative discussions in Chapter 4 – Monte Carlo Simulation.

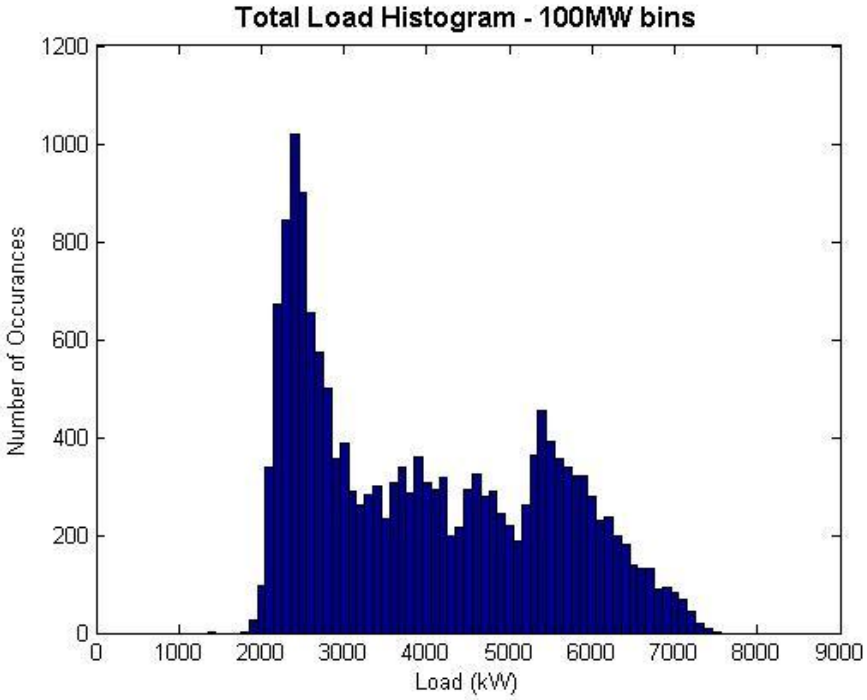

Figure 5.1: Total Load Histogram (2 years) with 100MW Bins

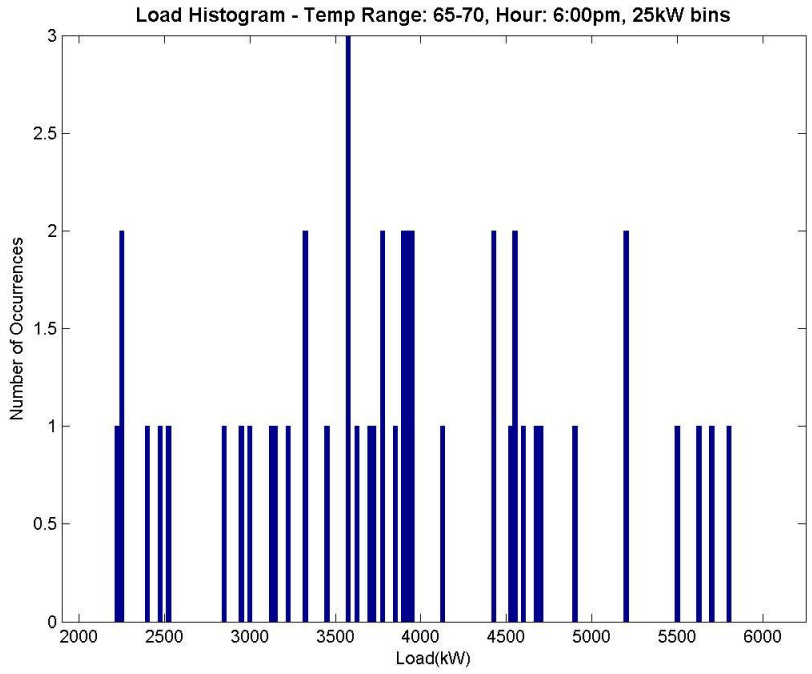

Figure 5.2: Load Histogram for 65-70 Temperature Range in the 6:00pm Hour with 25kW Bins

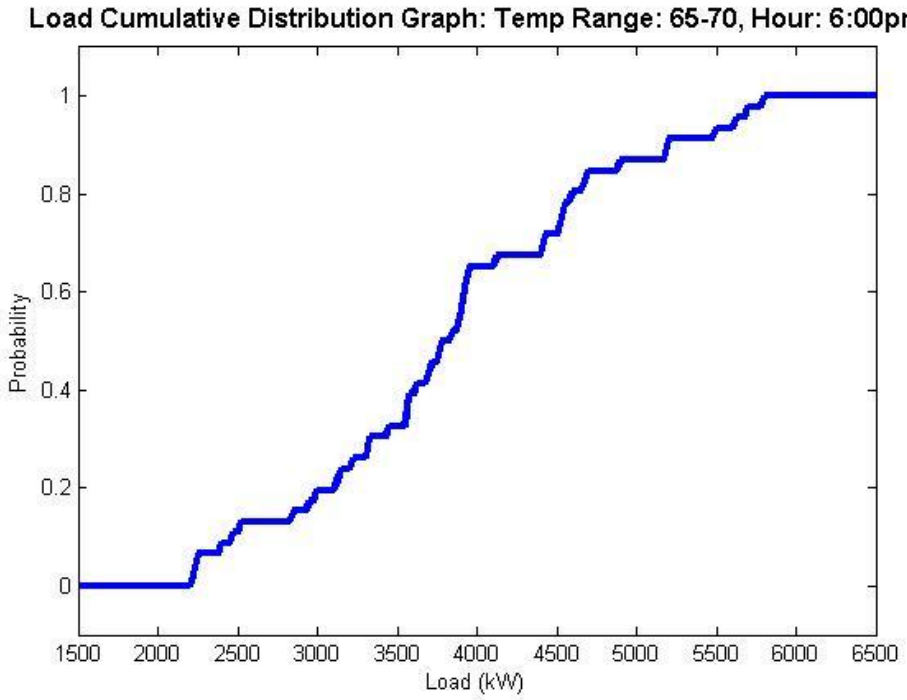

Figure 5.3: Load Cumulative Distribution Graph for 65 - 70 Temperature Range in the 6:00pm Hour

Figure 5.2 shows gaps in between some of the bars in the histogram. This means that there were no load readings in that 25kW bin. Because there were no historical readings in these bins the Monte Carlo simulation cannot choose these power levels. As shown in Figure 5.3, when these gaps occur there are no increases in probability; this means that the only load value that can be picked on the horizontal lines in Figure 5.3 is the leftmost value.

Sensitivity Analysis

The first part of the sensitivity analysis was to see how turbine size affected the results. To accomplish this power curves were created for 3.0, 4.0, 5.0, and 6.0 megawatt wind turbines; all power curves are shown in Appendix C. After creating the power curves the Monte Carlo simulation was run for each turbine size individually and a measure of variance was calculated; the results are shown in Table 5.1.

Table 5.1: Monte Carlo Simulation Turbine Size Sensitivity Analysis

	Turbine Size				
	2.0 MW	**3.0 MW**	**4.0 MW**	**5.0 MW**	**6.0 MW**
Start-up Cost					
20%/MW	$3,000,000	$3,600,000	$4,320,000	$5,184,000	$6,220,800
Total Generation					
Maximum	182,023 MWh	273,050 MWh	364,215 MWh	454,718 MWh	546,863 MWh
Average	181,050 MWh	271,500 MWh	362,030 MWh	452,620 MWh	543,170 MWh
Minimum	179,606 MWh	269,900 MWh	358,916 MWh	449,324 MWh	540,592 MWh
% Difference	1.346%	1.167%	1.476%	1.200%	1.160%
Total Energy Dump					
Maximum	0 MWh	6,197 MWh	26,583 MWh	60,009 MWh	108,358 MWh
Average	0 MWh	5,956 MWh	25,663 MWh	59,039 MWh	106,470 MWh
Minimum	0 MWh	5,752 MWh	25,066 MWh	57,750 MWh	104,516 MWh
% Difference	0.000%	7.736%	6.052%	3.912%	3.676%
Total Generation for Sale					
Maximum	182,023 MWh	267,160 MWh	338,569 MWh	396,220 MWh	440,716 MWh
Average	181,050 MWh	265,550 MWh	336,370 MWh	393,580 MWh	436,700 MWh
Minimum	179,606 MWh	263,700 MWh	332,914 MWh	390,430 MWh	433,051 MWh
% Difference	1.346%	1.312%	1.699%	1.483%	1.770%
Total Savings					
Maximum	$10,794,000	$15,843,000	$20,077,000	$23,496,000	$26,134,000
Average	$10,736,000	$15,747,000	$19,946,000	$23,339,000	$25,896,000
Minimum	$10,651,000	$15,638,000	$19,742,000	$23,153,000	$25,680,000
% Difference	1.343%	1.311%	1.697%	1.481%	1.768%
Total Present Worth					
Maximum	$5,306,000	$7,774,700	$9,857,800	$11,539,000	$12,866,000
Average	$5,271,000	$7,728,900	$9,791,000	$11,455,000	$12,712,000
Minimum	$5,235,000	$7,680,000	$9,692,600	$11,364,000	$12,598,000
% Difference	1.356%	1.233%	1.704%	1.540%	2.127%

Table 5.1 shows that as turbine size increases the amount of total generation increases as well. However, when the turbine is larger than 4.0MW the amount of power being dumped onto the grid increases at a fast rate, almost negating the benefits of a larger turbine. Even with these extreme power dumps, the present worth of owning a large turbine continues to increase; the increase is approximately one million dollars a year per megawatt of turbine increase compared to two million dollars with the turbines under 4.0MW. The results from Table 5.1 are further

examined in Figures 5.4 through 5.8. These figures show the total generation histograms for each turbine size from 250, 20 year Monte Carlo simulations.

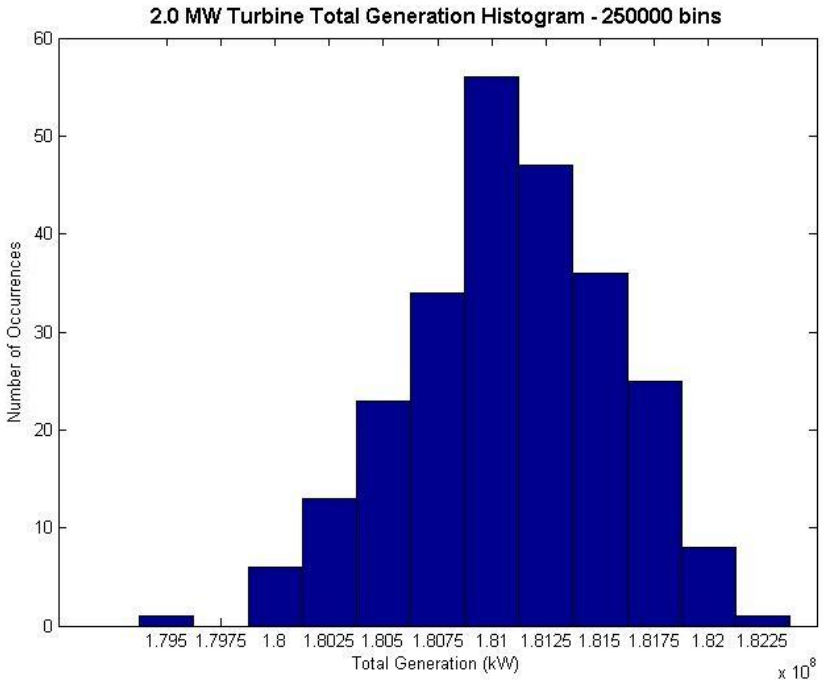

Figure 5.4: 2.0MW Wind Turbine Total Generation Histogram with 250,000kW Bins

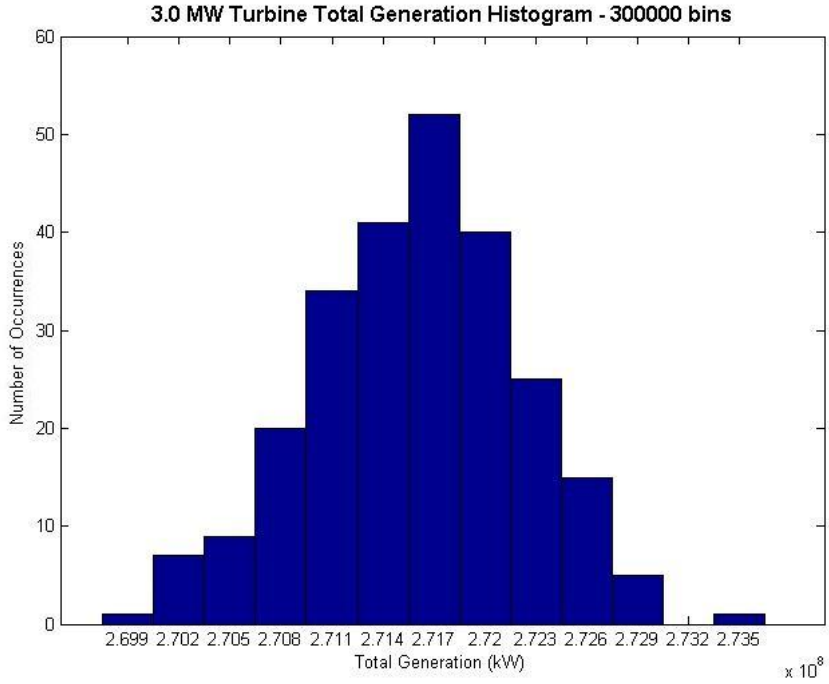

Figure 5.5: 3.0MW Wind Turbine Total Generation Histogram with 300,000kW Bins

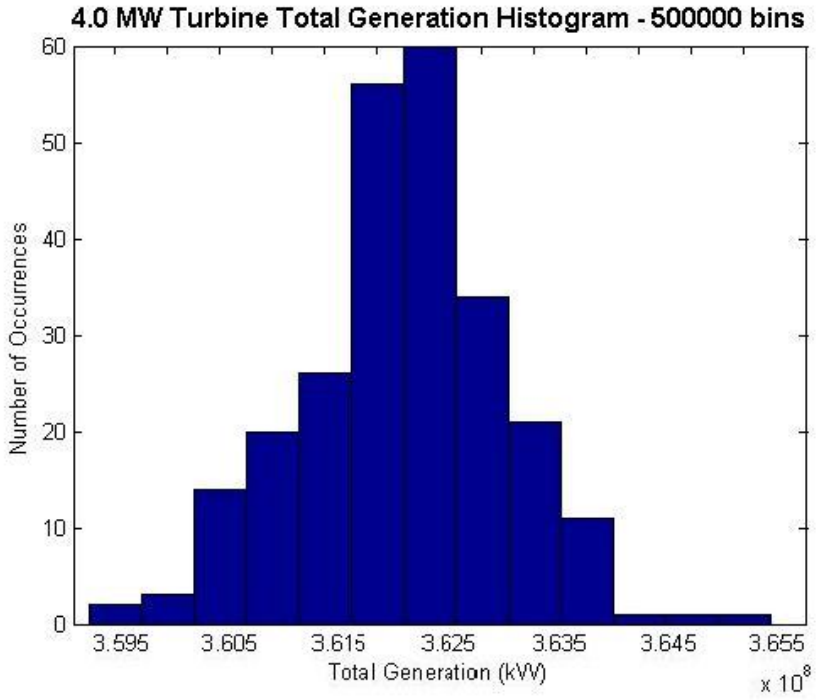

Figure 5.6: 4.0MW Wind Turbine Total Generation Histogram with 500,000kW Bins

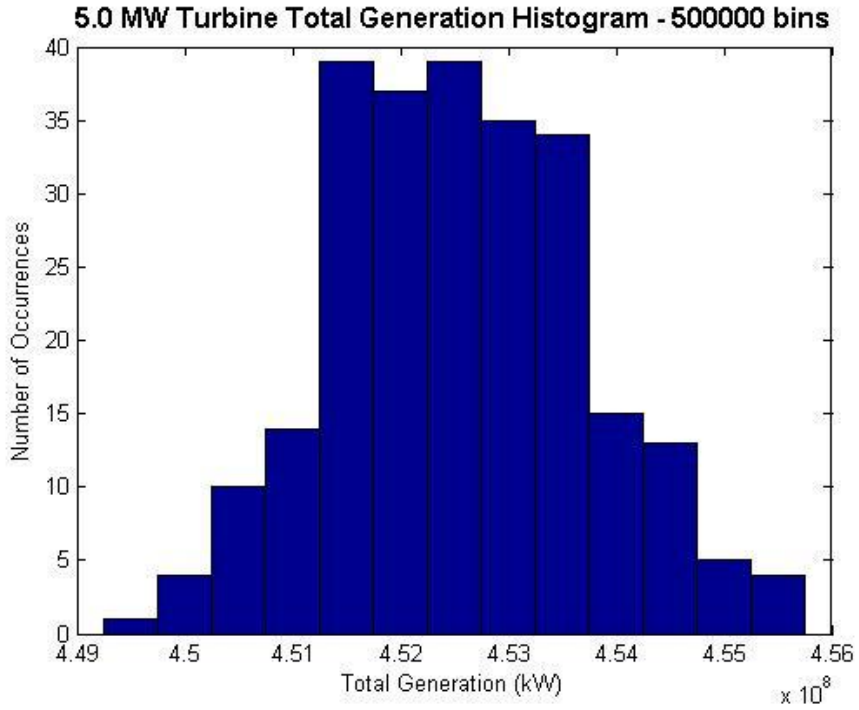

Figure 5.7: 5.0MW Wind Turbine Total Generation Histogram with 500,000kW Bins

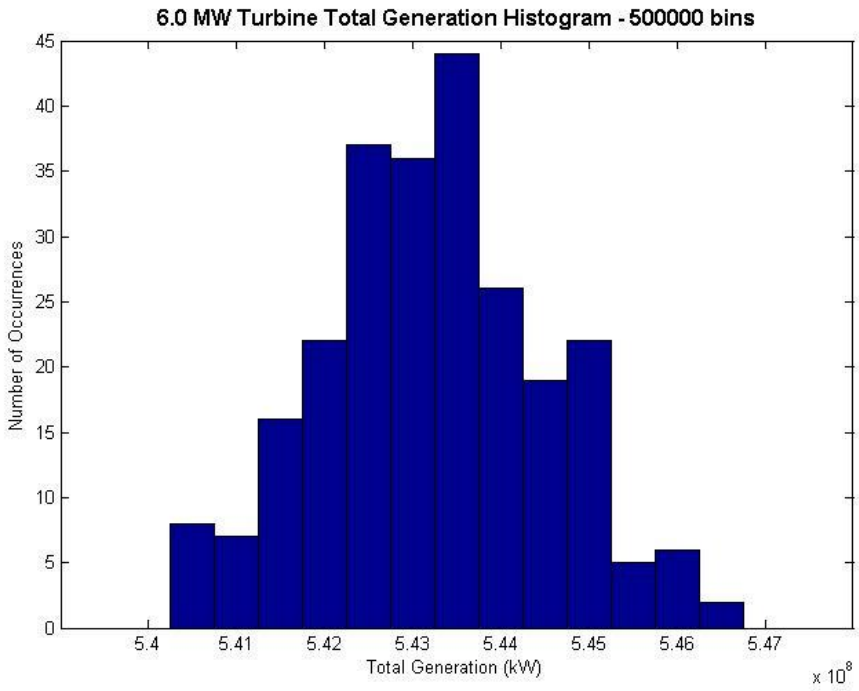

Figure 5.8: 6.0MW Wind Turbine Total Generation Histogram with 500,000kW Bins

As you can see from Table 5.1 and Figures 5.4 through 5.8, the results provided by the Monte Carlo simulation have low variance and good distributions. The spread of almost all the results is under 2%. The only category that the percent difference is larger is the power dump category; this is due to the limited amount of load data, two years of hourly data, available to be used in the simulation. For a closer look at the data above the mean values and the standard deviations of the histograms in Figures 5.4 through 5.8 are provided in Table 5.2.

Table 5.2: Sensitivity Analysis Total Generation Standard Deviations

Turbine Size	Total Generation (MWh)	Total Generation Standard Deviation (MWh)
2.0 MW	181,050	474.4
3.0 MW	271,500	619.4
4.0 MW	362,030	931.6
5.0 MW	452,620	1,161.5
6.0 MW	543,170	1,278.5

After examining the data provided in Tables 5.1 and 5.2 and Figures 5.4 through 5.8 a sensitivity analysis of the flat rate power selling price was performed. Flat rates of 3.0, 4.0, 5.0, 6.0, and 7.0 cents per kilowatt hour were used. The total savings was then computed; the results are shown in Table 5.3.

Table 5.3: 20 Year Present Worth Savings Sensitivity Analysis with Varying Rate and Turbine Size

20 Year Present Worth Savings Comparison

Turbine Size (MW) \ Flat Rate ($/kWh)	0.03	0.04	0.05	0.06	0.07
2.0	$ 2,666,400	$ 3,555,200	$ 4,443,900	$ 5,332,700	$ 6,221,500
3.0	$ 3,910,800	$ 5,214,400	$ 6,518,000	$ 7,821,600	$ 9,125,200
4.0	$ 4,953,800	$ 6,605,100	$ 8,256,300	$ 9,907,600	$ 11,559,000
5.0	$ 5,796,300	$ 7,728,500	$ 9,660,600	$ 11,593,000	$ 13,525,000
6.0	$ 6,431,400	$ 8,575,200	$ 10,719,000	$ 12,863,000	$ 15,007,000

Table 5.3 shows that as turbine size and flat rate increase total twenty-year savings also increase. The results shown in Table 5.3 are before operation and maintenance costs have been computed on either the sold or dumped power. Using the standard deviations in Table 5.2 with the present worth savings data in Table 5.3 a 99% confidence interval can be created for each turbine size. Table 5.4 and Figure 5.10 provide an example 99% confidence interval for the $0.06/kWh rate.

Table 5.4: 20 Year Preset Worth Savings 99% Confidence Interval for $0.06/kWh Flat Rate

20 Year Present Worth Savings 99% Confidence Interval for $0.06/kWh Flat Rate			
Turbine Size	**- 3σ**	**Mean Value**	**+3σ**
2.0 MW	$ 5,247,308	$ 5,332,700	$ 5,418,092
3.0 MW	$ 7,710,108	$ 7,821,600	$ 7,933,092
4.0 MW	$ 9,739,912	$ 9,907,600	$ 10,075,288
5.0 MW	$ 11,383,930	$ 11,593,000	$ 11,802,070
6.0 MW	$ 12,632,870	$ 12,863,000	$ 13,093,130

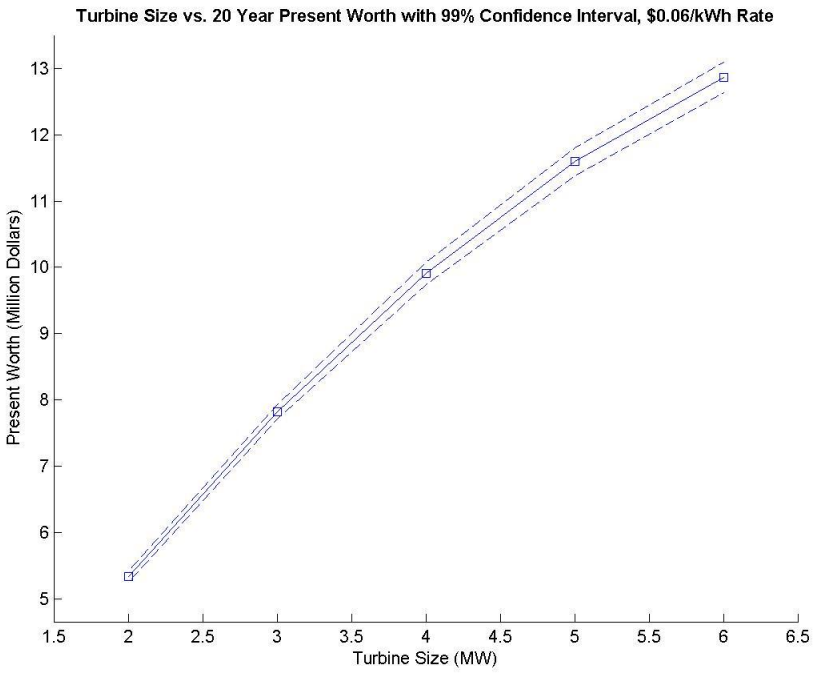

Figure 5.9: Turbine Size versus 20 Year Present Worth with 99% Confidence Interval and $0.06/kWh Rate

Operation and maintenance costs are included in the following break-even graphs. Figures 5.11 through 5.15 show present worth break-even graphs for each turbine size with variable flat rates.

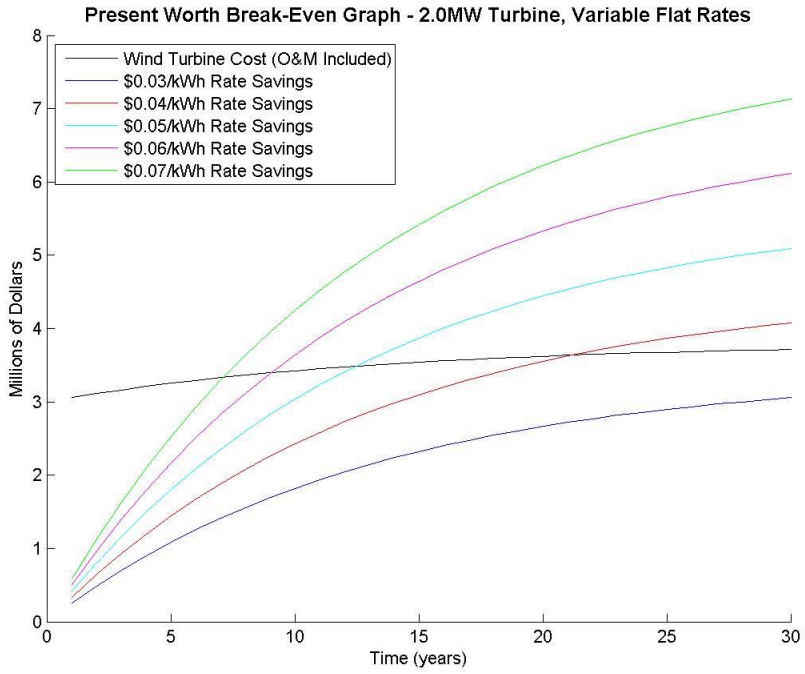

Figure 5.10: Present Worth Break-Even Graph with 2.0 MW Turbine and Variable Flat Rates

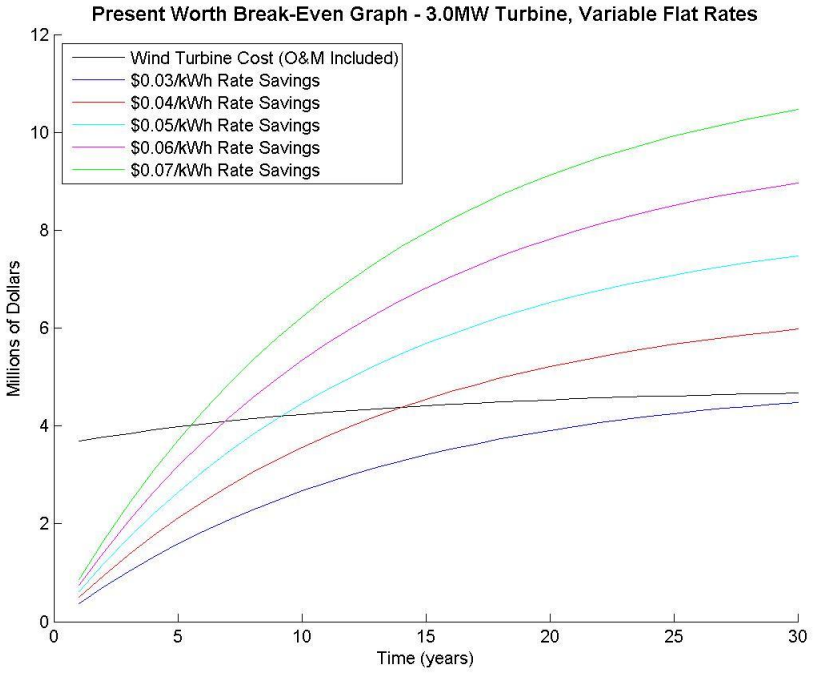

Figure 5.11: Present Worth Break-Even Graph with 3.0 MW Turbine and Variable Flat Rates

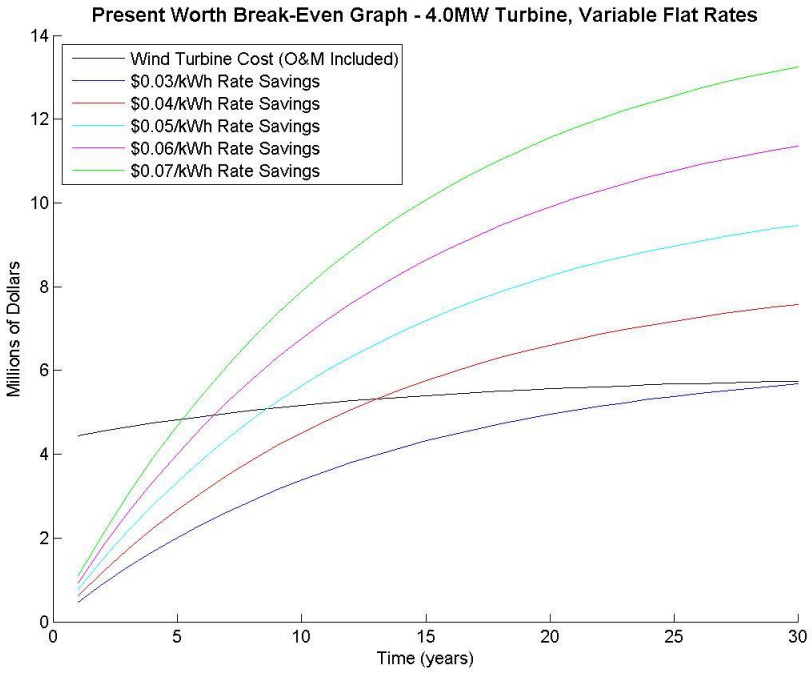

Figure 5.12: Present Worth Break-Even Graph with 4.0 MW Turbine and Variable Flat Rates

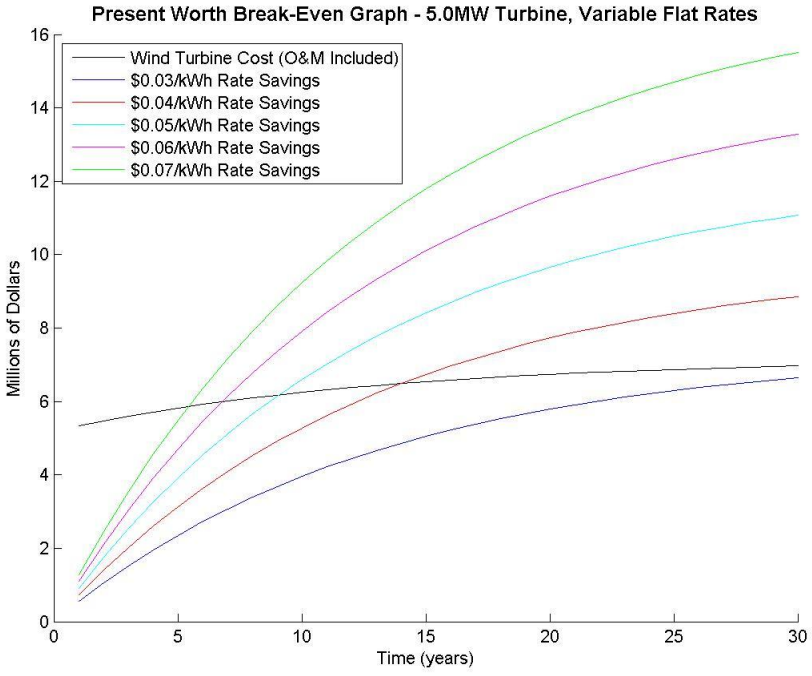

Figure 5.13: Present Worth Break-Even Graph with 5.0 MW Turbine and Variable Flat Rates

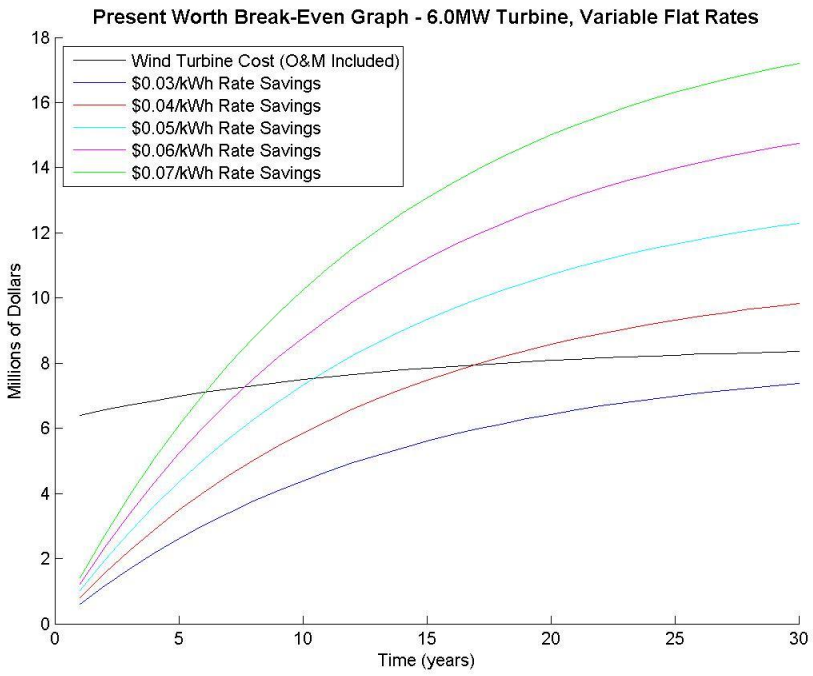

Figure 5.14: Present Worth Break-Even Graph with 6.0 MW Turbine and Variable Flat Rates

Conclusion

Figures 5.11 through 5.15 show how rate, turbine size, and profitability all relate. Looking at the graphs it is evident that at 20 years some profit will be made with a rate as low as $0.04/kWh; the break-even point for the rate across the turbines is near or just below 20 years. One interesting thing to note is that after the turbine reaches near the size of the load (5.0 MW and 6.0 MW) the profitability is very similar; this is most likely due to the fact that the excess power generated is getting dumped onto the grid at no profit while operation and maintenance costs are still being paid. This additional cost helps to balance the profitability; without it the 6.0MW turbine would be better in direct comparison with the 5.0 MW turbine. Overall the differences between the turbines and the percent errors calculated were much lower than expected. Figure 5.16 and Table 5.5 show the break-even points for the various turbine sizes with a rate of $0.06/kWh.

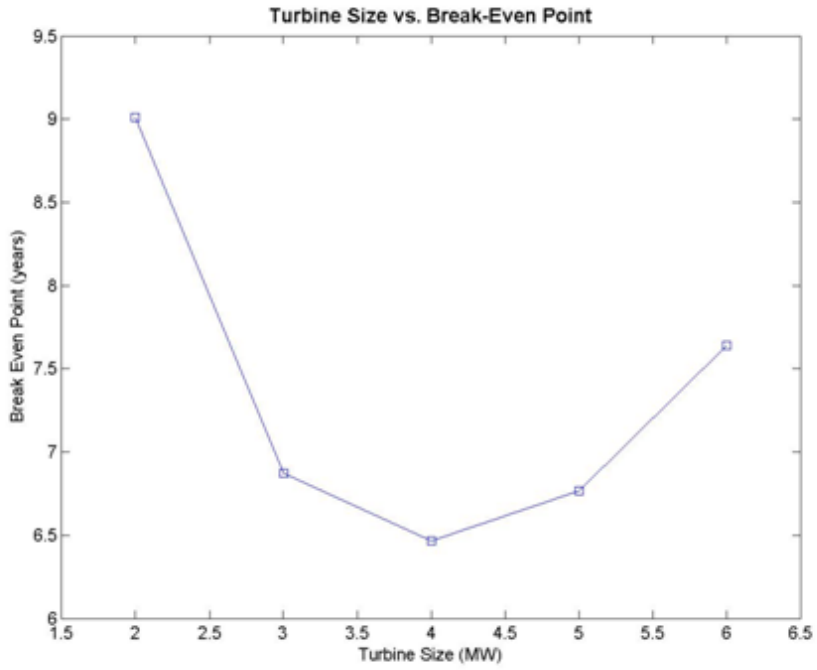

Figure 5.15: Turbine Size versus Break-Even Point in Years

Table 5.5: Turbine Size Specific Break-Even Points with $0.06/kWh Rate

Turbine Size Specific Break-Even Points with $0.06/kWh Rate	
Turbine Size (MW)	**Break-Even Point (Years)**
2.0	9.0128
3.0	6.8707
4.0	6.4677
5.0	6.7677
6.0	7.6441

Figure 5.16 and Table 5.5 show that the longest break-even period at $0.06/kWh is just over 9 years while the shortest is just under 6.5. The shortest break-even period occurs with a 4.0MW wind turbine; the 3.0MW and 5.0MW turbine's break-even periods are both less than 6 months longer than the 4.0MW while the 2.0MW and 6.0MW turbines have noticeably longer break-even periods. Based off of this data it is evident that the best single turbine in terms of break-even period would have a size close to 4.0MW; this simulation only considers single wind turbines, the results would not be the same with multiple smaller turbines.

Chapter 6 - Energy Storage Analysis

After completion of the sensitivity analysis in Chapter 5, it was decided that an energy storage analysis should be performed as well; specifically an examination of battery storage as a possible energy storage solution. Battery storage systems are commonly believed to be very expensive and never able to create enough savings to get a full return on the investment. The goal of the energy storage analysis is to determine if a battery storage system is economically feasible. The analysis in this chapter follows the same steps as the Monte Carlo simulation in Chapter 4 with a few additions for battery storage that will be described in the following sections.

Assumptions/Conditions

The battery storage analysis performed in this chapter is based off of the following assumptions and conditions:

- A flat energy rate of $0.0593/kWh will be used throughout the analysis.
- The analysis will examine the 4.0MW and 6.0MW turbines described in Chapter 5 with various battery storage sizes.
- The upfront cost for a 4.0MW wind turbine and the equipment required to connect it to the grid is 4,320,000 dollars.
- The upfront cost for a 6.0MW wind turbine and the equipment required to connect it to the grid is 6,220,800 dollars.
- The wind turbine sizes used assume the necessary technology exists to design, build, install, and operate the turbine.
- Excess power produced by the wind turbine that is not used by the batteries will be dumped at no cost onto the existing transmission system.
- The power dumped will be included in the operation and maintenance cost.
- Operation and maintenance costs are 0.7 cents per kilowatt-hour as suggested by the National Renewable Energy Laboratory (NREL) [20].
- The upfront cost for the batteries and necessary power electronics is $530/kW [21].

- The replacement cost for the batteries is $325/kW [21].
- The operation and maintenance cost for the batteries is $15/kW annually [21].
- Battery life is assumed to be 5 years.
- The batteries are 85% efficient while charging and 85% efficient while discharging [21].
- The batteries have a maximum charge and discharge per hour of 25% of the capacity of the battery system [22].
- The batteries have a minimum discharge level of 10% of the capacity of the battery system [22].

Monte Carlo Simulation Modification

The battery storage analysis requires minor alterations to the Monte Carlo simulation that was described in Chapters 4 and 5; additional inputs need to be added for battery constraints and the battery analysis needs to be added. The addition of the additional inputs is easy and straight-forward. The battery analysis is a little more complicated but not too difficult. The battery analysis needs to be added into the simulation at the end of each 20-year trial after the turbine simulation has been run. At this point matrices exist containing hourly data for total power generated and total load; these are the two matrices needed for the battery storage analysis. A loop was created that steps through the 20 years of data hour by hour, day by day, from start to finish. For each hour the battery storage analysis first determines if there is excess generation or excess load. If there is excess generation in the analysis it then checks the battery level; if the battery is full no energy is added, if the battery is not full energy is added either until the battery is full, until there is no energy to add, or until the battery has accepted the maximum amount of energy it can in that hour. Conversely, if there is excess load the analysis checks the battery level; if the battery is at the minimum allowed level then no energy is drawn from the battery, if the battery is not at its minimum level then energy is drawn from the battery until the battery is at the minimum level, until no more energy needs to be drawn, or until the maximum amount of energy has been drawn from the battery for the hour in question. The battery storage analysis keeps track of the amount of energy in the battery and a record of the amount of energy drawn from the battery. Figure 6.1 shows an example of the battery storage level for one year and Figure 6.2 shows an example of the battery storage level for 250 hours.

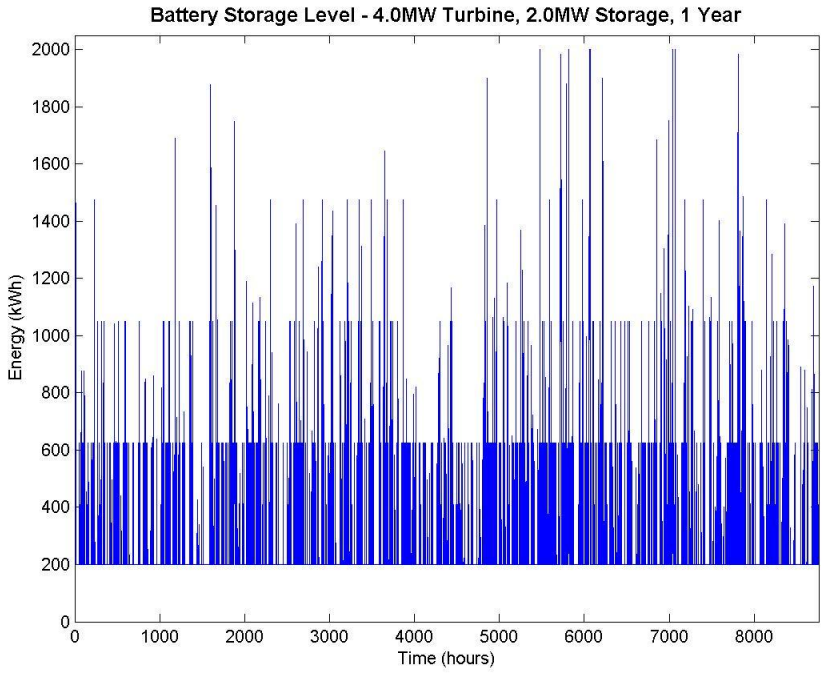

Figure 6.1: Battery Storage Level Example with 4.0MW Turbine and 2.0 MW Storage for 1 Year

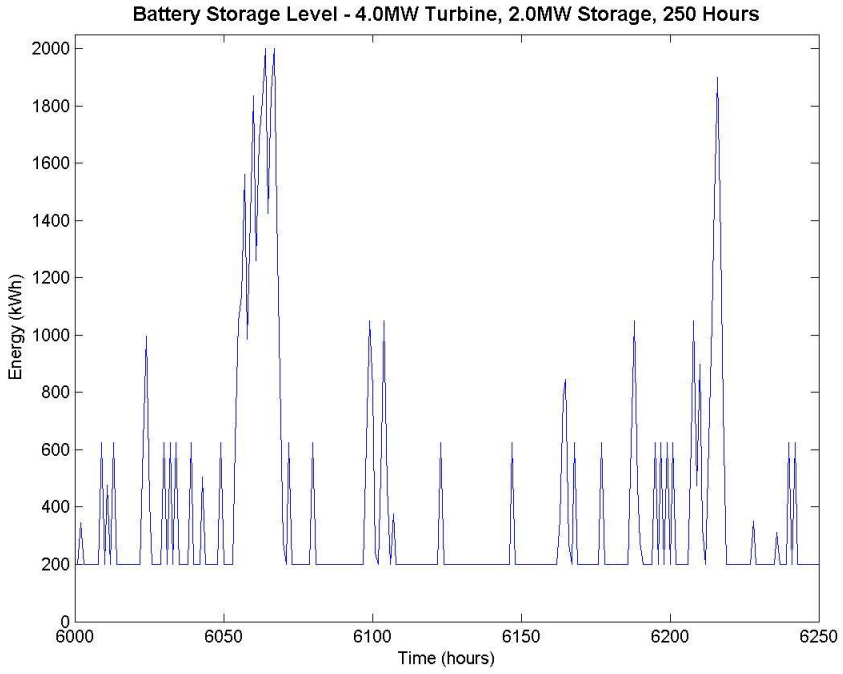

Figure 6.2: Battery Storage Level Example with 4.0MW Turbine and 2.0 MW Storage for 250 Hours

Figures 6.1 and 6.2 show the power stored in the battery system as time progresses. It is evident from the figures that the battery system is obeying its constraints; the battery never discharges below 10% and never overcharges. The battery also does not drop from fully charged to discharged in an hour. Figure 6.2 shows that the battery spends more time at minimal charge than charged over the course of 250 hours; this is not unexpected as the majority of the power produced by a 4.0MW wind turbine should be able to be directly used by the load on the grid.

Battery Storage Analysis

The first part of the battery storage analysis was to determine what size of wind turbines and battery storage to use. The Monte Carlo simulation was taking over 10 hours to run for 250 trials so it was decided to keep the storage analysis brief. In the end it was decided to perform analysis on the 4.0 MW and 6.0 MW wind turbines; these were chosen because turbines smaller than 4.0 MW had very little power that was not consumed by the grid. It was then decided that battery storage sizes of 25%, 50%, and 75% of the turbine size in question were going to be used for the analysis. Table 6.1 shows the average annual results found from the battery storage analysis.

Table 6.1: Battery Storage Analysis Average Annual Results

Average Annual Battery Storage Analysis

Turbine Size (MW)	4.0			6.0		
Battery Size (MW)	1.0	2.0	3.0	1.5	3.0	4.5
Average Annual Battery Energy Return Mean (MWh)	226.1	484.7	663.2	806.5	1491.3	2075.2
Annual Battery Energy Return Standard Deviation (MWh)	2.5866	6.0023	7.4827	4.0581	8.6097	13.001

Table 6.1 shows that as the turbines get larger and the storage gets larger the amount of annual energy used from the battery increases. The table also shows that the standard deviation in the 250 trials is very low. Figures 6.3 through 6.8 show histograms of total energy returned from the battery system over the 250, 20 year simulations; the corresponding standard deviations are show in Table 6.1 above.

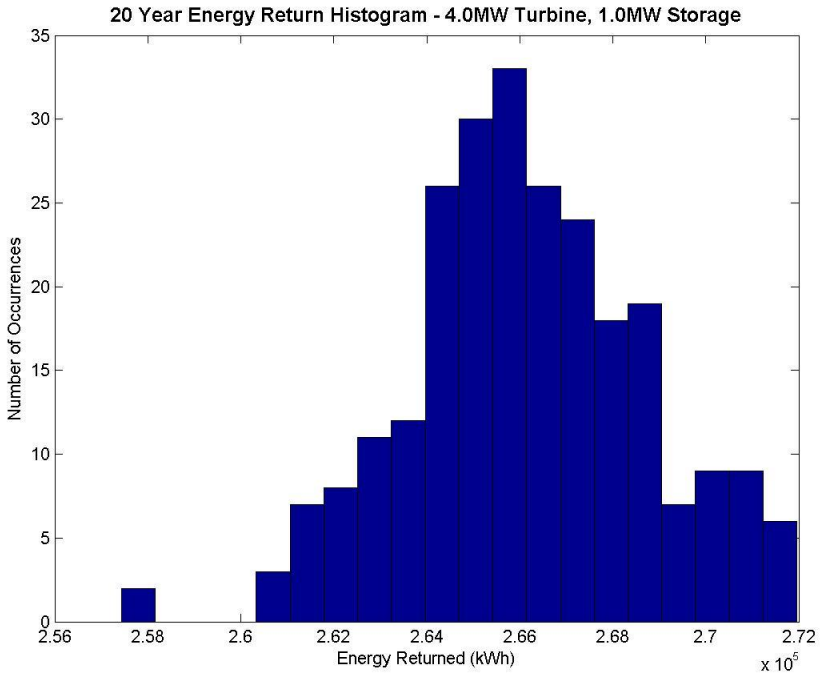

Figure 6.3: 20 Year Energy Return Histogram with 4.0MW Turbine, 1.0MW Storage, and 250 Trials

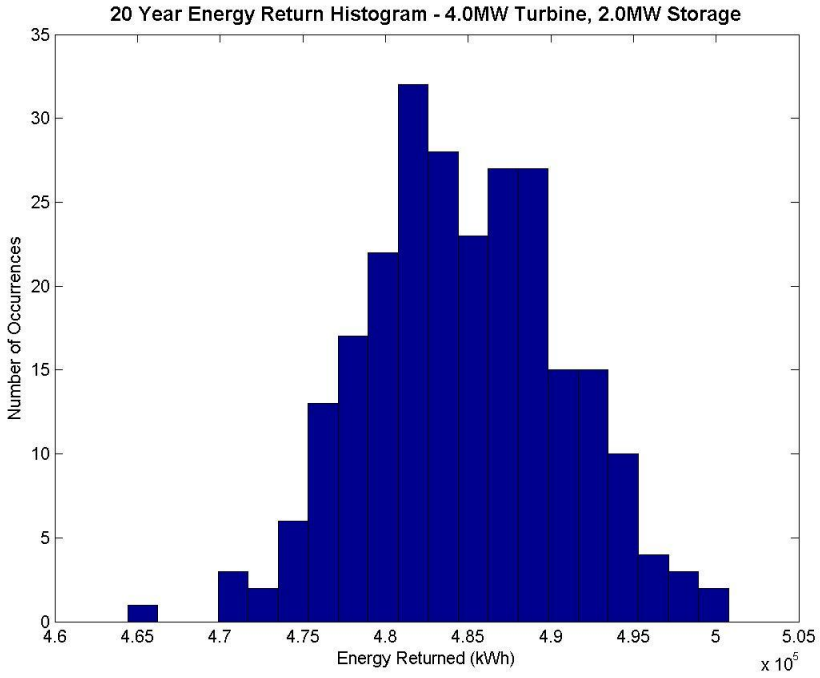

Figure 6.4: 20 Year Energy Return Histogram with 4.0MW Turbine, 2.0MW Storage, and 250 Trials

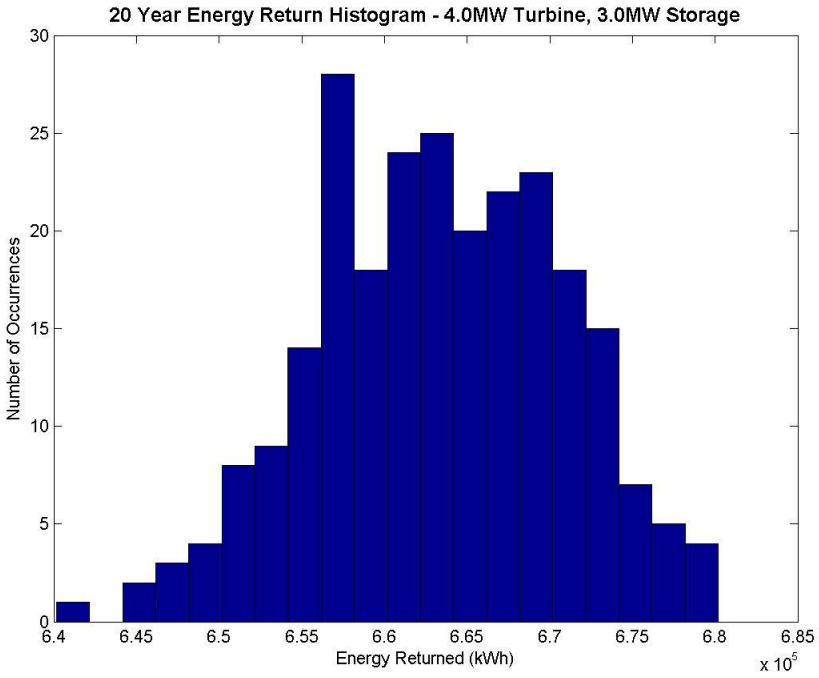

Figure 6.5: 20 Year Energy Return Histogram with 4.0MW Turbine, 3.0MW Storage, and 250 Trials

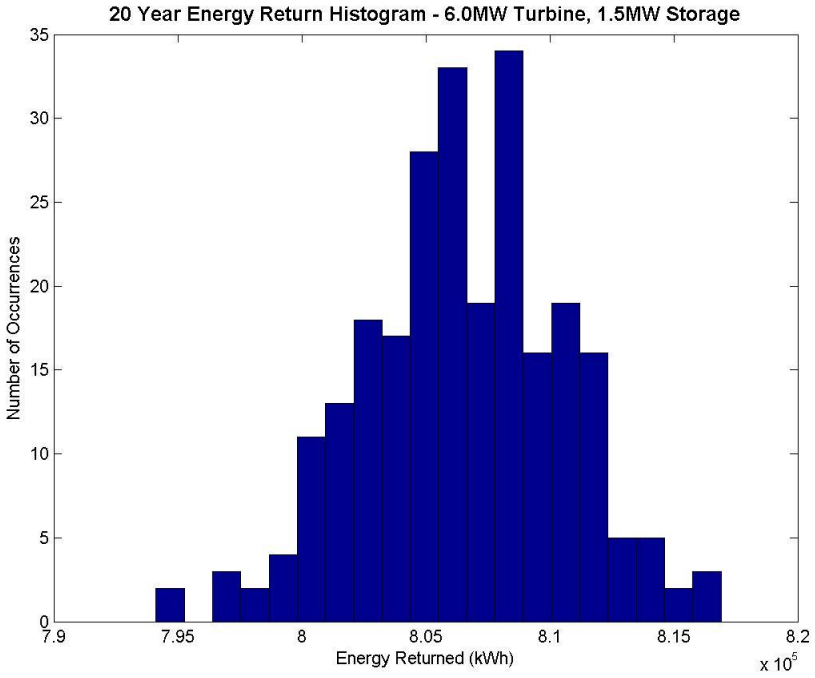

Figure 6.6: 20 Year Energy Return Histogram with 6.0MW Turbine, 1.5MW Storage, and 250 Trials

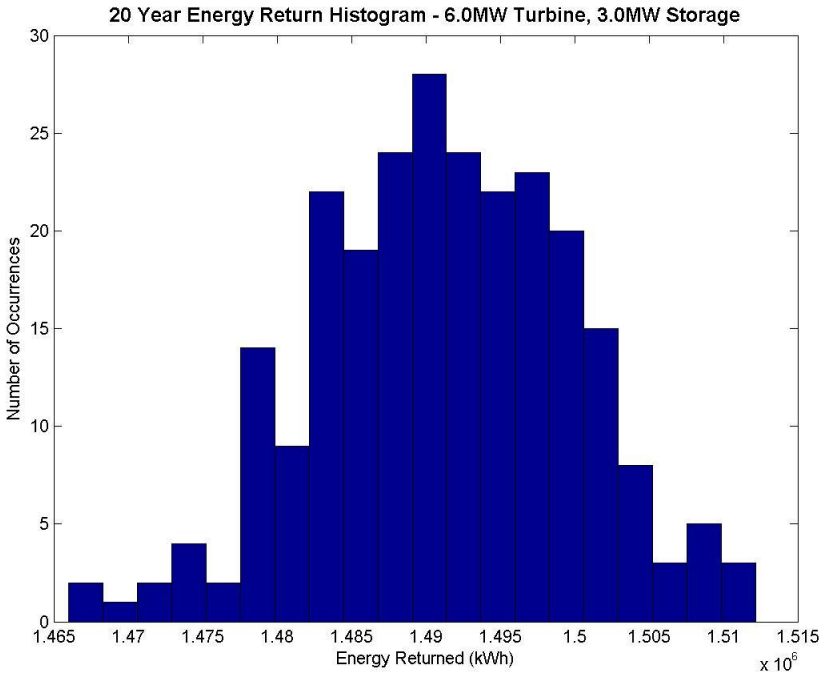

Figure 6.7: 20 Year Energy Return Histogram with 6.0MW Turbine, 3.0MW Storage, and 250 Trials

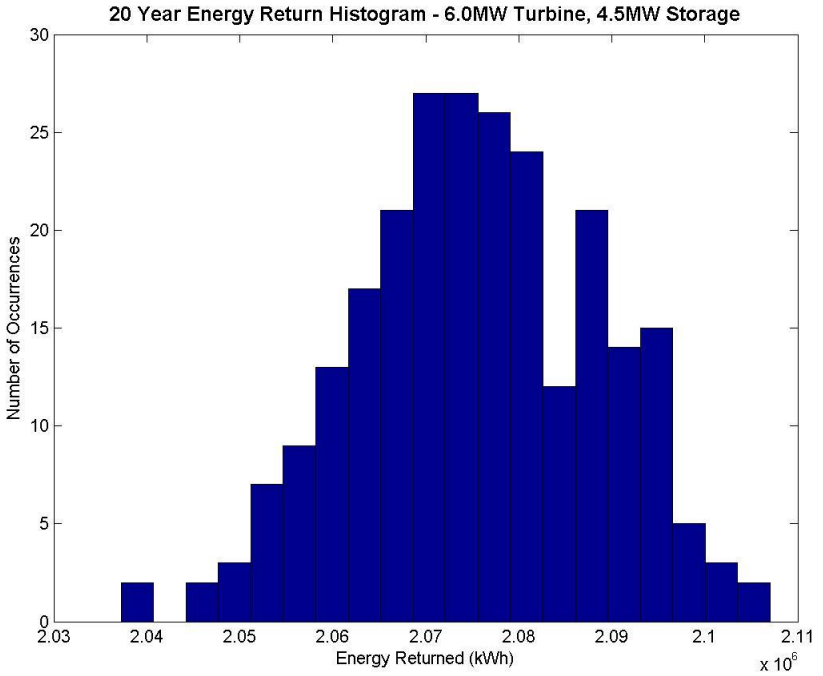

Figure 6.8: 20 Year Energy Return Histogram with 6.0MW Turbine, 4.5MW Storage, and 250 Trials

As you can see from Table 6.1 and Figures 6.3 through 6.8, the results provided by the Monte Carlo simulation for energy storage have low variance and good distributions. The difference spread, the percent of the mean that equals the distribution, of almost all the results is under 2%. For a closer look at the data above the standard deviations of the histograms in Figures 6.3 through 6.8 were provided in Table 6.1 prior to the figures.

Results

Upon completion of the analysis outlined in the above sections the output data was organized into a series of break-even graphs. Three different break-even graphs were created for comparison; a break-even graph of total savings without storage, a break-even graph for only the battery storage system, and a break-even graph of the entire generation system. Figures 6.9 through 6.15 show the break-even graphs for the 4.0MW turbine analysis.

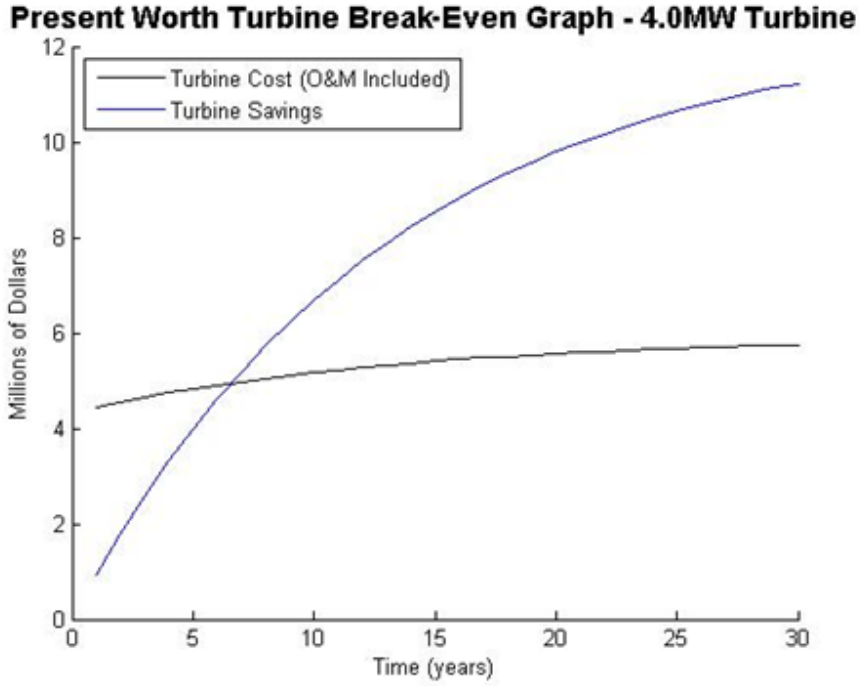

Figure 6.9: Present Worth Break-Even Graph for 4.0MW Turbine

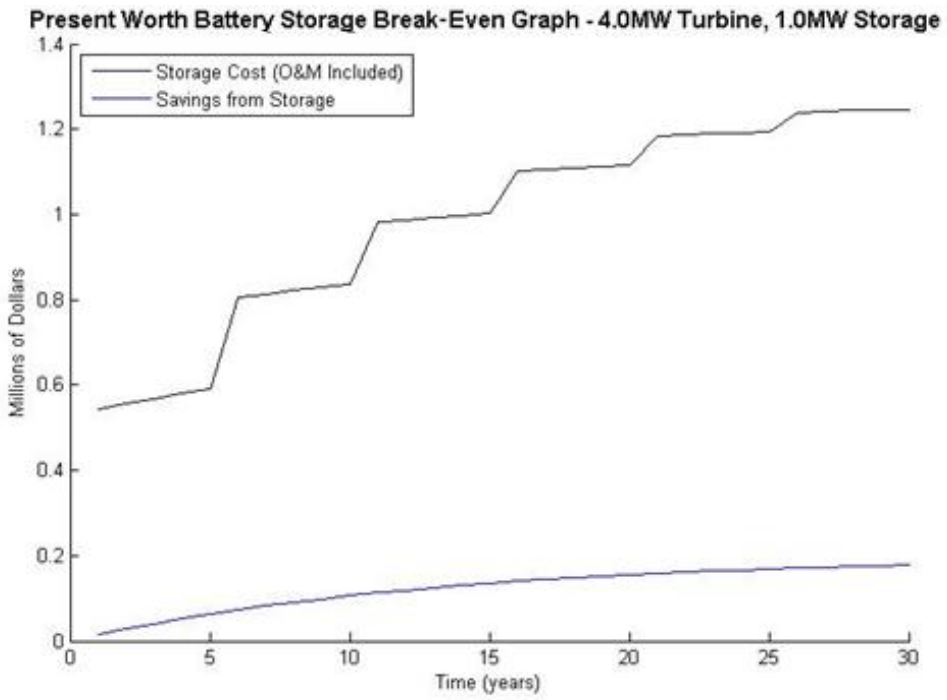

Figure 6.10: Present Worth Battery Storage Only Break-Even Graph for 4.0MW Turbine with 1.0MW Storage

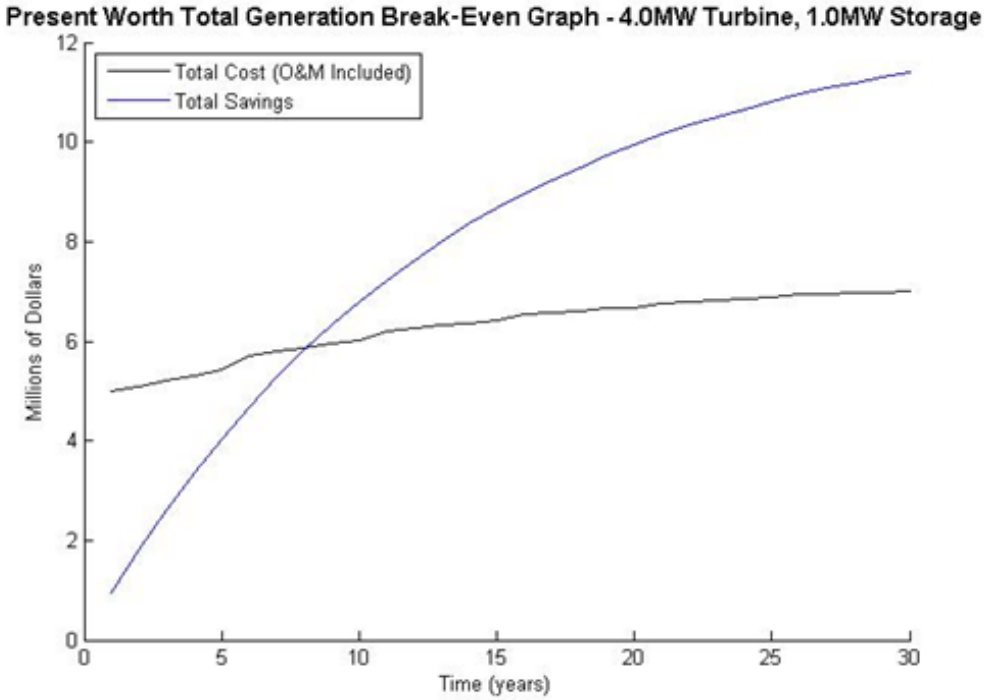

Figure 6.11: Present Worth Total Generation Break-Even Graph for 4.0MW Turbine with 1.0MW Storage

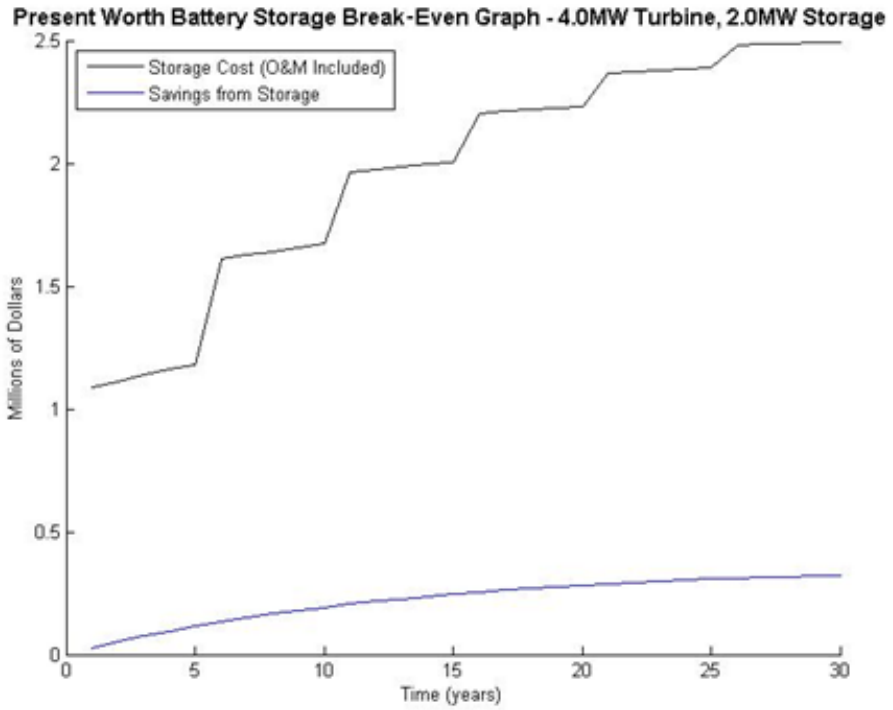

Figure 6.12: Present Worth Battery Storage Only Break-Even Graph for 4.0MW Turbine with 2.0MW Storage

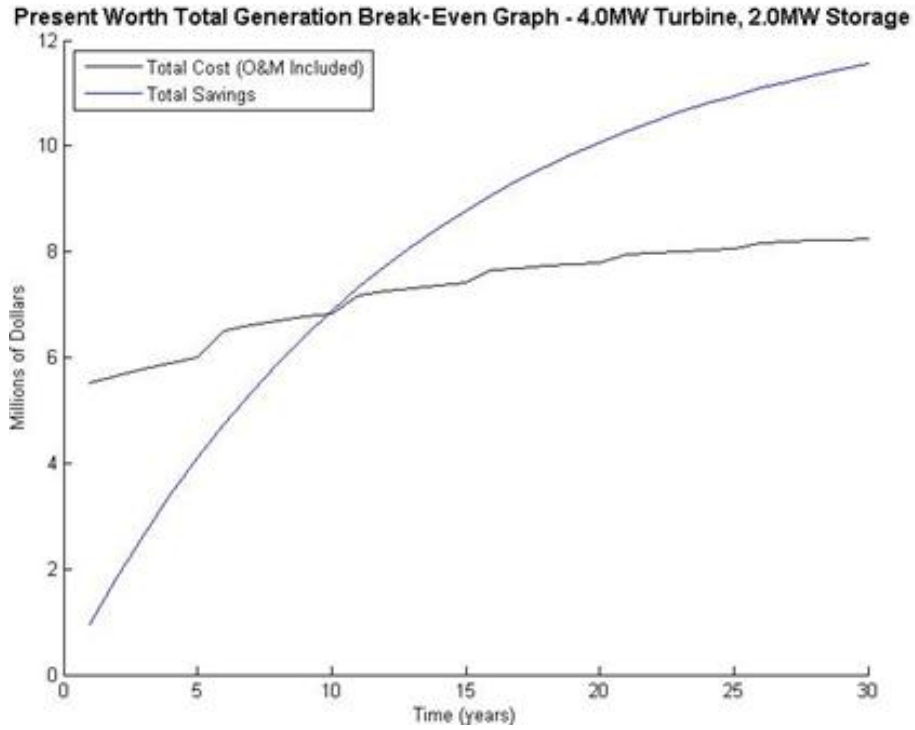

Figure 6.13: Present Worth Total Generation Break-Even Graph for 4.0MW Turbine with 2.0MW Storage

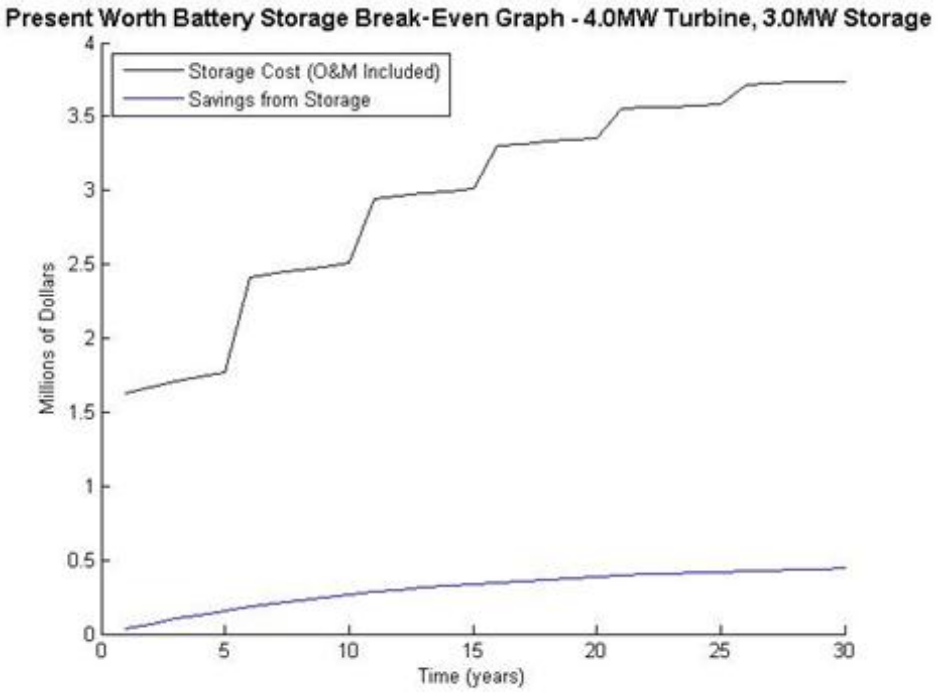

Figure 6.14: Present Worth Battery Storage Only Break-Even Graph for 4.0MW Turbine with 3.0MW Storage

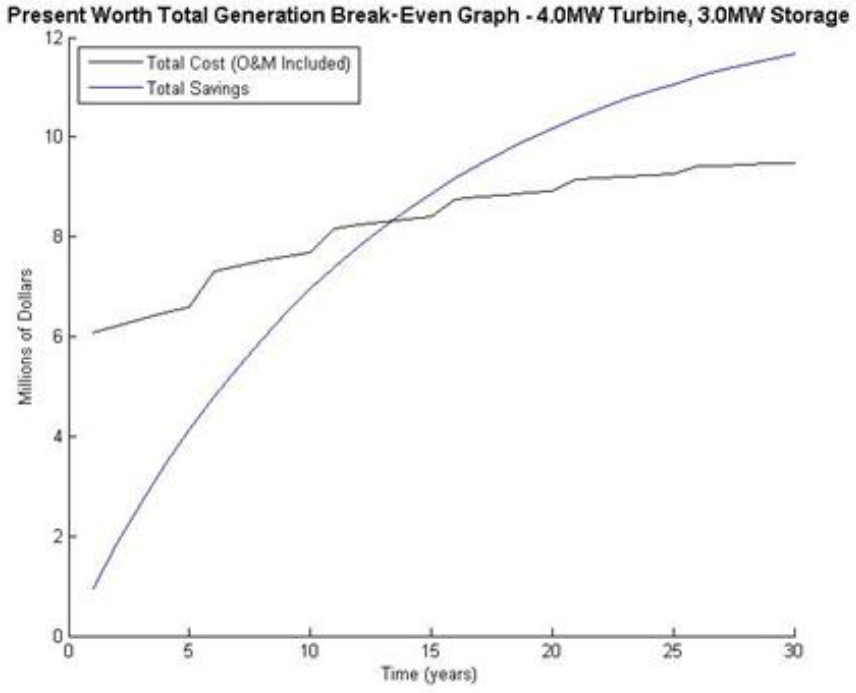

Figure 6.15: Present Worth Total Generation Break-Even Graph for 4.0MW Turbine with 3.0MW Storage

Figures 6.9 through 6.15 show present worth break-even graphs for the 4.0MW turbine energy storage analysis. It is apparent from the break-even graphs of the battery storage system (Figures 6.10, 6.12, and 6.14) that for a 4.0MW turbine an energy storage system is never economically viable. It is also important to note the large increases in cost each five years on these three figures; this is due to the replacement cost of the batteries which have an estimated life of five years. It is also pertinent to note that even without the increases in cost from replacing batteries the battery storage system would still not be economically viable. Figures 6.11, 6.13, and 6.15 show that even though the battery storage system is drastically increasing the cost, the turbine analysis with the storage system still produces an overall economically viable option. As storage sizes increase the amount of profit obtained from the system decreases from approximately five million dollars with no storage system to approximately 1.5 million dollars with 3MW storage over a 20 year period. For a 4.0MW wind turbine, the results above suggest that the most economically viable option is to have no battery storage system.

Figures 6.16 through 6.22 show the break-even graphs for the 6.0MW turbine analysis.

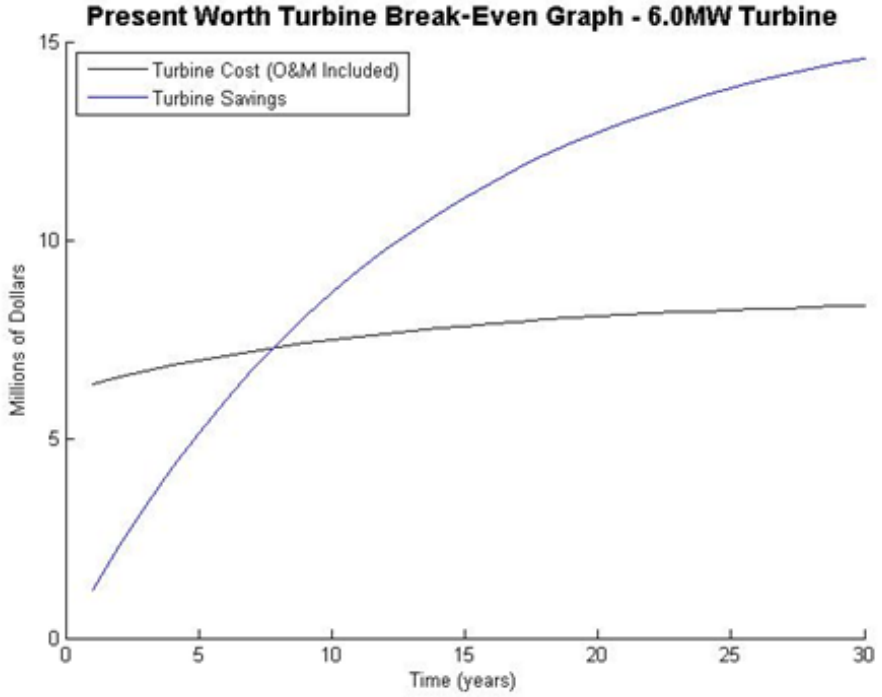

Figure 6.16: Present Worth Break-Even Graph for 6.0MW Turbine

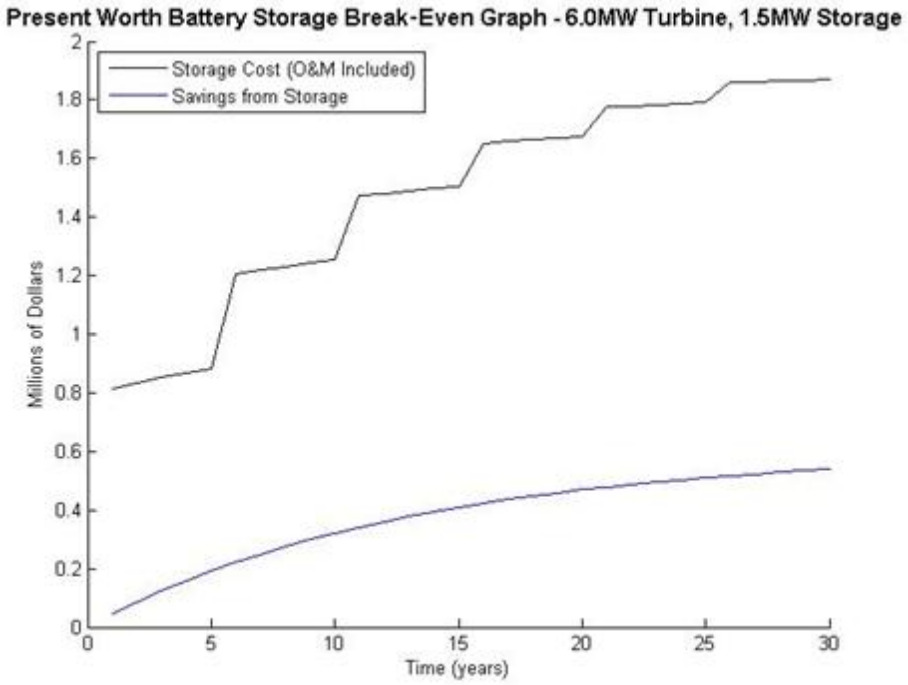

Figure 6.17: Present Worth Battery Storage Only Break-Even Graph for 6.0MW Turbine with 1.5MW Storage

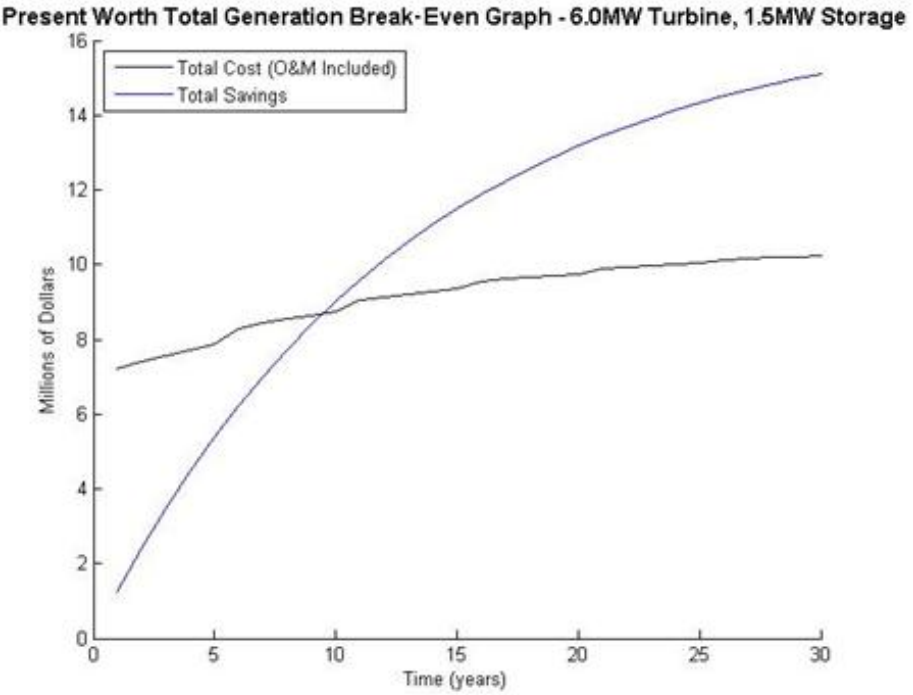

Figure 6.18: Present Worth Total Generation Break-Even Graph for 6.0MW Turbine with 1.5MW Storage

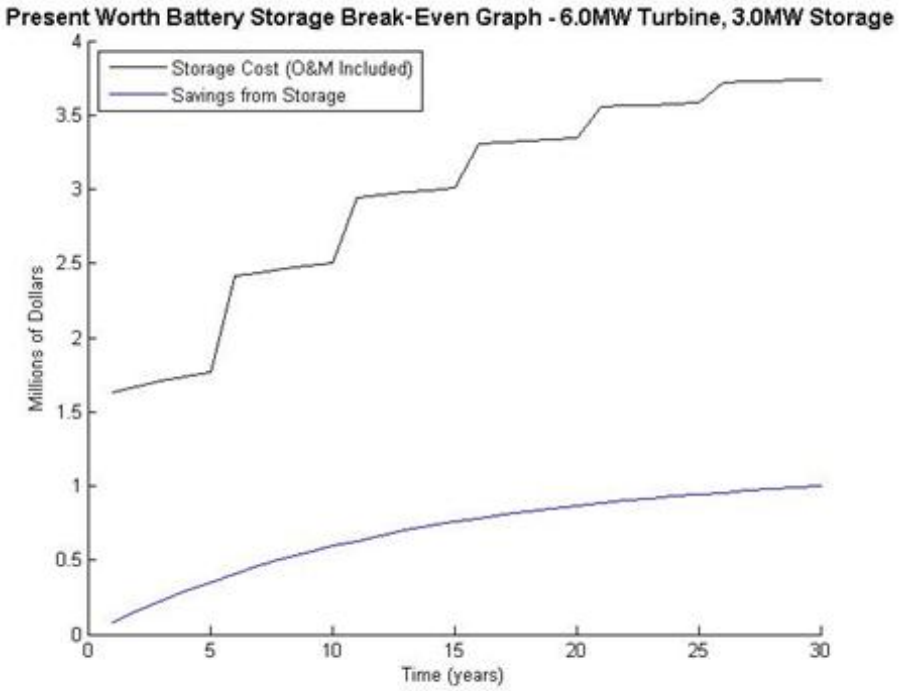

Figure 6.19: Present Worth Battery Storage Only Break-Even Graph for 6.0MW Turbine with 3.0MW Storage

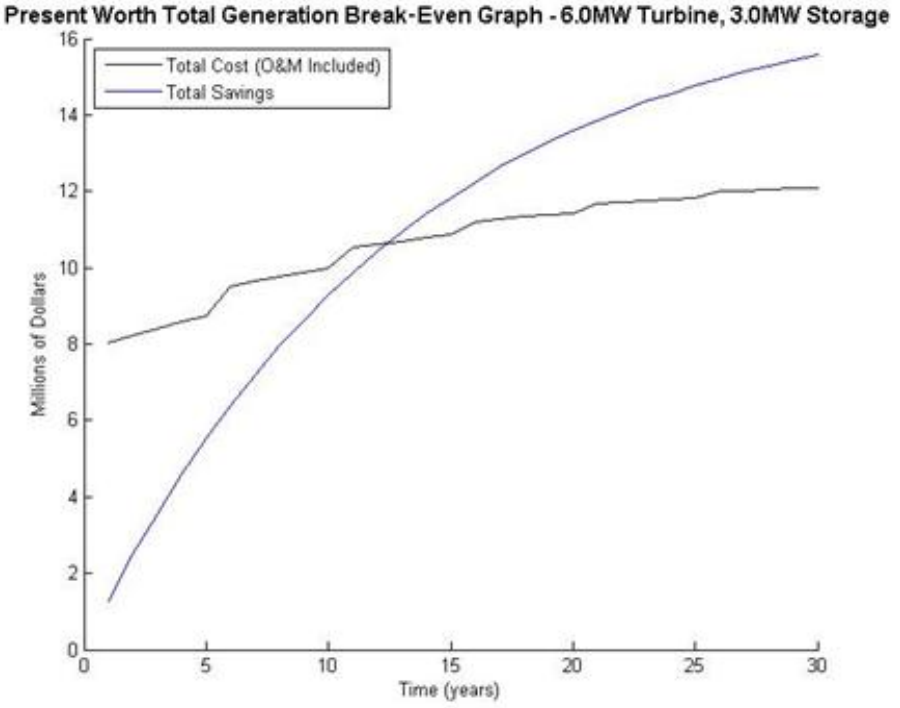

Figure 6.20: Present Worth Total Generation Break-Even Graph for 6.0MW Turbine with 3.0MW Storage

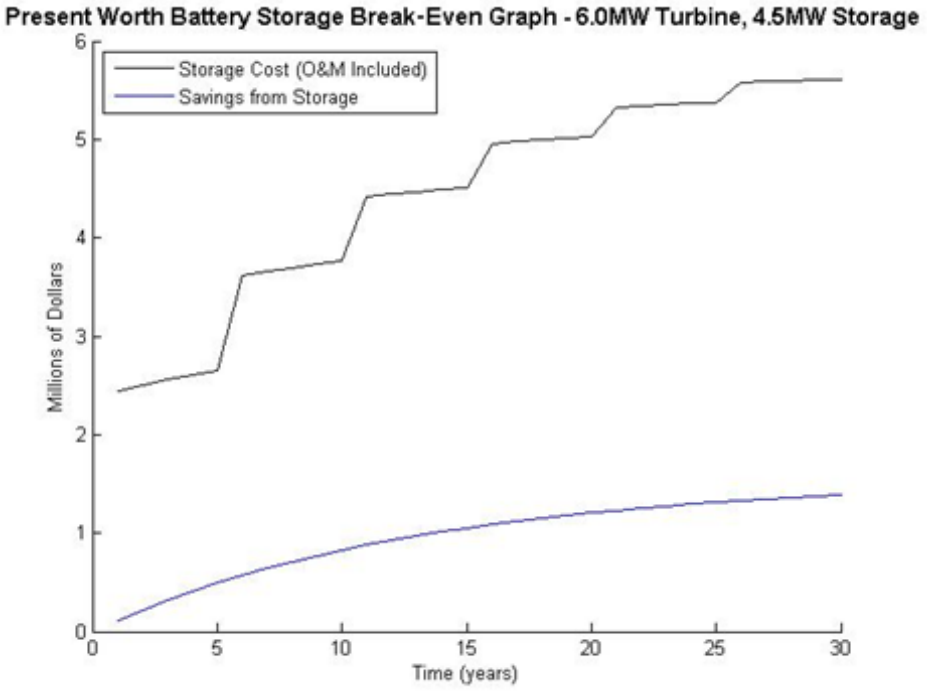

Figure 6.21: Present Worth Battery Storage Only Break-Even Graph for 6.0MW Turbine with 4.5MW Storage

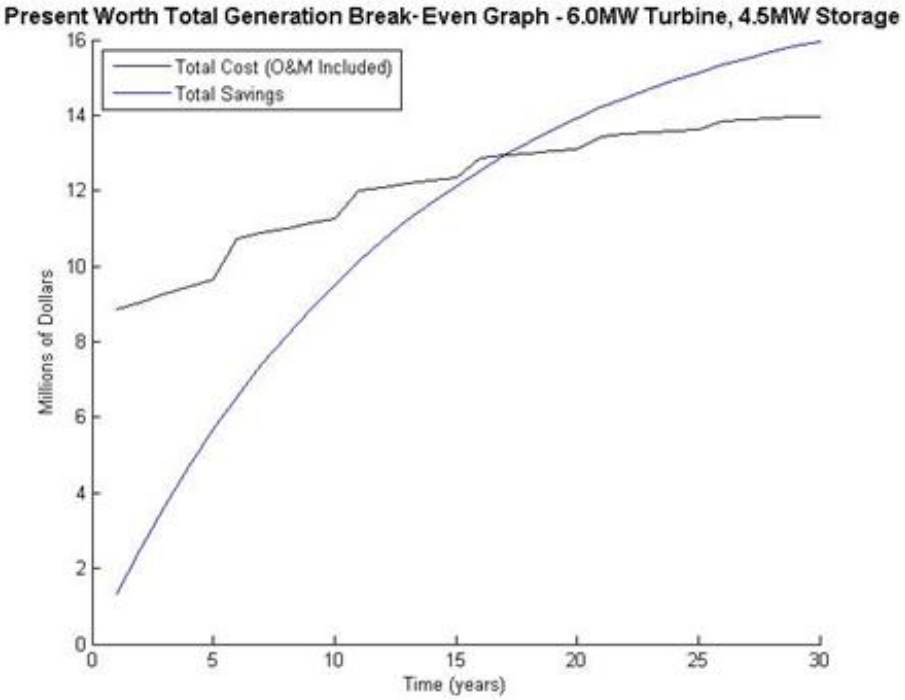

Figure 6.22: Present Worth Total Generation Break-Even Graph for 6.0MW Turbine with 4.5MW Storage

Figures 6.16 through 6.22 show present worth break-even graphs for the 6.0MW turbine energy storage analysis. It is apparent from examination of the break-even graphs that they show results similar to the 4.0MW turbine results. The main small difference is as storage sizes increase the amount of profit obtained from the system decreases from approximately five million dollars with no storage system to approximately one million dollars with 4.5MW storage over a 20 year period. For a 6.0MW wind turbine, the results suggest that the most economically viable storage system is no battery storage system.

Examination of Variance

Figure 6.23 shows the 99% confidence interval for the case with a 4.0MW turbine and 2.0MW storage.

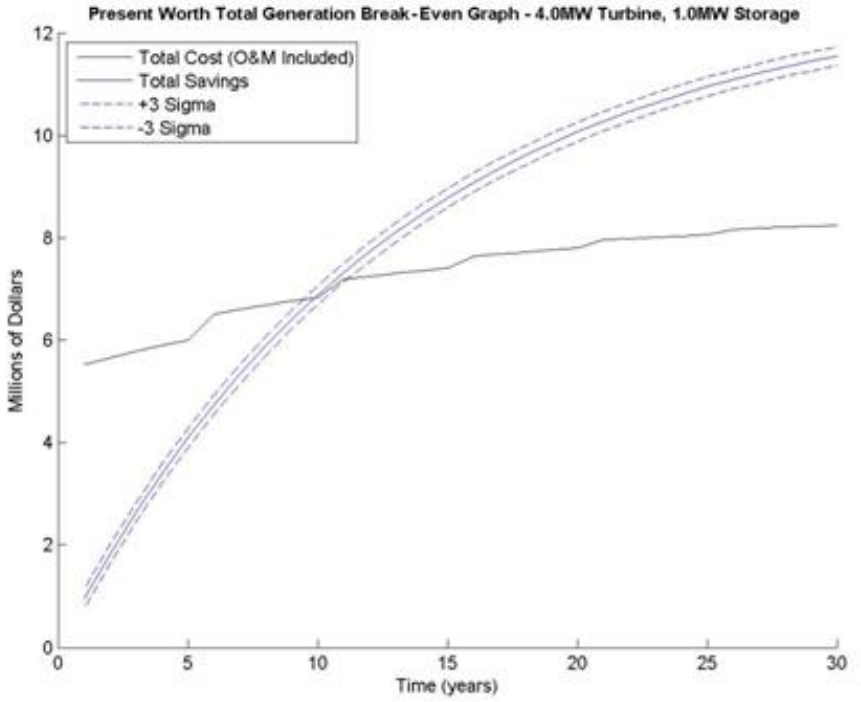

Figure 6.23: Present Worth Total Generation Break-Even Graph with 99% Confidence Interval for 4.0MW Turbine and 2.0 MW Storage

Figure 6.23 shows that the amount of variance in the Monte Carlo simulation and the battery storage simulations is very small. The dashed lines barely deviate from the solid savings line. It is clear that variance in the data does not noticeable affect the results.

Conclusion

Upon examining the results found throughout the course of the energy storage analysis it is clear that battery storage systems are still too expensive and inefficient to be economically viable with the cost conditions examined in this study. In all of the battery storage analyses performed the battery system was always between a one million and 4.5 million dollars negative benefit; in the best case scenario the battery system was adding a cumulative cost of one million dollars over a 20 year period. In light of these results, the most economically viable option is not to have a storage system.

Chapter 7 - Conclusions

Throughout the course of this research numerous conclusions have become evident. In the background information acquired for this research it became apparent early on that wind energy is a clean source of energy with relatively few drawbacks. It also became apparent that the main problem with wind energy is the lack of the ability to transport the energy generated from the wind to locations with large enough loads to use it. Upon further investigation a possible solution to the transportation problem was found; distributed generation such as community wind.

The economic analysis performed in this research allowed for the following conclusions to be made. First, economic analysis led to the determination that the flat rate structure was the most economically viable rate structure over demand rate and CPP. The economic analysis also provided the determination that if the historical data continued to repeat itself over a 20 year period a 2.0 MW wind turbine with a flat rate of $0.0593/kWh would produce an estimated present worth profit of near $3,000,000 over a twenty year period.

The Monte Carlo simulation and sensitivity and energy storage analyses provided further conclusions. The Monte Carlo simulation exhibited itself as a robust simulation through repeated results with relatively small error. It then confirmed what was found in the economic analysis section: that a 2.0 MW wind turbine with a flat rate of $0.0593/kWh would produce an estimated present worth profit of near $3,000,000 over a twenty-year period. The sensitivity analysis went on to show that when dumping excess generation onto the grid at no charge increasing turbine size produced increased profits; however, after reaching a turbine size of 5.0MW there was little to no economic benefit of further increase in turbine size. The sensitivity analysis also confirmed that hypothesis that as the flat rate for energy increases the economic viability of any size of wind turbine also increases. The energy storage simulation held up the idea that battery storage systems are not economically viable with current technology and limitations; none of the battery storage analyses conducted proved to be with a million dollars of being economically viable.

Future Work

Throughout the course of this research multiple areas for future work have been found. First, the examination of additional rate structures that may be used in other areas where community wind generation could be implemented would be a good addition to the research already presented. Also, the examination of multiple locations and load profiles to determine the effectiveness of community wind generation in other areas than rural western Kansas would potentially increase the reach of this research; more detailed work could be completed if the load and wind data were from the same time period at the same location. Further examination of the effect on the existing transmission and distribution systems of adding a large wind turbine to the system and the startup and installation costs of different sized wind turbines could provide more specific analysis. Also, an economic analysis of other types of emerging energy storage systems could be pursued to determine if any type of energy storage system is economically viable. Finally, an analysis of how much a battery system would need to cost to make it worth-while could be computed.

References

[1] Look Inside a Commercial Wind Turbine. (accessed August 2011). *Renewable Energy UK.* [Online]. Available: http://www.reuk.co.uk/Look-Inside-a-Commercial-Wind-Turbine.htm

[2] Fast Facts. (accessed August 2011). *National Wind Watch.* [Online] Available: http://www.windpower.org/en/tour/wtrb/size.htm

[3] Wind Turbine FAQ. (accessed August 2011). *Rainbow Power Company LTD.* [Online] Available: http://www.rpc.com.au/products/windturbines/wind_faq.html

[4] Getting the Best from a Wind Farm. (accessed August 2011). *Inventorpro.* [Online] Available: http://inventorpro.wordpress.com/

[5] Multi-Mode Windfarm Control System. (accessed August 2011). *Invertorpro.* [Online] Available: http://inventorpro.files.wordpress.com/2008/07/diagram4.jpg

[6] Wind Energy and the Economy. (accessed August 2011). *American Wind Energy Association.* [Online] Available: http://archive.awea.org/faq/wwt_economy.html

[7] Farming the Wind: Wind Power and Agriculture. (accessed August 2011). *Union of Concerned Scientists.* [Online] Available: http://www.ucsusa.org/clean_energy/technology_and_impacts/impacts/farming-the-wind-wind-power.html

[8] Wind Energy and the Environment. (accessed August 2011). *American Wind Energy Association.* [Online] Available: http://archive.awea.org/faq/wwt_environment.html

[9] 10 Steps in Building a Wind Farm. (accessed August 2011). *American Wind Energy Association Fact Sheet.* [Online] Available: http://archive.awea.org/pubs/factsheets/Ten_Steps.pdf

[10] Cleveland Welcomes Largest Wind Turbine in North America. (accessed August 2011). *Cleveland Magazine.* [Online] Available: http://clevelandmagazine.blogspot.com/2011/04/cleveland-welcomes-largest-wind-turbine.html

[11] Wind Energy Transmission. (accessed August 2011). *State Energy Conservation Office.* [Online] Available: http://www.seco.cpa.state.tx.us/re_wind-transmission.htm

[12] Types of Wind Turbine Energy Storage Technology. (accessed August 2011). *eHow* [Online] Available: http://www.ehow.com/list_5984642_types-turbine-energy-storage-technology.html

[13] Overview of Wind Power Storage Media. (accessed August 2011). *Windpower Engineering & Development.* [Online] Available: http://www.windpowerengineering.com/design/electrical/power-storage/overview-of-wind-power-storage-media/

[14] Distributed Generation in Local Plans. (accessed August 2011). *New Rules Project – A Program of the Institute for Local Self-Reliance.* [Online] Available: http://www.newrules.org/energy/rules/distributed-generation-local-plans

[15] Schwartz, L., Distributed Generation in Oregon: Overview, Regulatory Barriers and Recommendations. (accessed August 2011). *Oregon Public Utility Commission.* [Online] Available: http://www.oregon.gov/PUC/electric_gas/dg_report.pdf?ga=t

[16] Suzlon S88-2.1 MW. (accessed August 2011). *Suzlon.* [Online] Available: http://www.suzlon.com/products/l2.aspx?l1=2&l2=9

[17] Vestas V80-2.0 MW. (accessed August 2011). *Vestas Product Brochure.* [Online] Available: http://www.vestas.com/en/media/brochures.aspx

[18] Critical Peak Pricing FAQ. (accessed August 2011). *Siemens – Southern California Edison.* [Online] Available: http://www.buildingtechnologies.siemens.com/bt/us/SiteCollectionDocuments/sbt_internet_us/products-systems/rcs/CriticalPeakPricingFAQSCE.pdf

[19] Pahwa, Anil; "Economic Analysis of Distribution Systems." (2009)

[20] L. Fingersh, M. Hand, and A. Laxson. "Wind Turbine Design Cost and Scaling Model." (accessed September 2011). *National Renewable Energy Laboratory Technical Report*. [Online] Available: http://www.nrel.gov/docs/fy07osti/40566.pdf

[21] Poonpun, P.; Jewell, W.T.; "Analysis of the Cost per Kilowatt Hour to Store Electricity," *IEEE Transactions on Energy Conversion*, vol.23, no.2, pp.529-534, June 2008 doi: 10.1109/TEC.2007.914157

[22] Hopkins, M.; "Intelligent Dispatch for Distributed Renewable Resources," May 2009 [Online] Available: http://hdl.handle.net/2097/1512

[23] "About Cooperatives," *Touchstone Energy Cooperatives.* (accessed October 2011) [Online] Available: http://www.touchstoneenergy.com/about/Pages/default.aspx

[24] Jose, A.; "Economic Evaluation of Small Wind Generation Ownership under Different Electricity Pricing Scenarios." May 2011 [Online] Available: http://hdl.handle.net/2097/7075

[25] “Understanding Coefficient of Power (Cp) and Betz Limit,” *Kidwind Science Snack: Betz Limit.* (accessed November 2011) [Online] Available: learn.kidwind.org/sites/default/files/betz_limit_0.pdf

[26] Pereira, A.J.C.; Saraiva, J.T.; , "Economic evaluation of wind generation projects in electricity markets," *Energy Market (EEM), 2010 7th International Conference on the European* , vol., no., pp.1-8, 23-25 June 2010, doi: 10.1109/EEM.2010.5558768

[27] Wang Jinggang; Gao Xiaoxia; Du Hongbiao; , "The Economic Analysis of Wind Solar Hybrid Power Generation System in Villa," *Energy and Environment Technology, 2009. ICEET '09. International Conference on* , vol.1, no., pp.885-887, 16-18 Oct. 2009 doi: 10.1109/ICEET.2009.219

Appendix A - Load Average and Standard Deviation Graphs

The following graphs show the load average and standard deviation graphs for each predetermined temperature range.

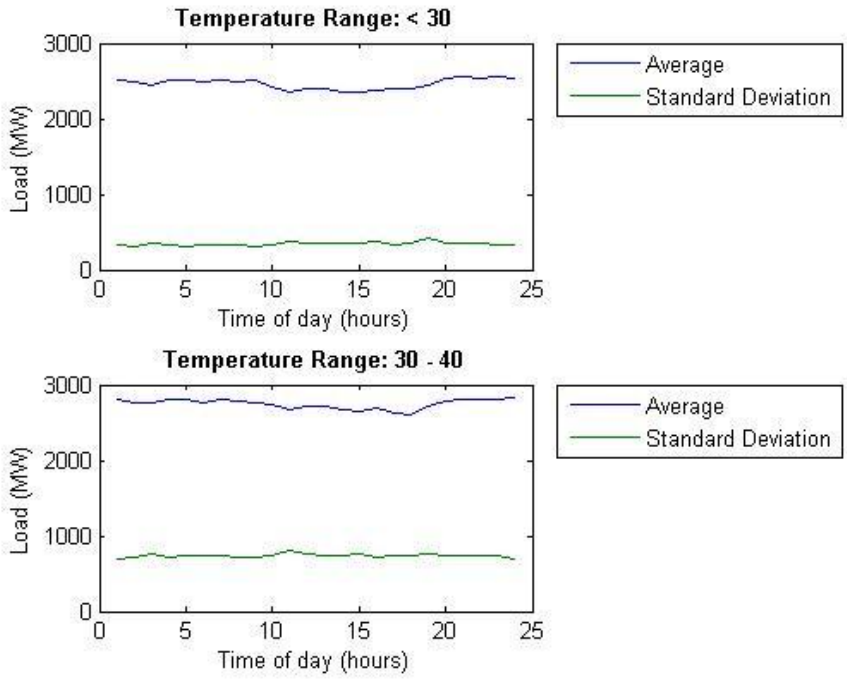

Figure A.1: Load (MW) Average and Standard Deviation for Temperature Ranges < 30 and 30 – 40

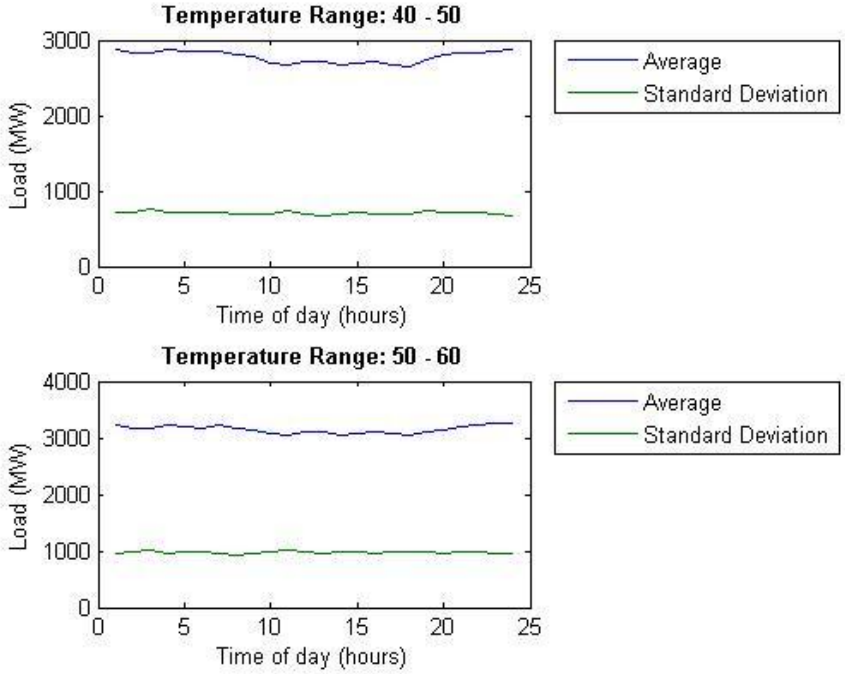

Figure A.2: Load (MW) Average and Standard Deviation for Temperature Ranges 40 - 50 and 50 - 60

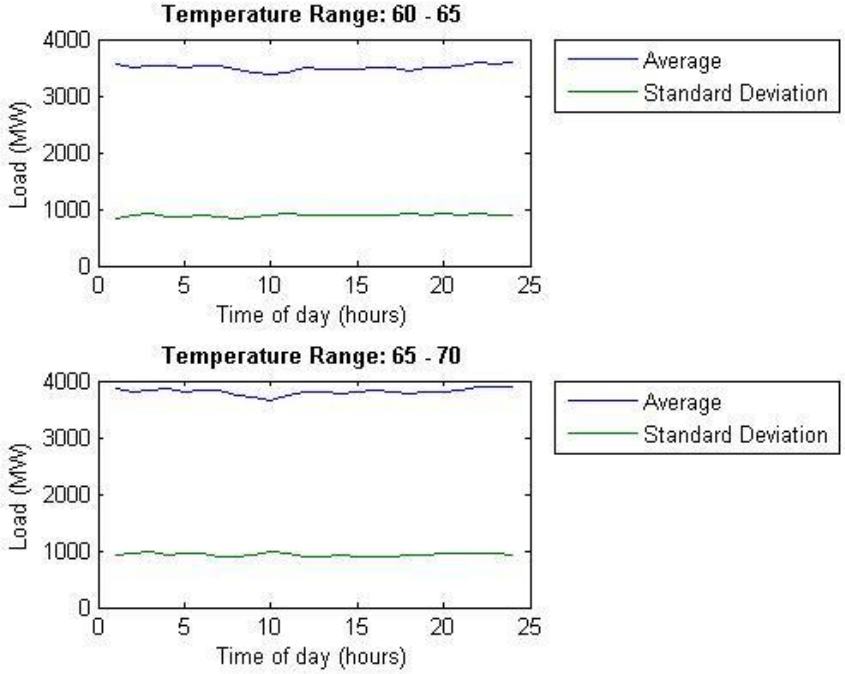

Figure A.3: Load (MW) Average and Standard Deviation for Temperature Ranges 60 - 65 and 65 - 70

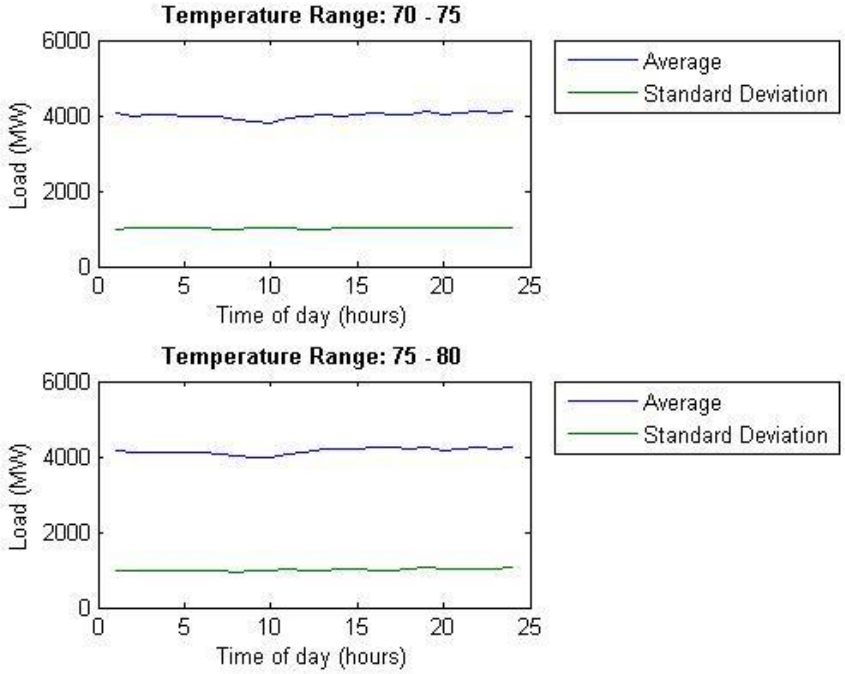

Figure A.4: Load (MW) Average and Standard Deviation for Temperature Ranges 70 - 75 and 75 - 80

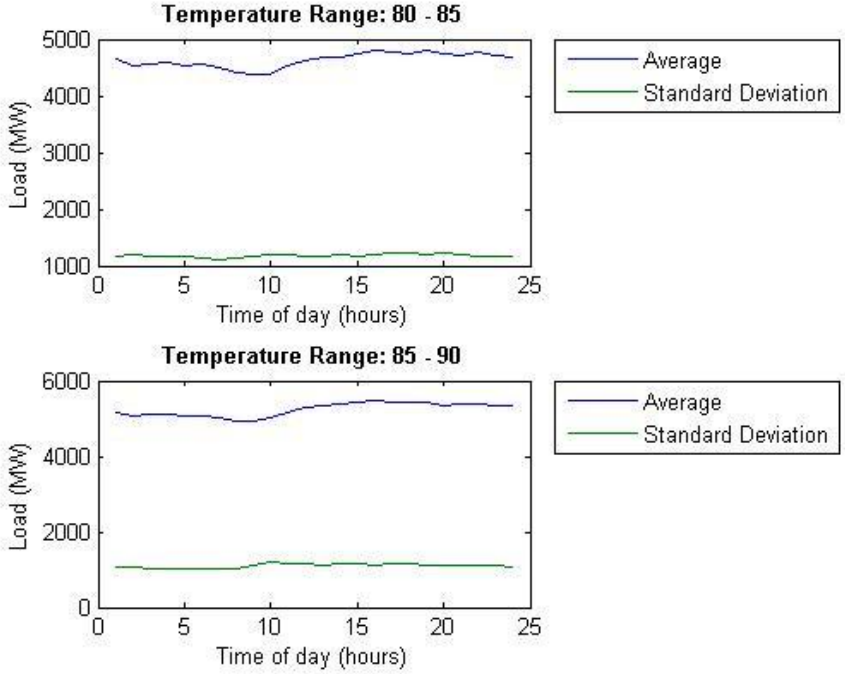

Figure A.5: Load (MW) Average and Standard Deviation for Temperature Ranges 80 - 85 and 85 - 90

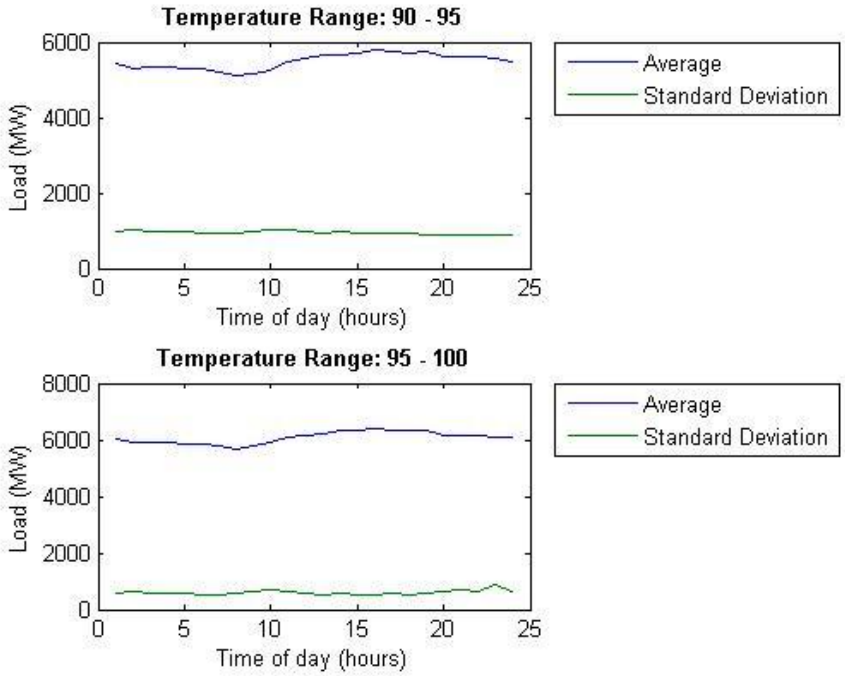

Figure A.6: Load (MW) Average and Standard Deviation for Temperature Ranges 90 - 95 and 95 - 100

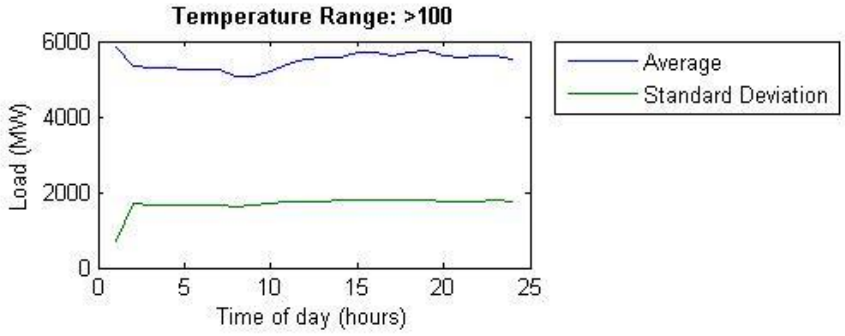

Figure A.7: Load (MW) Average and Standard Deviation for Temperature Range > 100

Appendix B - Wind Speed Average and Standard Deviation Graphs

The following graphs show the wind speed average and standard deviation graphs for each predetermined temperature range.

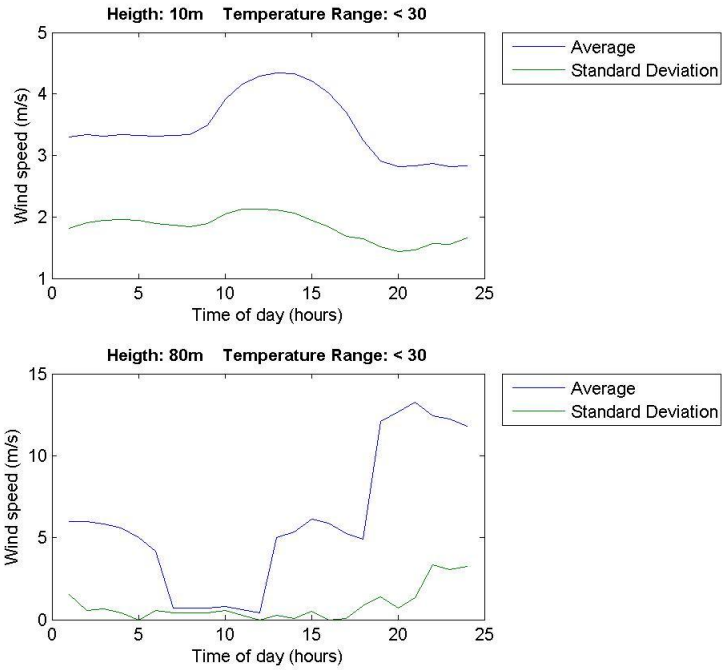

Figure B.1: 10m and 80m Wind Speed (m/s) Average and Standard Deviation for < 30 Degree Fahrenheit Temperature Range

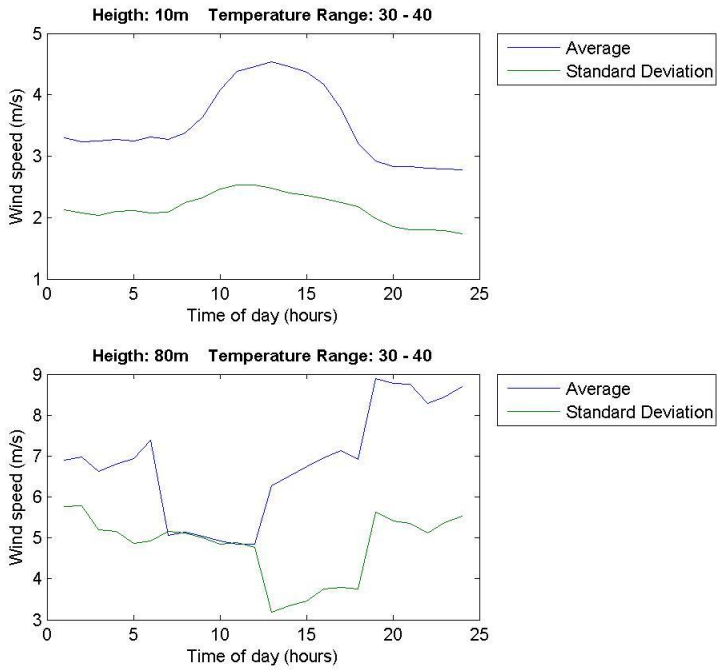

Figure B.2: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 30 - 40 Degree Fahrenheit Temperature Range

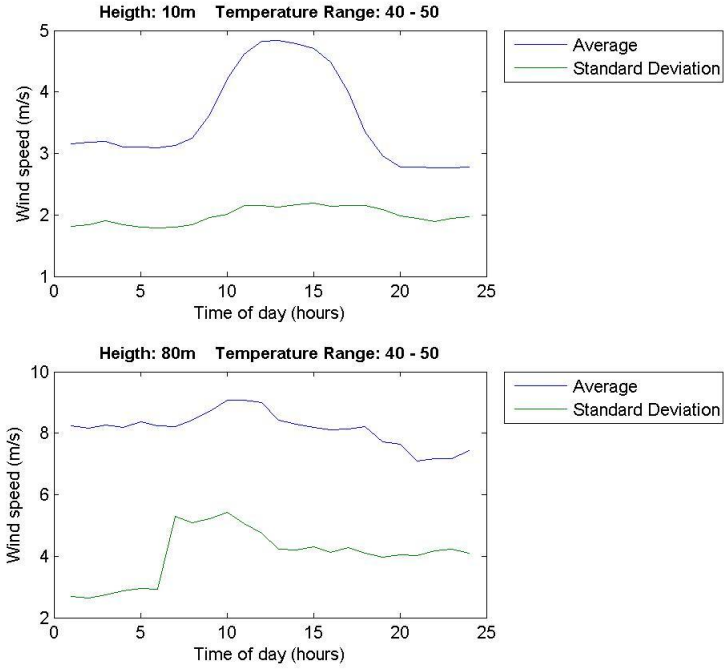

Figure B.3: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 40 - 50 Degree Fahrenheit Temperature Range

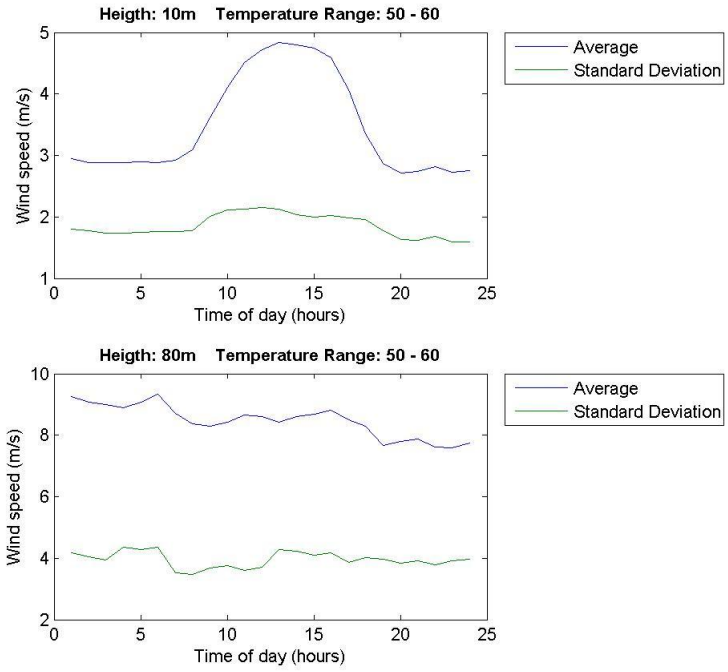

Figure B.4: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 50 - 60 Degree Fahrenheit Temperature Range

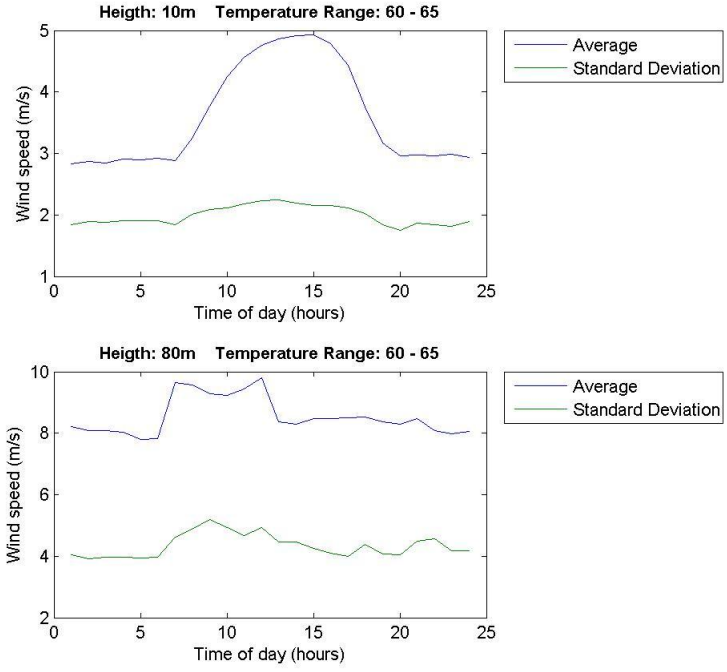

Figure B.5: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 60 - 65 Degree Fahrenheit Temperature Range

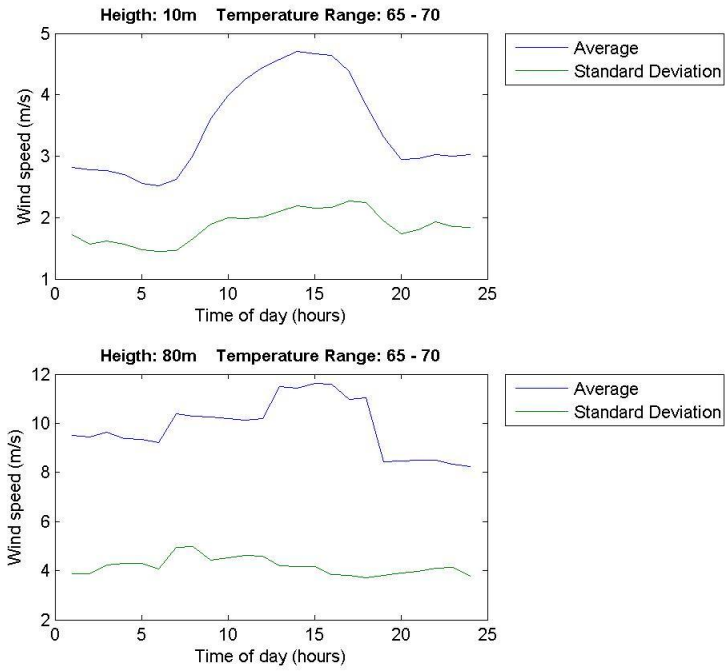

Figure B.6: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 65 - 70 Degree Fahrenheit Temperature Range

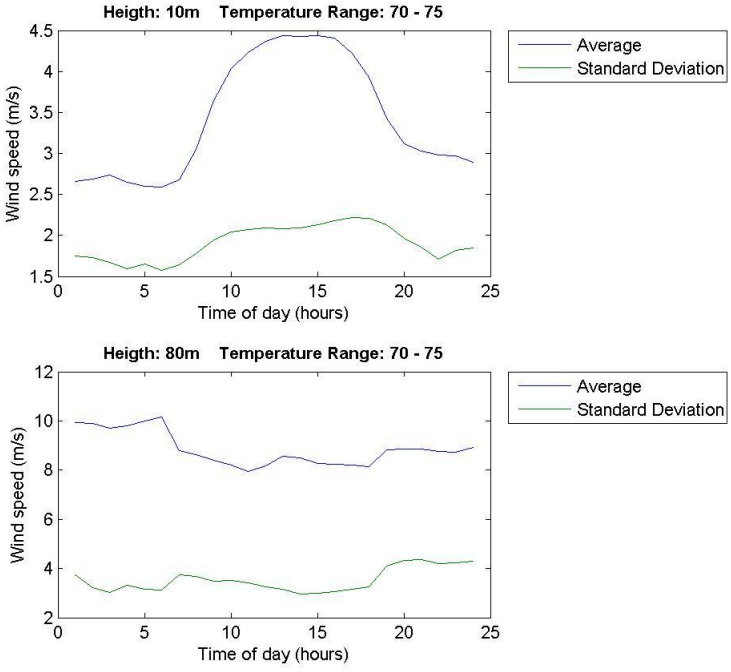

Figure B.7: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 70 - 75 Degree Fahrenheit Temperature Range

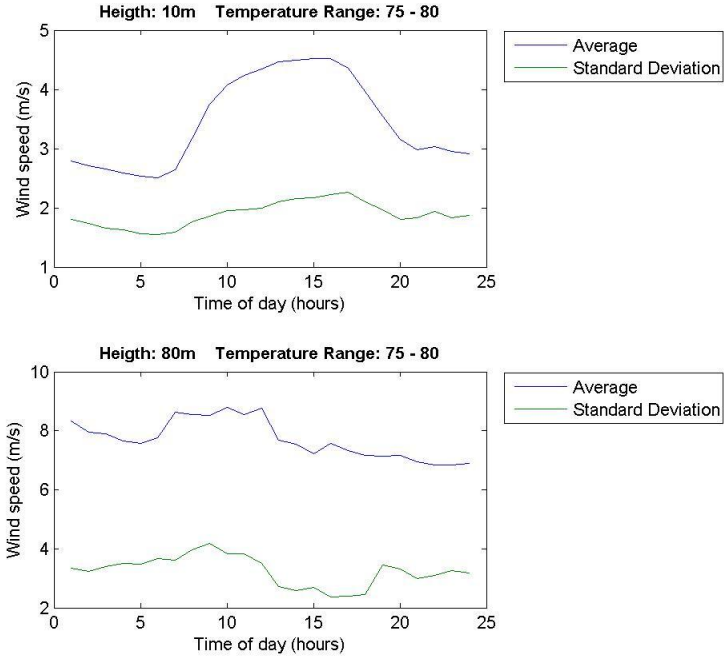

Figure B.8: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 75 - 80 Degree Fahrenheit Temperature Range

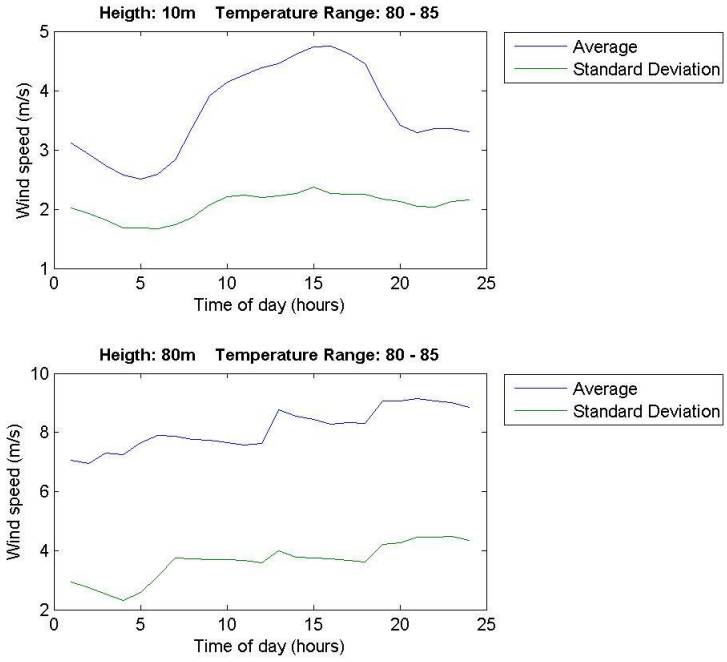

Figure B.9: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 80 - 85 Degree Fahrenheit Temperature Range

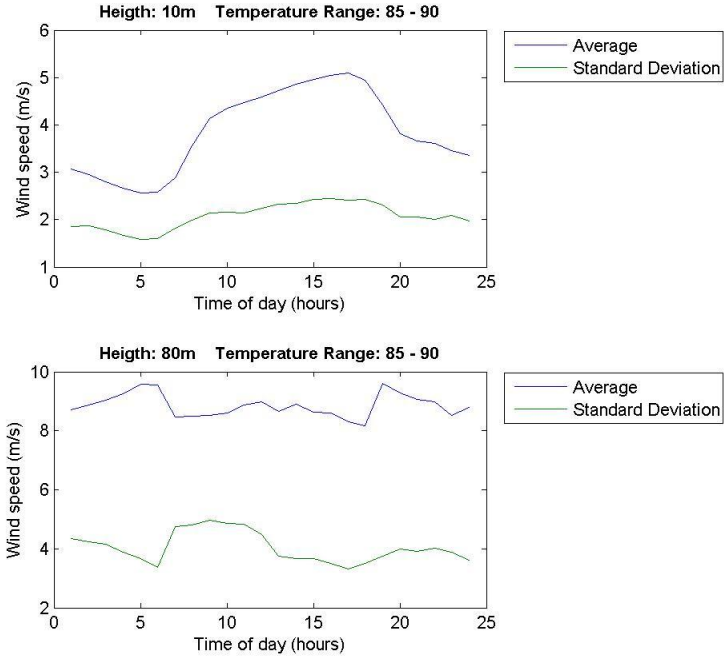

Figure B.10: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 85 - 90 Degree Fahrenheit Temperature Range

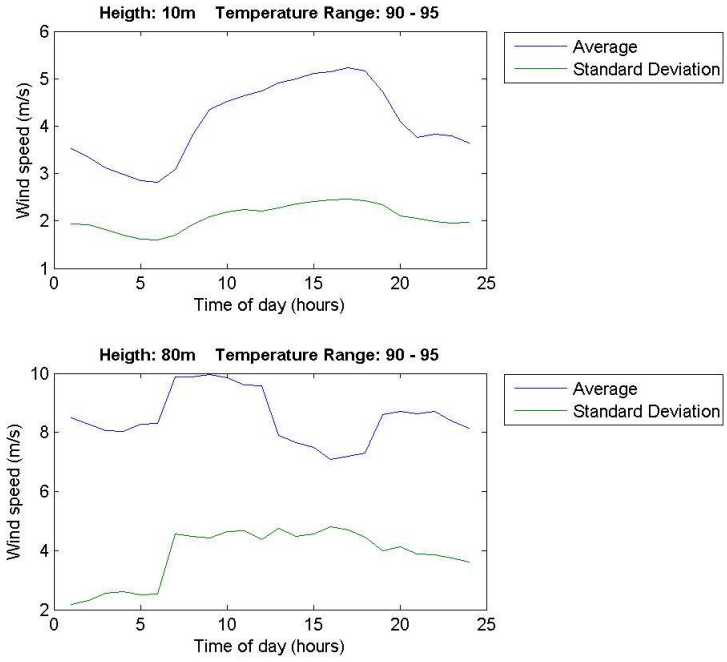

Figure B.11: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 90 - 95 Degree Fahrenheit Temperature Range

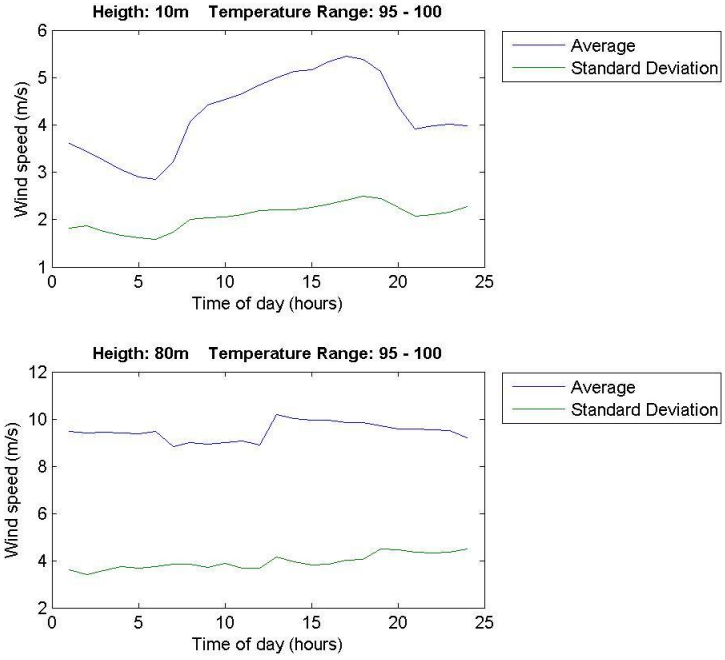

Figure B.12: 10m and 80m Wind Speed(m/s) Average and Standard Deviation for 95 - 100 Degree Fahrenheit Temperature Range

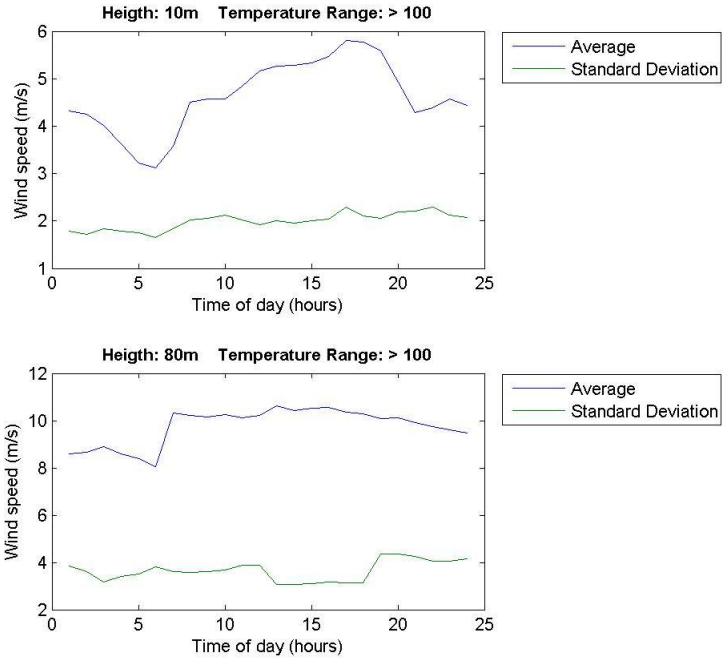

Figure B.13: 10m and 80m Wind Speed (m/s) Average and Standard Deviation for > 100 Degree Fahrenheit Temperature Range

Appendix C - Wind Turbine Power Curves

The following graphs show the wind turbine power curves created and used in the studies performed in this paper.

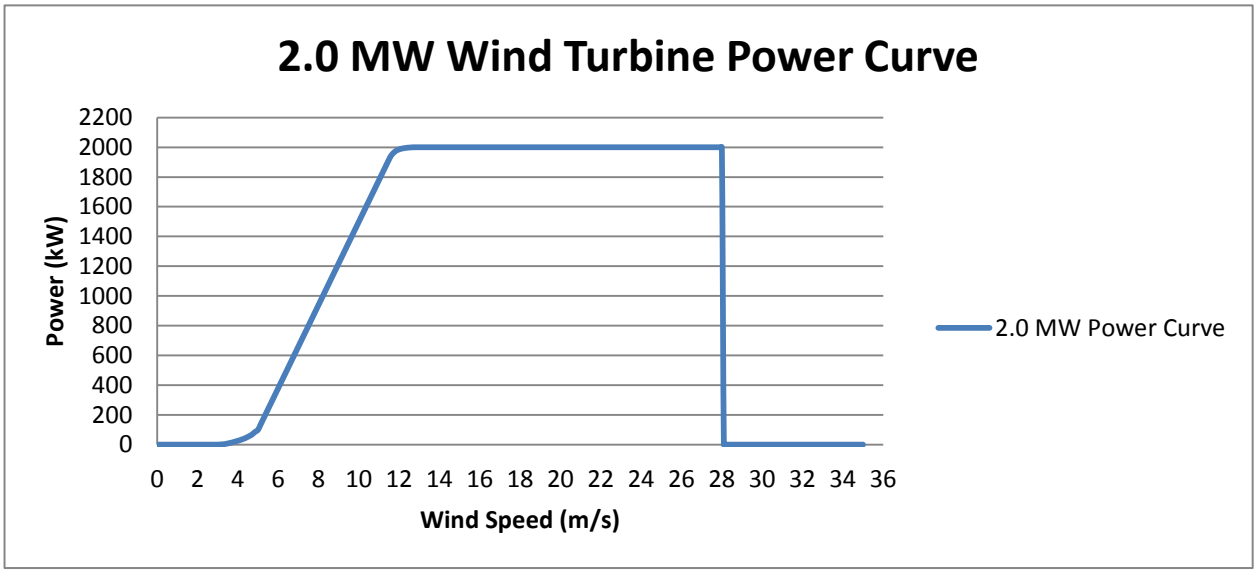

Figure C.1: 2.0 MW Wind Turbine Power Curve

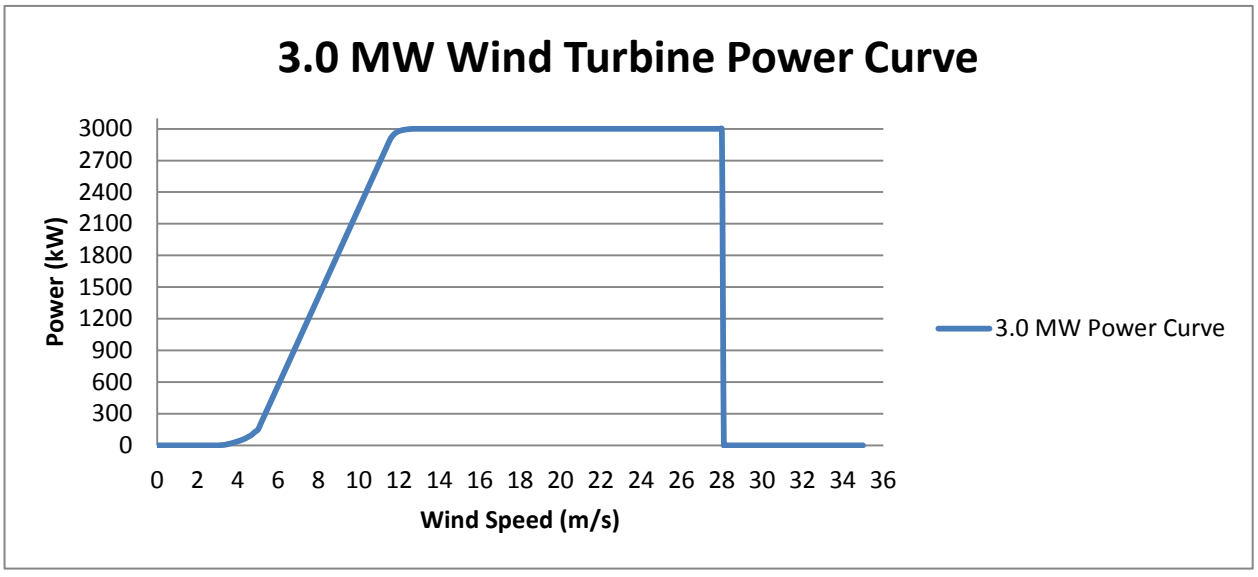

Figure C.2: 3.0 MW Wind Turbine Power Curve

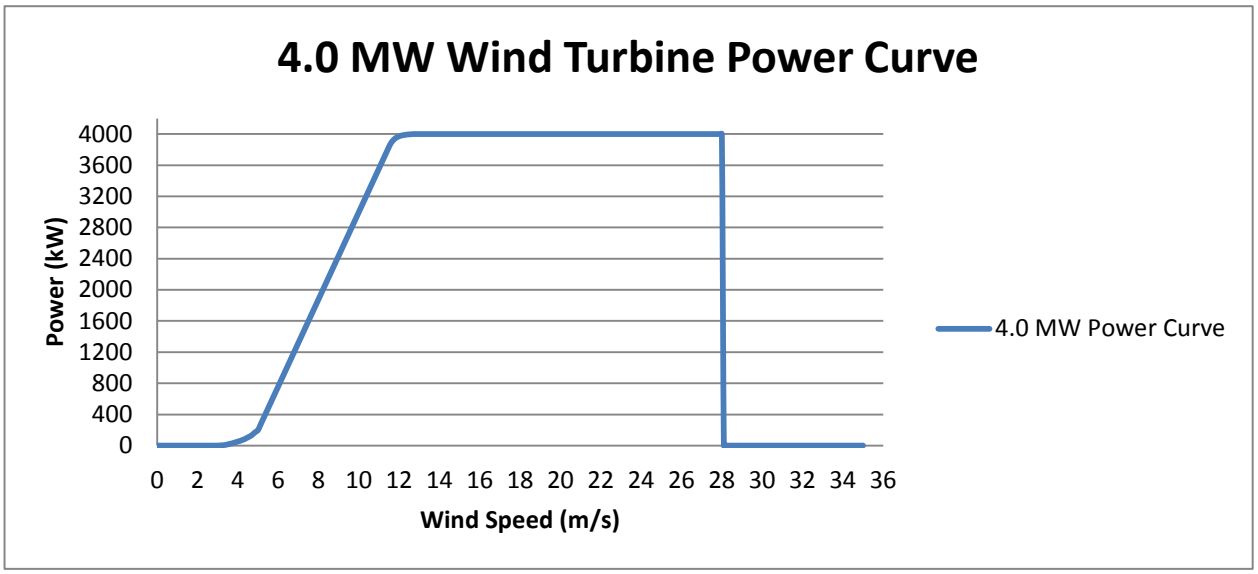

Figure C.3: 4.0 MW Wind Turbine Power Curve

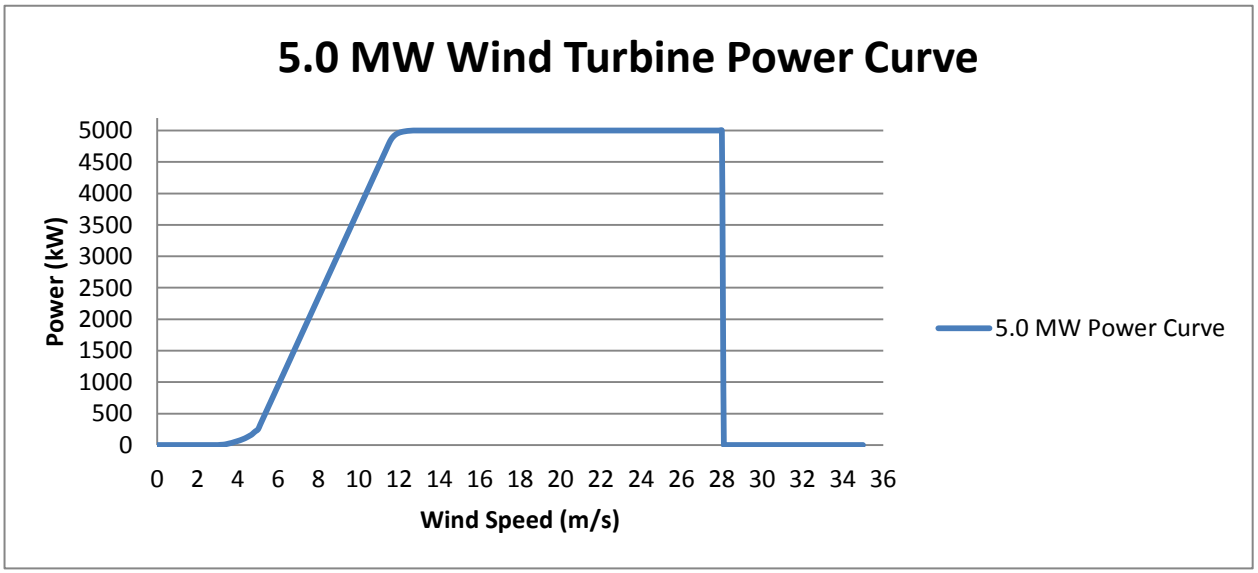

Figure C.4: 5.0 MW Wind Turbine Power Curve

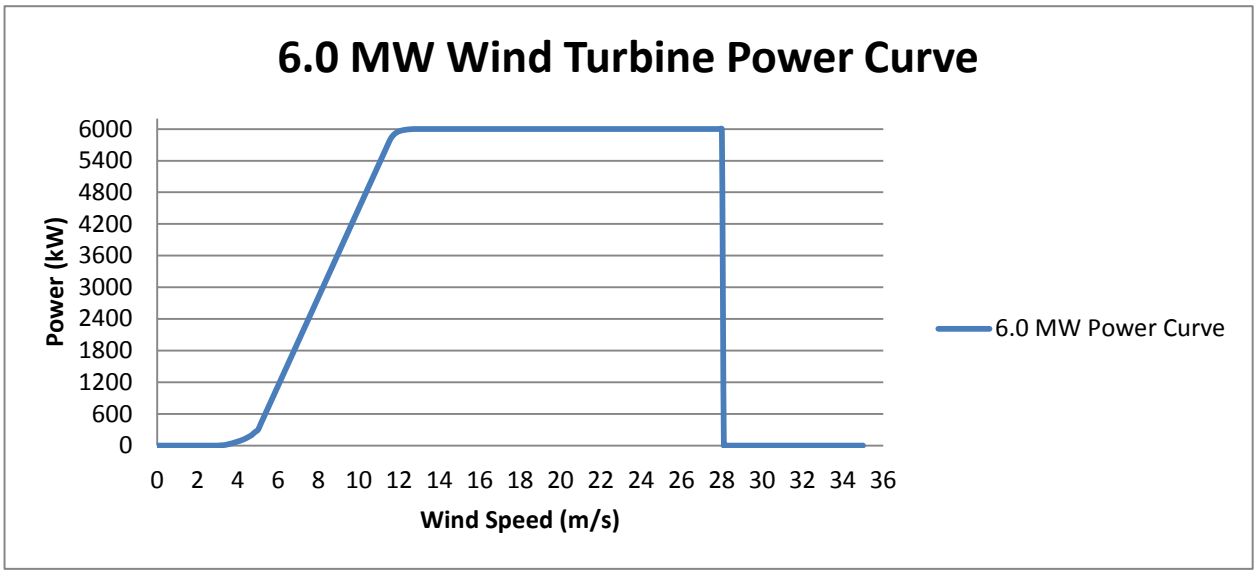

Figure C.5: 6.0 MW Wind Turbine Power Curve