AC 2007-1286: PLANNING A SMALL-SCALE WIND-ELECTRIC SYSTEM IN EAST-CENTRAL IOWA

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Planning a Small-Scale Wind-Electric System in East-Central Iowa

Abstract

The success of a wind-electric generating system depends on several factors. These would include: the available sites, choice of a site from those possibilities, well defined goals, efforts to make it work, adequate planning, matching the right equipment to each other and to the site and its' own unique characteristics, and an execution plan. A project concerning a small-scale wind-electric system is no different in those respects. This paper describes detailed steps taken in determining if a given site is appropriate for further development and the subsequent planning of a small-scale wind-electric system in East-Central Iowa. The wind is characterized and quantified. Equipment is described, but not analyzed. Electrical demand for the site is evaluated. The wind, the equipment and the demand are considered together to create a rough plan for a system that will satisfy a significant proportion of the sites' total demand. From these pieces, the proportion of each month's demand is estimated. This work constitutes a feasible case study for wind energy resource management in four-year institutions.

I. Introduction

57% of the electricity in the United States is generated by pulverized based coal-fired power plants. In the generation of one-kilowatt hour of electricity by burning coal, 1000 grams of CO_2, 7 grams of sulfur oxides, nitrogen oxides and particulates, more than 200 grams of ash and waste and trace amounts of several different metals are released. In 1996 CO_2 levels were around 354,000 parts per billion (ppb), contrasted to 290,000 ppb 100 years ago. The generation of electricity by fossil fuels is not, of course, the only cause of record levels of CO_2 and other greenhouse gases in the atmosphere, but it does represent a large share.

Generating electricity from the wind could replace coal for a much larger portion than is currently being realized. Unlike coal or nuclear sources, wind power can be generated at many different scales of size. In the case of small-scale generation – it can be produced near to its' point of use, thus reducing transmission line losses.

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The wind is characterized and quantified. Equipment is described, but not analyzed. Electrical demand for the site is evaluated. The wind, the equipment and the demand are considered together to create a rough plan for a system that will satisfy a significant proportion of the sites' total demand. From these pieces, the proportion of each months demand can be estimated.

II. Need

Small-scale wind power generation systems can play a role in increasing the percentage of Iowa's energy produced by renewable sources. It is hoped that this paper and the project it plans will promote increased attention to small-scale wind-electric generating systems in Iowa, and even nationally. The study site has been described as "always windy". That statement is not very well quantified, but it will serve as a starting point for this study.

Two new sustainable energy programs offering Associate Applied Science (AAS) degrees were recently established at two Iowa community colleges. The wind site selection, planning, and feasibility studies constitute a significant portion of the wind power education. Three major state universities in Iowa are also planning to offer advanced classes in the planning and management of small and large scale wind-electric based distributed energy systems.

Wind power technology has become one of the fastest growing technologies in the world. It also constitutes one of the most efficient green power technologies [1-2]. The wind power generation in Iowa is a clean, available, and cost effective alternative source of energy and, better yet, can be readily integrated into both existing and new power grids [3-5].

III. Methodology

Generation of electrical energy from wind can be economically achieved only where a significant wind resource exists. Because of the cubic relationship between wind velocity and output energy, sites with small percentage differences in average wind speeds can have substantial differences in available energy. Therefore, accurate and thorough monitoring of wind resource at potential sites is a critical factor in the placing of wind turbines. An accurately measured wind-speed frequency spectrum at a site is another important factor. For assessment of the wind-power potential of a site, most investigators have used simple wind-speed distributions that are determined solely by the arithmetic mean of the wind speed. Assessment of power output of a wind turbine will be accurate if the wind speeds measured at the hub height (30–50 m) of a wind turbine-generator are known. However, the existing wind data available at most of the meteorological stations worldwide is measured at a height of 10 or 20 m above the ground. Therefore, wind speeds measured at anemometer heights are extrapolated to the hub height of the wind turbine. Many investigators have proposed simple expressions for height extrapolation of wind speeds. This paper reviews wind-speed prediction and forecasting, and development of techniques for accurate assessment of wind-power potential.

The wind is caused by pressure differences when the air goes from places where air pressure is higher to places where the air pressure is lower, attempting to bring the two areas into a state of equilibrium [6]. The formula for the amount of power contained within a unit of air flowing past a point is [7]:

$$\text{Power} = (\text{Area of wind-stream intercepted}) * (\text{Density} / 2) * (\text{wind-speed})^3$$

As density or velocity increases, power does also. The density effect is linear, while the velocity effect is exponential (cubic). At standard temperature and pressure, the density of air is 1.293

kg/m^3 [6]. With all other variables held constant, as temperature rises, density will decrease. Likewise, with all variables held constant, if pressure increases, so will density.

There are other factors affecting the power contained in the wind-stream at a specific site. Turbulence and drag caused by the shape of the surrounding landforms, buildings and other obstacles and the roughness of the groundcover can have a marked effect on the power available at a specific site. This can be different from what is measured nearby [8]. Each site needs to be considered independently as the sum of all contributing factors 8. Turbulence can be caused by anything within hundreds of meters from the wind site [8]. The larger or closer an object is to the wind site the more likely it is to cause drag or turbulence. The shape of surrounding land contours can have a significant effect on wind plant performance [9]. Ideally, one would locate the equipment at the top of a bald hill. Available land, neighboring buildings, existing trees and other vegetation are all part of the less than ideal situations one will typically run into [9].

Since infinite combinations of land contours exist it is impossible to cover all possibilities so general situations will be described here. Compression effects occur when the cross section of the flow is reduced [10]. This can happen when the flow is forced up a hill or into the side of a large building. The momentum of the flow slightly compresses itself. This increases density. Separation of the flow can occur when the cross sectional area of the flow is increased [10]. Separation lowers pressure and therefore density. Uneven separation will cause turbulence. Drastic changes in compression or separation across short distances will cause turbulence.

The roughness of the groundcover can slow surface winds considerably [8]. Smooth, flat surfaces will have wind-speeds at the surface much closer to higher altitude winds than will hilly areas with dense plant cover [8]. Most residential sites do not receive much more consideration than to locate where it seems like a good idea [8]. For this study, the proposed site will be studied for one year. The monitoring equipment was located at the exact location of the proposed site. This eliminates any chance of differences existing between the measurement and generator sites. Wind speed and direction were measured following wind study standards at an elevation of 10 meters [7-8] and a frequency of every hour [9]. Temperature and pressure data were collected at ground level every hour [9]. Any other data that the equipment would also record (humidity, rainfall, etc.) was left intact as reference data.

Project STORM at the University of Northern Iowa (the nearest reliable site) was checked for rough correlation with this data during analysis. The intervals and methods employed are equal to or very close to each other. The study site is a residential lot located at approximately 42 degrees, 16 minutes and 14 seconds North latitude and 92 degrees, 21 minutes and 0 seconds W longitude. It lies at an elevation of 940 feet (286.5 meters) above sea level. It measures 150 feet (45.7 meters) in the North/South direction and 535 feet (163.1 meters) in the East/West direction. One design parameter is that if the tower does fall, it should fall on this lot, not any of the neighboring properties (or any buildings on this lot). If a maximum tower height of 75 feet is used, that limits the tower sites to a line running east to west down the center of the property at least 75 feet from the buildings. This eliminates the front 185 feet (56.4 meters). Approximately 250 feet (76.1 meters) behind the house is the highest remaining point on this line. All other points on this centerline were compared against this high point for all other factors and could not surpass it when taking all other things into consideration. The landform is described as rolling hills, with ridges run SE to NW, and are similar to sand dunes, except they are made of dirt, clay and rock.

Significant buildings and trees are marked in site map shown in Figure 1. Their heights and distances are noted on the attached table, for later consideration as possible obstacles. The groundcover is lawn. Surrounding areas have been left to grow as natural prairie and are typically 12 to 24 inches tall, comprised of grass, weeds and wildflowers. There are occasional evergreen and cedar trees dispersed in these areas. All elevations are given as relative to ground level at the proposed tower site. Due to drag effects on the flow of the wind at the surface of the earth, wind speeds vary with altitude. This is described by the formula:

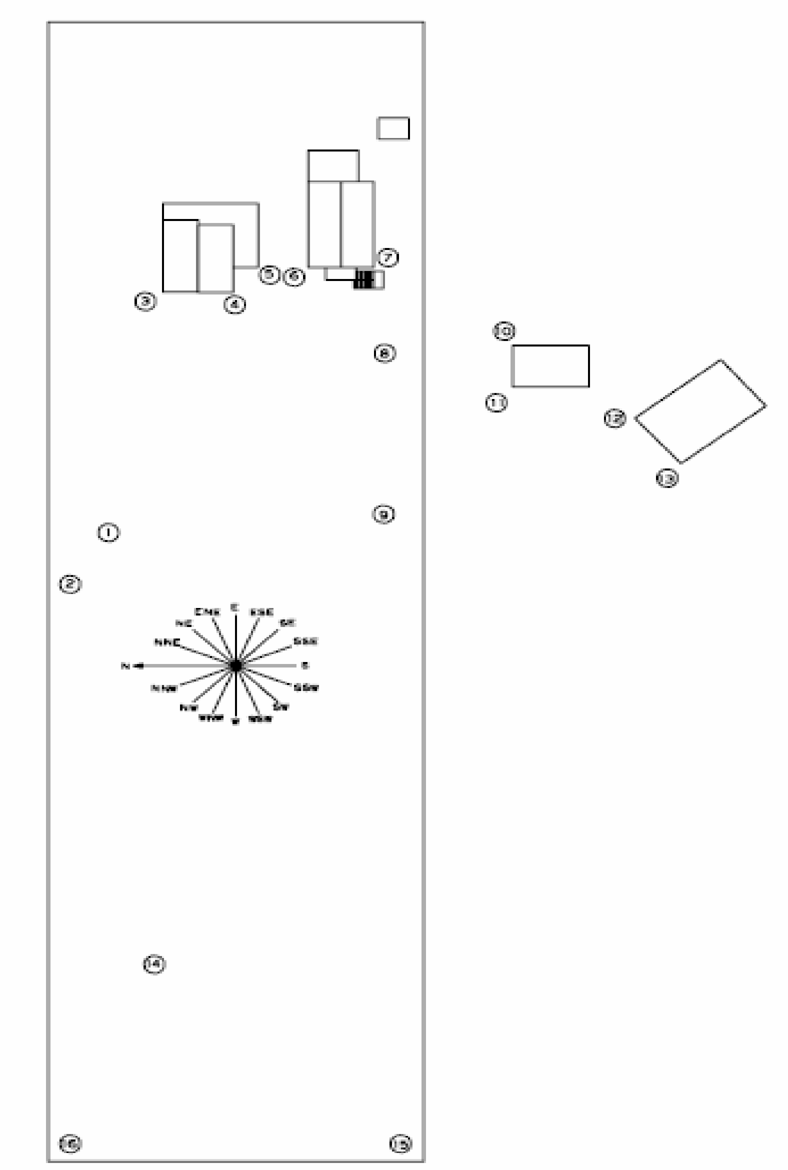
$$v_{new} = v_{known} * (h / h_{known})^{a}$$

where: v_{new} is the velocity of the wind to be determined at the new height
v_{known} is the measured velocity – in most cases (including this study) this is the velocity measured at 10 m above ground level.
h is the new height for which velocity is being determined.
h_{known} is the height at which measurements are taken.
a is an exponent, typically ranging from 0.14 to 0.17, and is dependant upon how smooth the adjacent ground cover is [7]. At this site it is 0.15.

They were then checked for elevation relative to the tower site. This was to assure that there were no obstacles that were within 9 m (30 feet) in elevation of the proposed height of the generator and 91 m (300 feet) distance from the tower. All possible obstacles within 300 feet were noted, and mapped. These objects can be seen in Figure 1 and are noted there for location as well.

IV. Meteorological Data Collection and Recording

Weather monitors can cover quite a price range. Since this project was running under a limited budget, the search focused on the lower priced units. A low cost weather monitoring station (LaCrosse Technologies Model WS-2310) was found and purchased. The accuracies for wind speed (±0.1 mph), direction (16 compass point resolution), temperature (± 0.2 ° C.) and pressure (±0.1 inches of Hg) were within desired ranges. Since the data gathering equipment became operational close to the end of the year in 2004, it was decided to use calendar year 2005 as the data-gathering period. In the early weeks, there were several additional difficulties encountered. There were several ice storms. These coated the anemometer with ice and would not let it turn. There were additional data transmission problems. The lost data was covered by the data recorded by the UNI Earth Sciences department (http://www.uni.edu/storm/). These data points are recorded in the daily data as bold type to designate it as different from the site data.



1	Valley trees south edge
2	Valley trees north edge
3	NW house corner
4	SW house corner
5	SW porch corner
6	NW garage corner
7	SW garage corner
8	South border maple 1
9	South border maple 2
10	Neighbors' garage east
11	Neighbor's garage west
12	Neighbor's house east
13	Neighbor's house west
14	West evergreen
15	West fence-row grove south
16	West fence-row grove north

Figure 1. Site Map showing significant buildings and trees

The data that was sent to the base computer was not in a form that was easily translated. It was necessary to transfer the daily data, by hand, onto paper for later re-entry into spreadsheet form for later manipulation. An example spreadsheet is shown in Table 1.

V. Analysis of Meteorological Data

A list of what the important information to be calculated and displayed was created:

1. Monthly and annual wind roses for speed vs. direction.
2. Monthly and annual wind roses for frequency vs. direction.
3. Monthly and annual histograms to show the frequency of winds at different speeds.
4. Monthly averages for pressure, temperature and wind speed.

The averages for the 24 hourly readings for barometric pressure, temperature, wind direction, wind speed and humidity were calculated for each day and recorded on the daily data sheets. Individual data points for wind speed were pulled from the daily data and re-entered as wind speeds listed within each of the sixteen compass points – by month. For the frequency wind roses, these points within each months sixteen compass point had to be counted and recorded for each of the sixteen points. Examples for these graphical displays of data follow.

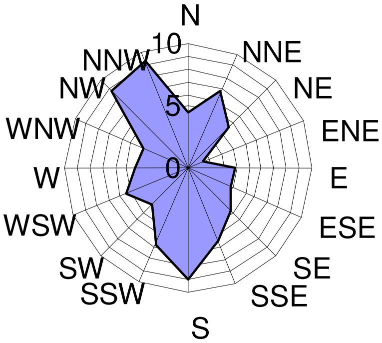


Figure 2. Wind Rose for January 2005. This shows the average strength of the wind for each of the 16 compass points during the month of January.

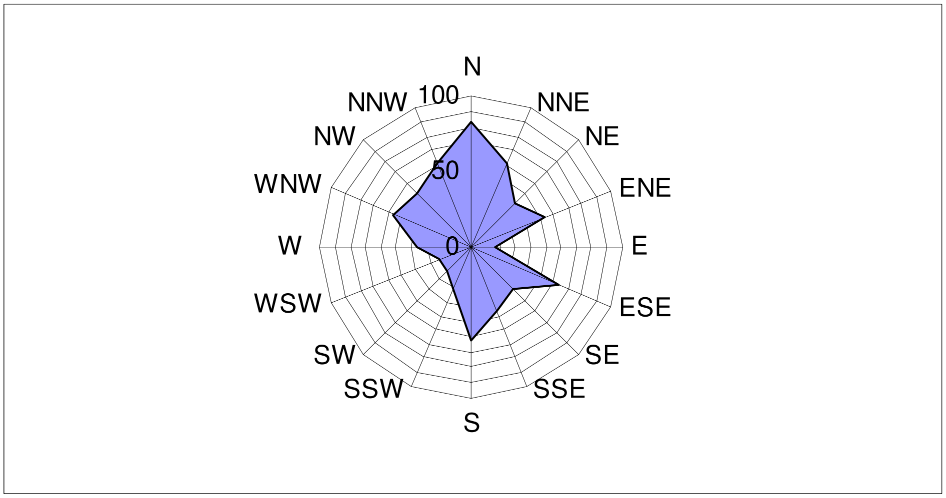


Figure 3. Frequency Wind Rose for January 2005. This figure graphically shows the frequency (in hourly readings) that the wind comes from each of the 16 compass points.

The data sets from the wind roses were copied into files and sorted in ascending order. The data was then grouped into the appropriate intervals and the data points counted within those intervals. These were recorded as paired sets of wind speed ranges and frequency of occurrence. The daily averages for pressure, temperature and wind speed were calculated as monthly and annual means.

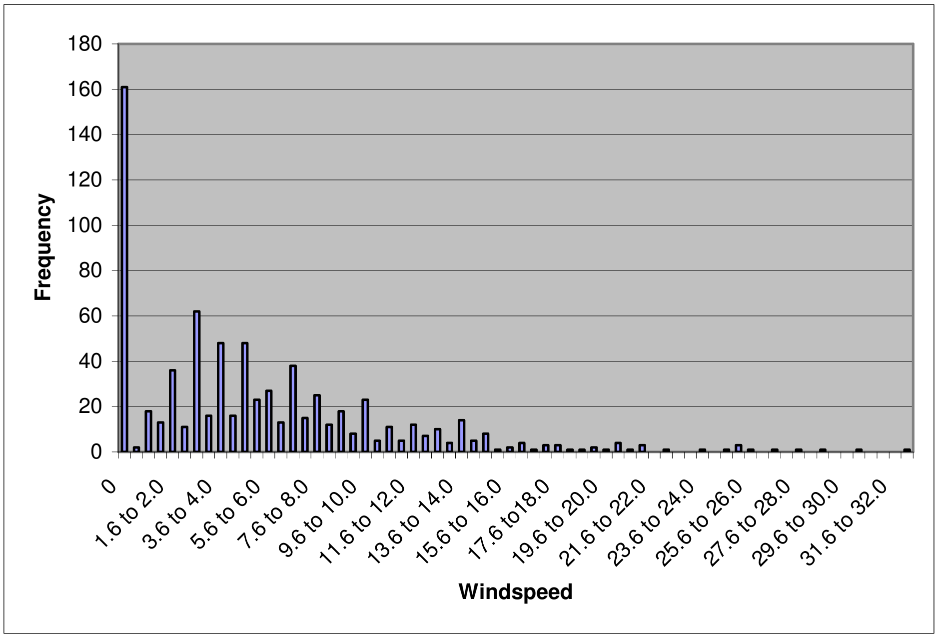


Figure 4. Frequency vs. Wind Speed for January 2005.

Table 1. Summary of Monthly Pressure, Temperature and Wind Speeds at the Test Site

Month	Pressure [inches Hg]	Temperature [^{o}C]	Wind Speed [mph]
January	29.72	-8.45	5.67
February	30.03	0.02	6.42
March	29.84	1.86	8.25
April	29.86	12.41	8.22
May	29.90	15.17	7.42
June	29.93	24.08	6.35
July	29.93	25.20	4.76
August	29.93	22.84	3.74
September	29.98	20.25	5.42
October	30.01	11.81	5.79
November	29.84	3.73	8.33
December	29.94	-8.37	5.79
Annual	29.90	10.05	6.35

VI. Discussion of Equipment

The equipment used is what is required to capture energy from the wind, transform it into a useable form and safely deliver it to the distribution panel. Ancillary devices to protect the system are also included.

The rotor (shown as 1, in Figure 5) transforms the kinetic energy of a flowing mass of compressible gas (the wind) into a mechanical form of energy. The alternator, 2, then transforms this into a wild (not synchronized with grid) AC power, typically multiphase. Since the rotor needs to be held up into the smoother and faster winds that are to be found higher of the ground, a tower, 3, is used. Since the tower may tend to attract lightning, an arrestor, 4, just for that is used. The arrestor will ground the lightning strikes by a ground rod, 5, at the base of the tower. Lightning arrestors, 11, 13, and ground rods, 6, 12, 14, 17, are used in other places where damage could occur. The power is transmitted from the alternator to the distribution panel, 16. Conductors, 7, of the proper ampacity and insulation type are used. These may vary in size and insulation throughout the installation. National Electrical Code (NEC) and applicable local requirements must be satisfied in choosing these conductors. The wild AC, possibly multiphase, is not useable by many standard household devices. To assure 100% compatibility with all devices, a grid intertie inverter, 9, is used. The inverter will convert a variety of inputs, (some inverters will do this simultaneously), into standard 115/230 VAC power at a 60 Hz wave in-sync with the utility power it is tied into and within acceptable limits for Total Harmonic Distortion (THD). The inverter also provides for system disconnect in case the grid, 20, goes down, per NEC requirements. NEC requires that all devices in the system have the capability for upstream and downstream disconnects, 8, 10, 15, to allow for safe service work. The utility disconnect, 19, allows for a lockable utility disconnect required by most utilities. Plans were made for the possibility of including solar PV to feed into the inverter, but will not be discussed here. These items are shown as numbers 22 through 28 in the diagram. There are many considerations for specifying each device listed above. All must work together to give maximum performance and safety. Space to cover these considerations is not given here.

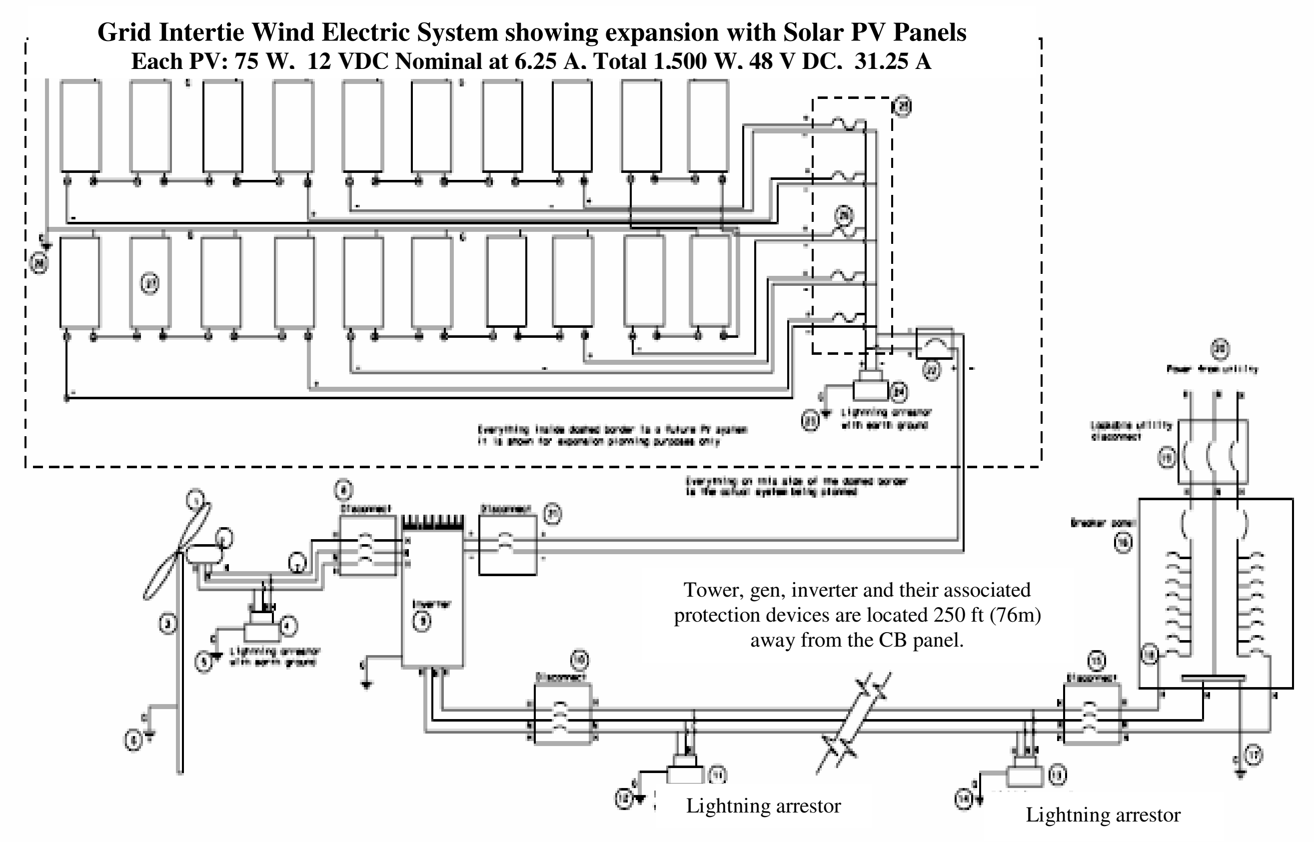


Figure 5. System Layout: Grid intertie wind electric system showing expansion with solar PVs

VII. Determination of Residential Electrical Demand

According to Marier [9], estimating time to use for all electrical loads for a month may determine the estimated monthly demand. Since this is an existing residence, it was decided to exploit the accuracy of past utility bills as a predictor of future demand. The residential electrical demand data is shown in Table 2. The mean for that period is 1027 kWh. The minimum electrical usage during this period was 765 kWh, and the maximum was 1299 kWh.

Table 2. Residential Electrical Demand –Corrected for Analysis

From	To	Metered kWh	Corrected kWh
15 November 2005	15 December 2004	790	790
15 December 2004	15 January 2005	1299	1299
15 January 2005	15 February 2005	1149	1149
15 February 2005	15 March 2005	2624	1000 *
15 March 2005	15 April 2005	2278	1000 *
15 April 2005	15 May 2005	1379	1000 *
15 May 2005	15 June 2005	1085	1085
15 June 2005	15 July 2005	905	905
15 July 2005	15 August 2005	976	976
15 August 2005	15 September 2005	1289	1289
15 September 2005	15 October 2005	1066	1066
15 October 2005	15 November 2005	765	765

* These months were reduced due to problems with the geothermal heating unit. The heating unit was not functioning properly and used significantly more power than normal conditions would show.

VIII. Analysis of Site Factors

From Figure 1, it was observed that there were no objects within 300 feet (94 meters) that would be within less than 30 feet (9 meters) in elevation from the hub of the rotor. As a second check, the 12 monthly frequency wind roses (figure 2 as an example) were looked at as well to see how often the taller obstacles might have a minor effect on the flow. As an unexpected positive outcome, the directions the larger objects are located do not often coincide with the predominant direction the winds come from.

IX. Estimation of System Performance

System performance is measured in Watts available at the distribution panel. The performance of each component from the rotor to the distribution panel needs to be considered. The first thing to consider is the height at which the data was collected vs. the height at which power will be generated. It is always best to use the tallest tower that you can. A self-imposed limit for the tower is that it must be no more than 75 feet (22.86 m) tall. The data was collected at 10 m. At 22.86 m, the tower will be 2.286 times as tall. From the site section, the terrain can be described as tall grass and sparse, low shrubs – which allows wind speed to grow as an exponential function with height where the exponent is 0.15. The increase is seen as:

$(\text{altitude}_{\text{tower top}} / \text{altitude}_{\text{measured}})^{\text{altitude exponent}}$ = Wind speed increase factor at tower top altitude [6].

When the numbers are substituted in this equation, the following is obtained:

$$(22.86 \text{ m} / 10.00 \text{ m})^{0.15} = 1.13204$$

This means that the wind will be 1.132 times faster at 22.86 m than it was at 10 m. This also means that all of the wind speeds from 10 m must be factored upward to account for the higher speeds at altitude.

The next step that must be done is to look up the projected power at the given wind speeds for each generator being considered. For this paper, the Bergey XL.1, 3000 Watt rated machine will be used. The estimated electrical generation by month is listed in Table 3.

Table 3. Wind Speeds and Energy Output by Month

Month	Average Wind Speeds m/s 10 m	22.86 m	Generator Output kWh Bergey XL.1
January	5.667	6.427	74.25
February	6.423	7.270	90.38
March	8.251	9.340	135.00
April	8.225	9.311	134.38
May	7.417	8.396	113.88
June	6.35	7.188	88.75
July	4.758	5.386	56.00
August	3.739	4.233	38.00
September	5.442	6.138	69.00
October	5.785	6.549	76.50
November	8.334	9.434	137.25
December	5.762	6.557	76.63
Annual	6.348	7.186	1090.0
Monthly Avg.			90.83

Downstream system inefficiencies reduce the amount of power available at the distribution panel. Many inverters will operate at an efficiency of about 95 to 96 %. A high capacity underground line was previously buried. Due to the capacity of this line, it will only lose about 1% of the power being transmitted over its' 300 foot (91.44 m) length. The contacts of the switchgear do have some resistive losses. Data could not be found to quantify this performance degradation, therefore a figure of a .99 transmission efficiency will be used as an overall estimate to account for this loss. Combining all of these losses:

$.95_{\text{inverter eff.}} \times .99_{\text{power transmission eff.}} \times .99_{\text{switchgear eff.}} = .931_{\text{overall eff.}}$

Gives 0.931 as a factor to account for system losses. Considering this efficiency, the figures are adjusted in Table 4 to account for the system losses.

Table 4. Annual Production considering account system losses

Generator	Monthly Average Raw	Monthly Average Adjusted	Annual Production Raw	Annual Production Adjusted
Bergey XL.1	90.83 kWh	84.57 kWh	1090.00 kWh	1014.79 kWh

X. Proportion of Demand Satisfied

The estimated performance is disappointing, as can be seen on the chart below. Further conservation efforts could bring these numbers up.

Table 5. Proportion of Residential Electrical Demand Satisfied by Month

Month	Demand kWh	Bergey XL.1 m/s
January	1149	6.46
February	1000	9.04
March	1000	13.50
April	1000	13.44
May	905	12.58
June	533	16.65
July	840	6.67
August	827	4.59
September	808	8.54
October	822	9.31
November	790	17.37
December	1299	5.90
Annual	12324	8.84
Monthly Avg.	1027.0	8.84

XI. Conclusions and Recommendations

The annual electrical demand was found to be 1027 kWh/month. This includes all home heating, domestic hot water, lights and appliances. Continuing conservation efforts will help trim this figure. If that is done, a larger proportion of demand will be satisfied.

Is there a difference between this site and a nearby reliable site?

The wind maps available on-line show wind speeds that would lead one to believe that this was a good site [11-12]. It also seemed to be a good idea to check another site that is nearby and holds credibility. For that, the meteorological data recorded by the UNI project STORM (http://www.uni.edu/storm/) was used. A comparison is shown in Table 6.The data from the study site and the UNI site support each other. They are typically within a couple of mph of each other. They do not agree with the wind maps. In 11th of 12th months, the study site had stronger winds than Project STORM. Another reason would be that winds have been observed as very light in 2005. This could explain the rough correlation between the study site and UNI, but disagreement with the wind maps. An anomaly of an entire year was not expected. Although a year with light winds would conveniently explain the differences, it cannot be counted on for an absolute accounting of the spread. Other means would need to be explored.

How much power can be expected to be generated at this site?

The Bergey XL.1 is rated at 300 Watts, but rarely would have used much of that potential during 2005 [13]. The XL.1 could be looked to for 1090 kWh during 2005, satisfying 8.84% of the residential demand. Due to the large discrepancy between the study site and the wind maps, repeating this study would be a step toward answering if it was the year or the site creating the difference. This would require a second year of data collection. If winds are just 2 mph higher, the site would change from a bad site to a borderline site. If that could be increased by 4 mph, it would be a definite choice.

Table 6. Comparison of wind speed in mph at test site, Project STORM & NREL Wind Maps

			NREL Wind Maps	
Month	Study Site	Project STORM	From Map	Extrapolated
	At 10 m	At 10 m	At 50 m	to 10 m
	mph	mph	mph	mph
January	5.677	5.034	15.7 – 16.8	13.99
February	6.433	5.195	15.7 – 16.8	13.99
March	8.251	6.391	16.8 – 17.9	14.98
April	8.225	5.068	16.8 – 17.9	14.98
May	7.417	5.225	14.5 – 15.7	12.93
June	6.350	4.771	13.4 – 14.5	11.94
July	4.758	2.490	12.3 – 13.4	10.96
August	3.739	0.780	12.3 – 13.4	10.96
September	5.422	6.138	13.4 – 14.5	11.94
October	5.785	3.441	14.5 – 15.7	12.93
November	8.334	6.150	15.7 – 16.8	13.99
December	5.792	4.484	15.7 – 16.8	13.99
Annual Avg.	6.348	4.477	14.5 – 15.7	11.42

Considering the data in Table 6, the different distributions having the same mean wind speeds could have very different results in the amounts of power generated. To prevent this, a study would need to be constructed to give instantaneous power estimates that could be summed and manipulated. This would give a better prediction of the amount of power that could be generated. Wind power development has excelled very quickly in Iowa recently. The Clipper Windpower Inc., nation's one of the largest wind turbine manufacturing companies has established one major plant in Cedar Rapids, Iowa where very large wind turbines are built. Company has already hired few new graduates from UNI and is very interested in hiring more employees having knowledge and skills on wind power technologies, wind site assessment, and wind farms in general. This study will help similar and enhanced work in the wind power area for Iowa's energy independence goals.

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