Applications of Small Wind Turbines Emphasizing the Economic Viability of Integration into a Home Energy System

By

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Abstract

Given the amount of electrical consumption associated with living in contemporary society, renewable energy technologies that offer a distributed and cost effective means of generating electricity need to be further developed and researched. Small wind turbines have the capacity to provide the electrical needs of many residences in the United States. While the benefits associated with using renewable resources and being self-sufficient are widely recognized, these turbines are often marketed without an accompanied understanding of how wind turbines can be successfully integrated into the home energy system (HES) in an efficient and cost effective manner. The result of this is that the cost of energy (COE) associated with small wind turbines is too high and prohibits many potential customers from utilizing this form of energy. In order for the small wind turbine market to gain market prominence in the residential sector, there needs to be a better conceptual understanding of how wind turbines can be integrated into the HES. Moreover, small wind turbines can also offer an effective means for generating electricity for off-grid locations in developing countries. This technology primarily competes with conventional petroleum based generators and solar photovoltaic technology, and the advantages of using small wind turbine technology over these other two technologies is often not clear.

This thesis researches how heat pumps can be used to better integrate wind turbines into the HES. Because wind turbine COE is the primary deterrent to their more widespread use, the impact that this technology can have in reducing the COE of wind turbines is analyzed. Through simulating potential wind turbine applications utilizing heat pumps, this research furthers the conceptual understanding of the systems by which wind turbines can be utilized in an efficient and cost effective manner. The relationship between a prevailing wind and the thermal load on a residence is analyzed, and this analysis coupled with the use of heat pumps to better integrate a wind turbine into the HES represents a unique contribution to this area of literature. This research also studies the performance of a small wind turbine

in a developing country. Given a specific electric load requirement, it analyzes how well suited the wind turbine is for supplying the needed electricity as compared to a conventional gasoline generator and to the potential use of solar photovoltaics. The specific advantages and disadvantages of each of these three technologies are discussed.

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Chapter 1: Introduction

Nomenclature

C_f	[~]	Capacity factor-ratio of actual energy production to that if operated at rated power 100% of the time
CESS	[~]	Conventional energy storage system-use of battery bank to store energy
COE	[$/(kW-hr)]	Cost of Energy-price at which turbine will generate electricity
FCR	[%]	Fixed charged rate-annual percentage rate that is being paid back each year
IC	[$]	Installed cost of the wind turbine system including installation
HES	[~]	Home energy system
MC	[$]	Maintenance cost of turbine, including insurance
NAEP	[kW-hrs]	Net annual energy production of the wind turbine including availability factor

Energy use in the United States is an important issue; for that matter, energy use anywhere is an important issue. It is safe to say that in the current energy dialogue, the issue of the supply of energy garners most of the attention. In comparison, how energy is used receives relatively less discussion. The consumption of energy in the U.S. is massive, exceeding one-hundred quadrillion BTUs annually [1]. Much of this consumption is necessary, and converting resources into useful forms of energy is vital to society. However, the responsible use of energy, in terms of both usage and production, must be considered in society's management of energy. Irresponsible use of energy is often related to a disconnection between the consumption and production of goods present in many peoples' lives; this disconnection almost inevitably results in poorer stewardship of a resource [2].

One resource common to most everybody is that of electricity inside a home. Electricity in a home is needed for many aspects of living such as lighting, heating and cooling, cooking, washing, cleaning, electronics, etc. Small-scale wind turbines have the potential to provide this electricity for a number of residences in the United States and people across the world. Two primary markets that exist for small-scale wind turbines are on-grid residential application and off-grid power generation.

The utility network in the U.S. is well developed, and the majority of residential applications will have the ability to connect to a local utility. The impact of this is that the turbine is not meant to be a stand-alone system, and often is intended only to supplement the electrical supply coming from the grid. Currently, the market for these turbines is quite constrained. Given the prevalent attitude of being “green” among many and being “self-sufficient” among others, it is rather surprising that relatively few residential wind turbines have been installed across the U.S. in the previous decade [3]. One of the main reasons why is that residential wind turbines have been marketed without an accompanied understanding of how residential usage should be integrated into the home energy system (*HES*). This has resulted in a high cost associated with utilizing small wind turbines that has limited their market growth. In order for these residential wind turbines to work as an effective means of generating electricity, they have to be system integrated in a cost effective manner. This thesis attempts to identify the methods or applications in which residential turbines can be integrated into the *HES* in an effective and marketable way.

Small wind turbines also can serve as an effective means of generating electricity in remote (i.e., off grid) locations. Markets for these types of applications exist all over the world, but one major opportunity for small wind turbines is in developing countries. Many developing countries have very limited power distribution to rural locations, and small wind turbines have proven to be an effective means of bringing electricity to many people and villages in remote locations [4]. These turbines serve many rudimentary functions, such as pumping water and refrigeration, that help to increase the quality of life for many people. This thesis will consider the varying ways that wind turbines are being utilized in developing countries, and it will attempt to identify an application to which wind turbines are particularly suited.

The advantage of these wind turbines in both applications is not only that they represent a renewable source of energy, but also that they would allow the end user to have some connection in the production of the electricity on which he or she depends. Whether this connection consists in the homeowner selecting, erecting or maintaining the turbine, or simply in being conscious about matching electricity usage to the energy available in the wind, small wind turbines can enable people to play a role in producing the electricity on which they dependand provide people the opportunity to be better stewards of the electricity that they are using.

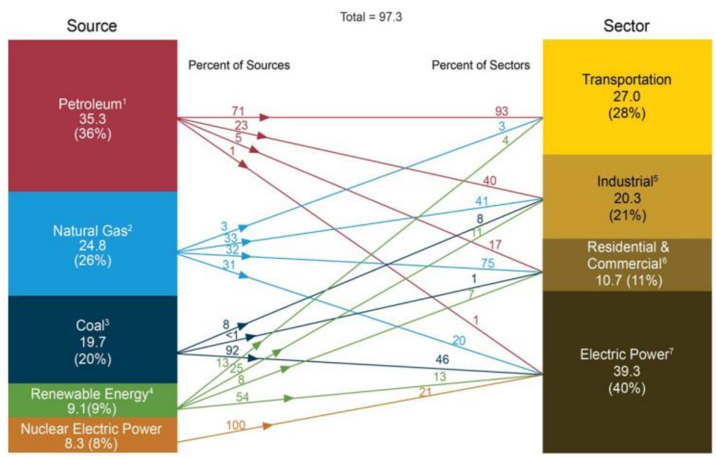


Figure 1: Primary energy consumption by source and sector in 2011 [1].

Residential Application in the United States

According to the Annual Energy Review (AER) [1], in 2011 the U.S. consumed ninety-seven quadrillion BTUs. Energy consumption is divided into four main demand sectors: transportation, industrial, commercial and residential, and electric power. Figure 1 displays the relation between the sources of energy and their respective usage. This figure illustrates that the highest expenditure of energy goes toward generating electricity. Since electricity is used in the other three sectors, there is delineation between demand sectors and end use sectors. The four end use sectors are transportation, industrial, commercial, and residential. A substantial amount of energy is consumed each year to provide the energy needs of houses and apartments. According to the AER, the residential sector uses 22% of end use energy.

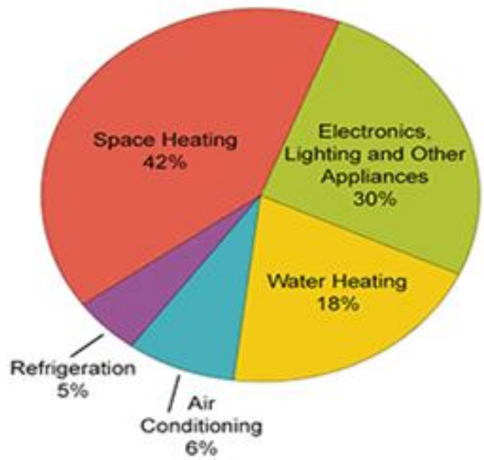


Figure 2: How energy is used in homes in 2009 [5].

Figure 2 shows the household energy consumption broken down into different applications. If 35% of the heating demand and 80% of the cooling demand is supplied by electricity [5], then as a national average 60% of the energy consumed in homes is in the form of electricity. Wind turbines, both small and large, are a technology that have the potential to generate a sizable percentage of this electricity. The wind industry has seen substantial growth in the U.S. in the last 10 years. Annual electric production has increased from 70 trillion BTUs in 2001, to 1,168 trillion BTU's equivalent in 2011 [1]. Overall, wind energy accounts for 13% of the total renewable energy production in the country, which is well ahead of thermal/photovoltaic at 2%. According to the American Wind Energy Association (AWEA), at the end of the 2013 third quarter there was 60,078 MW of installed wind capacity in the states [6]. Utility scale wind turbines, defined as those capable of producing 100kW of power or more, produce the vast majority of this capacity. These turbines are typically installed in wind farms, and the distribution of the generated electricity is distributed to major power centers.

Status of Small-scale Wind Energy

Small-scale turbines are those producing less than 100 kW [7]. These are typically installed singly, and the generated electricity is intended for relatively local use. As of 2011, the installed capacity of small wind turbines in the U.S. was 198 MW [6], over a 100% increase in the installed capacity since 2002. Small-scale turbines are further classified into commercial, residential, and micro turbines [6]. Commercial turbines range between 11 and 100 kW and typical applications include providing power for schools or large farm operations. Residential turbines range between 1 and 10 kW in size and are intended to generate some or all of the electricity consumed in a residence. Micro turbines are those smaller than 1 kW and are primarily used for low power applications on remote sites and battery charging. There is a market for both on and off-grid applications, though the number of grid tied residential turbines is substantially higher. Between 2006 and 2011, roughly 12,000 residential turbines were installed in the U.S., which added an estimated capacity of 40,000 kW. Of note, there is some concern over the relationship between wind turbines and the bird mortality rate. While numerous studies on bird mortality caused by commercial scale turbines have been undertaken, residential turbines which have much smaller blades and short tower heights are deemed to not pose a threat to birds [8].

Given how much electricity is consumed in homes, a market certainly exists for small-scale residential wind power. Depending on the size of the turbine and local average wind speed, residential wind turbines can generate a significant percentage of the electricity consumed in homes. However, not every residence is suited for a wind turbine. In 2007, the Department of Energy (DOE) published a consumer's guide to small wind turbines [7]. In this guide, they state that a small wind turbine can work for a customer if the following five conditions are met:

- There is enough wind to warrant installation of a turbine

- The property is large enough to accommodate a wind turbine
- Local building codes allow the installation of a wind turbine
- There is a substantial electric consumption
- The investment makes economic sense to the customer

These conditions help assess the viability of installing a residential wind turbine with economics playing a large role in acceptance by the consumer. According to the most recent data from the U.S. Energy Information Administration [9], based on 127 million customers nationwide, in 2012 the average annual electric consumption in a residence was 10,837 kW-hrs. At an average price of 11.88 cents/kW-hr [9], the average customer is spending $1287 per year on electricity. Kansas average residential consumption is slightly higher at 11,334 kW-hrs per year [9], and the cost is slightly lower averaging 11.24 cents/kW-hr [9] resulting in a cost of $1274 per year. Therefore, a residential wind turbine must consider the return on investment given the current cost of electricity.

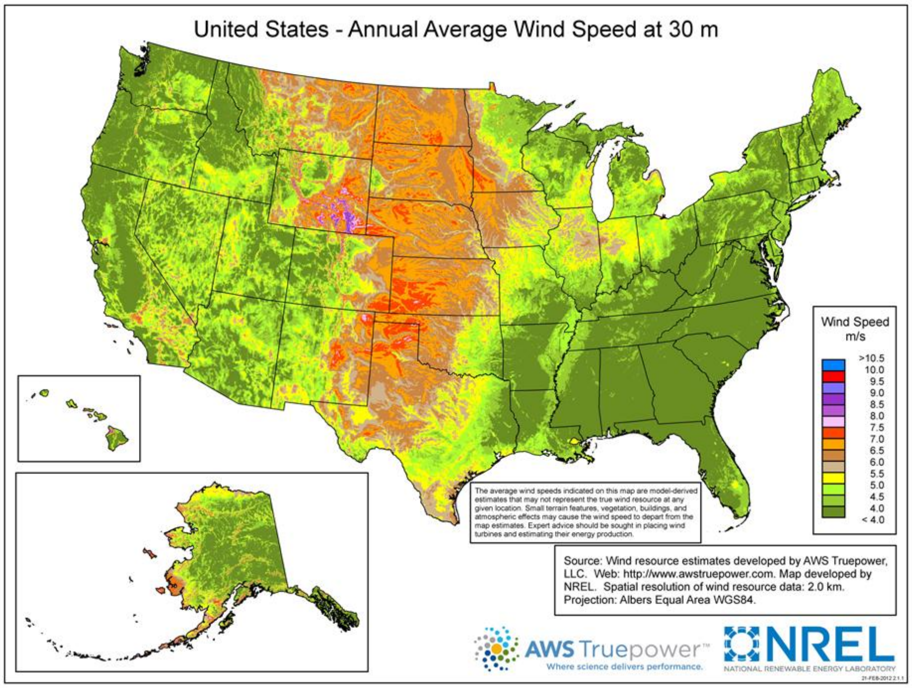


Figure 3: NREL wind speed map at 30m [10]

The energy in the wind varies according to the cube of the wind velocity, and at low wind locations, installing a wind turbine is not practical. Figure 3 is a map of the distribution of the average wind speed across the nation at a height 30 meters above the ground. As can be seen, the Midwest has relatively good wind resources, as does the West in certain areas. The East and Southeast are generally dead spots, and the market for residential turbines in those areas is constrained simply because of the wind.

The size of property attached to the residence is another factor that affects the viability of installing a turbine. These turbines are large enough that installing them attached to the house is not an option, and (typically) they are installed on towers separate from the residence. There are various types of towers, each differing amounts of space, but a general consensus is that these wind turbines require at least one acre of property for feasible implementation [7]. For the most part, this requirement restricts the market for residential turbines to rural properties that dramatically reduces the number of potential customers. However, according to the 2007 DOE guide, there are approximately 21 million homes in the U.S. built on one-acre and larger sites, and almost a quarter of the population live in rural areas [7]. Assuming that most rural county building and planning codes allow for the implementation of residential wind turbines and that rural properties have a normal electricity consumption profile, there exists a number of potential applications to constitute a viable market for residential wind turbines.

Two Market Issues with Residential Wind Turbines

Currently, the residential wind turbine market is not doing well. As mentioned prior, between 2006 and 2011, only 12,000 units were installed nationwide, a mere 2000 turbines a year. South West Wind Power, one of the foremost residential turbine manufacturers in the U.S since 1987, went bankrupt in early 2013, and many other prominent manufacturers of small wind turbines (e.g., ARE and Proven) are no longer in the business. This is because for most applications residential wind turbines do not make economic sense to the consumer. Assessing the economic viability in detail will take place in a later chapter, but a simple way to analyze the cost economics of the wind turbine is to consider the cost of energy (COE) associated with the turbine. The COE is an estimate of the price at which the turbine will generate electricity; it takes into account initial cost of the turbine, maintenance, interest rates, and the electricity generated by the turbine [11].

$$COE = (IC * FCR + MC) / NAEP \tag{1}$$

where IC is the initial cost, FCR is the fixed charge rate (essentially the percentage one is paying back per year, normally considered at 10% [11]), MC is the maintenance cost and $NAEP$ is the net annual energy production. While evaluating the COE is not the only metric for determining economic viability, it serves as a quick check to compare one form of energy against another. For example, Bergey sells a

10kW turbine for $31,700 and a standard 30 m Guyed tower for $14,145 [12]. The $NAEP$ of a turbine can be analyzed through a term called the capacity factor (C_f). The C_f is the ratio of the actual energy produced over a given time period to the amount of energy that would be produced if the wind turbine were operating at full power over that whole period. A study performed in the UK [13] reported that 1.5-10 kW turbines have average C_{fs} of 0.17. Assuming a capacity factor of 0.17, the $NAEP$ would be 14,892 kW-hrs/yr for the Bergey 10 kW turbine. Assuming MC of $.02/kW-hr[11], this would result in a COE of $0.31/kW-hr. Depending on one's location, the COE associated with grid electricity is between $0.07 and $0.16/kW-hr in the state of Kansas. Economically speaking, this appears to make the COE associated with small-scale energy roughly 2-4 times as expensive as compared to conventional grid energy. This is a significant reason why small-scale wind turbines are having a difficult time gaining prominence in the market.

In order for small-scale wind turbines to be more competitive, they need to represent an economically feasible option. However, the demand is not driven entirely by economics. Many people place value on such things as energy independence, clean energy, and self-reliance that residential wind turbines can impart. This being the case, there are relatively few customers for whom this high COE would not pose an obstacle despite these advantages attached to wind turbines. In order for residential wind turbines to gain prominence among consumers, the COE associated with investing in a wind turbine needs to be reduced.

Reviewing the COE, it is high for two main reasons. The first is that the installed cost of the turbine is exorbitant. In the example of the Bergey 10kW, the tower and turbine together cost close to $45,000 or $4500/kW, which on the surface appears to be much higher than the cost associated with solar photovoltaics. A main reason for the high costs of these turbines is that these turbine companies sell only a few units each year; hence, the overhead on each unit remains significantly high. It is often easy to compare the cost effectiveness of wind turbines to solar panels by analyzing their respective cost per installed kW figures. While this can be meaningful at times, it neglects to consider the corresponding capacity factors, and thus does not consider the actual differences in energy generation and associated COE. Though likely the installed cost per kW of a small wind turbine will not match that of a small solar panel, this is not necessary for making small wind turbines competitive with solar panels. That being said, it does seem necessary that the installed cost of the wind turbine be reduced in order to make small wind turbines economically viable. This will be further analyzed at a later point in this report.

The other main reason for the high COE is the relatively low net annual energy production. Many turbines are simply not operating with comparatively high performance efficiencies. In the 2011 AWEA Small Wind Market Study, one of the stated small wind industry goals is to increase blade efficiencies from 32% to 45% [3]. For 21st century blade design and manufacturing, a blade efficiency of 32% (or essentially a power coefficient of 0.32) is quite poor. A value of 0.45 is standard for utility scale wind turbines [11]; small wind turbines are less efficient than utility sized turbines but manufacturers still claim relatively high performance. Compounding this low efficiency rating is that currently, there is no certification process for small wind manufacturers. As a result, manufacturers are not required to rigorously test their products or make public their results. Most manufacturers list the expected annual energy production of their turbine for a given average wind speed, but this is usually a theoretical projection that only considers a smooth and laminar wind flow. In reality, wind turbines operate in turbulent environments that drastically affect the performance of the wind turbine. In most cases, actual energy production is much less than the expected amount. From a 2008 study of twenty-one residential turbines installed in Massachusetts [14], it was found that (on average) the turbines generated only 29% of the installers expected output, and that the turbines operated with a 4.9% capacity factor. It is noted that one of the main reasons for the discrepancy is that the expected energy generation was based on wind maps rather than on local meteorological data. However, the underperformance was also due to inaccurate turbine performance data and unexpected equipment losses [14]. This less than expected energy generation is a common feature of the majority of small wind turbine applications, and it is a main obstacle to the growth of residential wind turbines. In order for residential turbines to be a viable economic investment, their operational efficiency needs to increase as costs are reduced.

Small-scale Subsidies

One way to reduce the COE of small wind turbines is to subsidize their market. These subsidies are primarily in the form of incentives, either to the customer or to the industry. The primary federal incentive to the customer is the Emergency Economic Stabilization Act of 2008 that allows a 30% investment tax credit for the costs associated with installing a small wind turbine. Of note, this policy will extend through December 2016. State incentives generally resulted in a larger impact on the success of the small wind industry [15]. Customer incentives vary considerably between states, but for most states, they exist in some form of financial incentive or in a net metering policy (discussed later). Common financial incentives are grants, tax exemptions, and low interest rate loans. One of the main financial tools to help customers afford the high initial cost of wind turbines is a Property Assessed Clean Energy (PACE) bond. This program attaches the cost of the turbine to the property, the owner of which pays back the loan through increased property tax payments.

There is no doubt that the small-scale wind industry benefits from state and federal subsidies. It has been a common trend that when competing against traditional energy sources, renewable energy has a difficult time being economically competitive on its own merit. While in general this is true, there are certainly applications in which this is not the case. Given that incentive policies vary between locations and over time, a design that manages to integrate a residential turbine onto a residence successfully in an economically viable manner without relying on subsidies is superior to one that does rely on subsidies. If wind turbines can be designed and system integrated in such a way that they warrant their own installation, then the market for residential wind turbines should gain prominence.

Problem of Energy Management

Therefore, in order for residential wind turbines to gain prominence in the market, their associated COE needs to be reduced, primarily through decreasing initial cost and increasing energy production. If this reduction in COE can happen without relying on government subsidies then the market for the turbines will be that much stronger. However, one further obstacle that affects the viability of residential wind turbines is that of energy management. The electricity generated by the turbine does not always balance with the electric load in the house, and at times it is necessary to store the excess electricity (electricity not immediately consumed in the house) generated by the turbine. Though some residential wind systems are designed to simply “dump” excess electricity, for most applications a residential wind energy system that does not manage to use all or nearly all of the generated electricity is not going to be economically viable. This generally requires some form of electrical storage.

The most popular option is to connect the turbine to the local electric grid, essentially treating the grid as a giant battery. The federal Public Utility Regulatory Policies Act (PURPA) of 1978 [7] requires utilities to connect with and purchase electricity from residential wind systems. Thus, for all applications that have a local electric grid (the vast majority), putting excess electricity back onto the grid is an option. However, unless the utility company offers some form of net metering program, this option is not very desirable to the customer. Net metering is a policy in which utility companies credit their customers with the electricity that they put back onto the grid. Some utility companies offer this policy without being required to by state law. Most states have some form of residential wind turbine incentive, with net metering being the most popular [15]. Currently, only sixteen states have statewide policies that require all public and private utility companies to offer net metering [3]. In Kansas, as of 2009 investor-owned utilities (Westar, Kansas City Power and Light, Empire Power District) are required to offer net metering to their customers, while publicly owned utilities (electric cooperatives) are not [16].

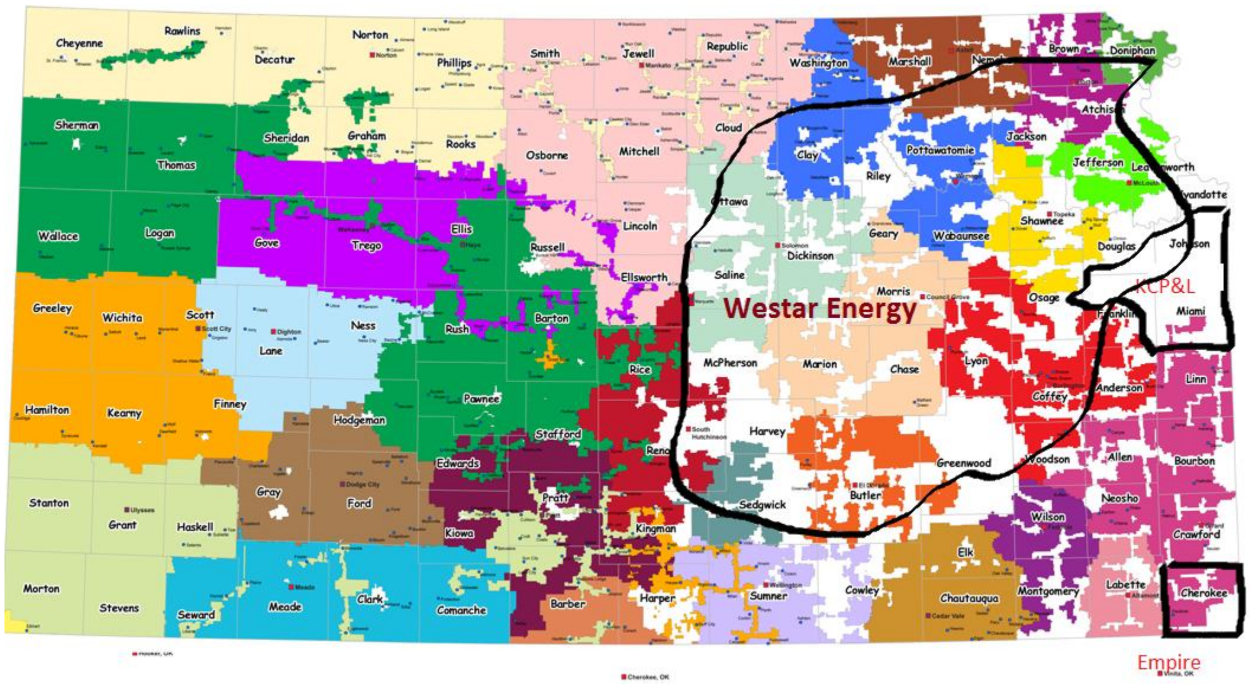


Figure 4: Service territory map of electric cooperatives in Kansas [17]

Figure 4 shows the service area of the electric cooperatives in Kansas as well as the general service areas of the investor owned utility companies operating in Kansas. As can be seen, in much of Kansas, especially western Kansas, the electricity is supplied by electric cooperatives. Kansas City Power and Light as well as Empire Power District serve primarily in Missouri; Westar services approximately 700,000 Kansas in the central and eastern part of the state. Electric cooperatives can provide net metering incentives, but they are not required to do so by state law as mentioned prior.

The feed in tariff rate is the rate at which the utility companies will purchase electricity from the customer. While it is relatively profitable in Europe, and even in some parts of the U.S., in general this rate in the U.S is low. It is valued as the avoided cost that the utility companies observe by not having to produce the electricity, and the market price is usually around 2-3 cents/kW-hr. For wind turbines to be economically viable, all or nearly all of the electricity they produce needs to have a value commensurate to the price that could be purchased from the grid. If a substantial amount of the energy generated is being sold below market prices, investing in a turbine will not make economic sense.

Because of this low market price for applications without a net metering policy in place, to maximize the economics one might consider alternative methods of utilizing the excess electricity generated that maintains the value of the electricity (i.e., 2-3 cents/kW-hr to sell, or around 11-12 cents/kW-hr to store and use later). One method has been to employ an auxiliary load, such as a water pump, to utilize this excess electricity. A second more popular method has been to use some form of energy storage local to the property, most commonly with batteries, to be referred from here on as the *conventional energy storage system (CESS)*. There are two drawbacks to this strategy. The first is the additional cost of the system that, depending on the size of the battery bank, can be substantial. The second is the physical space that the system requires. This includes both the batteries themselves and the place to store the batteries. Unless there exists on the residence some suitable place to store the batteries, some form of energy storage shed will need to be constructed for the system. However, this is a difficult quantity to cost and will not be considered in the evaluation of the economic viability of the system. Instead, it is assumed that ample room exists in the residence (e.g., basement) that can house the system.

Focus of Research

One purpose of this thesis is to explore the viability of employing a heat pump as an auxiliary load to utilize excess electricity by heating or cooling the house to desirable temperatures. As the temperatures in a house fluctuate, this effectively uses the house as a medium for storing energy. Specific importance will be given to understanding how wind affects the heating and cooling loads of the house, and, thus, how well wind turbines are suited to provide the electricity for that load. This method assumes that the cost of the energy storage is external to the cost of the wind energy system. This will occur by assuming that the heat pump already exists on a given property, and the wind turbine will concentrate on the economics of integrating a wind turbine into the existing residence.

Off-Grid Small Wind Turbines in Developing Countries

Another market for small-scale wind turbines is providing power in off-grid locations. Off-grid locations are those that do not have access to a centralized power grid and instead rely on distributed energy sources for power generation. In these applications, the power generating units are relatively small and located at or near the consumer sites, and the power is utilized at a relatively local level [18]. The driving force for utilizing a distributed energy source is that a centralized utility network does not exist, expanding it is not possible, or expanding it would be relatively expensive. In these instances, distributed sources offer the only feasible means of electric power production. Though distributed energy generation itself does not entail being off-grid and generating units can be as large as 300 MW [19], distributed energy sources that are off-grid are generally utilized on the small and micro scale (500 W - 5 MW[19]). A number of small-scale distributed generation technologies exist including reciprocating engines, gas turbines, hyrdo turbines, wind turbines, photovoltaics, fuel cells, geothermal, and thermal solar [20].

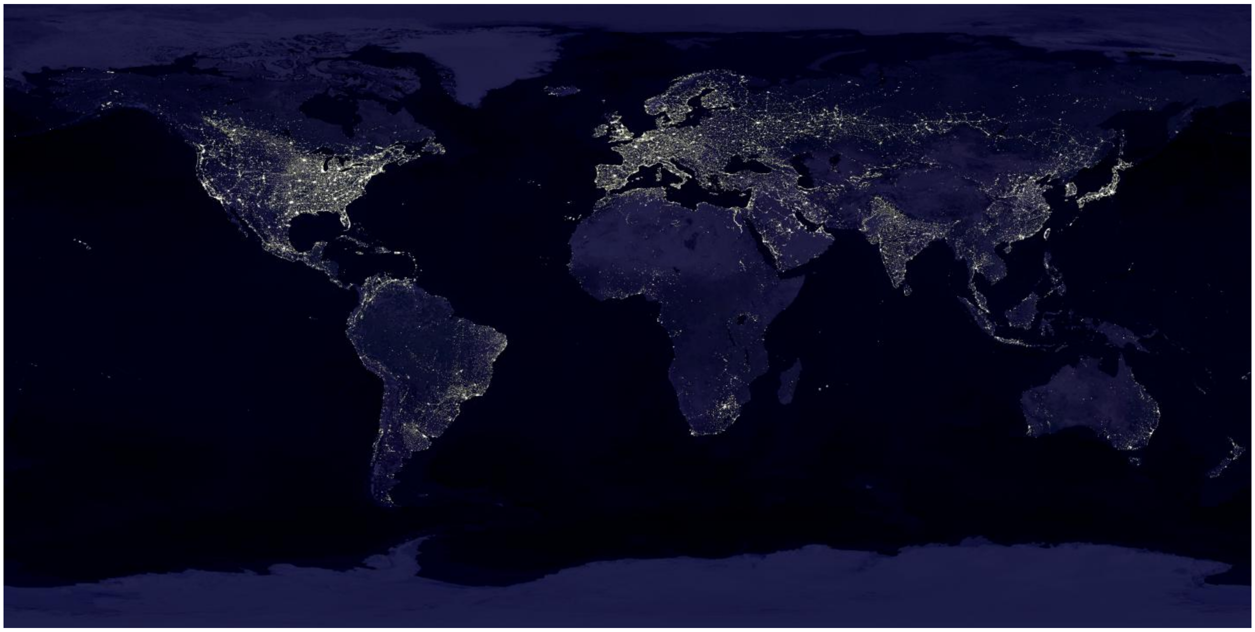


Figure 5: NASA satellite image of earth at night [21]

A major market for these small distributed energy sources exists in developing countries. As mentioned prior, the utility network in the U.S. is quite extensive, and there are relatively few population areas that do not have access to grid electricity. While using distributed energy sources in the U.S. is important for balancing loads and avoiding over-centralized energy production, it is not in the strict sense necessary the majority of the time. This is not the case in many developing countries. Figure 5 is a nighttime satellite image of the earth's energy consumption at a given point in time. Though it does not represent exactly the extent and location of electric networks, it visually illustrates how much farther advanced first world country's electric networks are compared to developing countries, and how more than one billion people can be living without access to electricity [22]. As can be seen from the picture, vast areas of Africa and Asia are literally without any major power distribution centers. Small villages in these countries have especially limited access to electricity. In 1971, a report on the status of rural electrification in India stated that only 12% of villages with population under 500 had access to electricity (small villages accounting for 60% of the total number of villages) [23]. Currently, in India it is estimated that 56% of rural households are without access to electricity [24]. Though grid extension continues to grow, without major power generation distribution centers and a primary power grid, many locations in developing countries rely on small distributed sources of energy for electrical generation.

Renewable energy sources are effective means of providing this distributed energy. Renewable energy technologies are distinguished from other distributed energy technologies in that they rely on a resource that is naturally replenished in a relatively short time scale. Given current technology, the primary renewable energy sources considered for electric generation in developing countries are solar photovoltaic, wind, and hydroelectric. A main advantage associated with using renewable energy is that the source of fuel is internal to the system. This is unlike a reciprocating engine that requires an external supply of petroleum. This has two important entailments. First, the fuel source and thus a large part of the operating cost is essentially free, and the ability to operate the generator is not dependent on cost economics associated with variability in the price of fuel and the purchasing thereof. Secondly, the supply of the fuel is in a sense constant, and issues concerning the transportation of fuel are not present. In terms of both the logistics of the transportation of fuel to remote locations and the cost associated with transportation, this is a major advantage. Though these are two clear advantages to renewable technologies, this independent fuel supply can also at times be a disadvantage in that an indeterminate fuel input results in an unsteady power output. This limitation influences the applications for which renewable technologies are suited along with the associated system requirements.

In developing countries, rural electrification often does not entail a vast expansion of electrical consumption, but rather a limited use of electricity to perform basic functions. Electrical usage in small villages can be distinguished between agricultural and domestic uses. In terms of agriculture, a substantial amount of energy is put into drawing water for irrigation, and it is estimated that in Indian villages that have been electrified, around 80% of the electric consumption is used for this purpose [23]. It is characteristic in poorer countries that a substantial amount of the energy used to draw water for irrigation comes from human and bullock labor [23], and larger renewable energy systems could certainly provide a more efficient and appropriate means of providing energy for this purpose. In terms of domestic usage, small amounts of electricity can significantly increase the quality of life in many third world villages [11]. In India, it was estimated that an installed generating capacity of 25 kW is sufficient for a village with a population of 1000 [23]. Traditional use of electricity has been for lighting purposes [23]; other uses include pumping drinking water, water heating, cooking, television, radio, and cellular battery charging [25].

Figure 6: A small village in Pakistan electrified solely by small wind turbines [4]

Small wind turbines have the potential to provide electricity for a number of these applications. Historically in the U.S., rural electrification was one of the primary functions of small electric wind turbines [11]. Now, as many developing countries are slowly beginning to expand their rural electrification, wind turbines are being utilized as a feasible option in many locations. One country beginning to increase its utilization of wind energy is Pakistan. As of 2003, the country did not have a single wind turbine installed on record with a capacity over 500 W [4]. Since then, it has increased its wind energy production, on both the small and utility scale, and has installed 151 kW of small wind turbine capacity to aid rural electrification. Figure 6 depicts the first village in Pakistan to be electrified through wind energy using 26 micro turbines each rated at 500W.

Viable Energy Sources for Small-scale Applications in Developing Coutries

For small-scale off-grid operations, gasoline or diesel generators have been the conventional technology of choice. As long as a reliable supply of fuel is present, these generators can deliver a constant electric output that is subject to user-demand. One main disadvantage though of this technology is the reliance upon petroleum fuel, which as mentioned prior, can become expensive to buy and or transport. Two alternative technologies competing with this conventional means are solar photovoltaics and wind energy. For small-scale applications, solar photovoltaics generally offer a more affordable option [26]. Also, solar photovoltaic technology is much simpler to install, control, and maintain. In addition, because of the stochastic nature of the wind, it is much easier to estimate the energy output of a solar panel versus a wind turbine. Over a given time, and this can make designing an off-grid power system a simpler task. One main advantage that wind energy holds over solar photovoltaics is that depending on the wind resources of the location, wind can have a much higher energy density than solar energy [11], even to the point of making wind a more affordable option than solar.

Often these sources are utilized in conjunction with each other, referred to as hybrid systems. A hybrid system is one that uses multiple technologies to generate energy for the same function. Hybrid systems have the advantage of producing a relatively more stable power supply by combining the strengths of the different technologies, and it is common to see all three technologies utilized in many off-grid applications. While this is true, for remote locations in developing countries, it is often more desirable to design standalone systems (e.g., systems that use only one technology to provide energy for a given function). There are a number of reasons for this, the primary one being the higher simplicity of the resulting system.

Focus of Research

Another purpose of this research effort is to identify a domestic electrical need in a developing country for which a small wind turbine could be utilized and then to experimentally investigate if the wind turbine is suited for the application. The wind turbine should successfully generate the electricity according to a set of system requirements and prescriptions (cost economics included), and that it produces the electricity relatively better than other alternative methods (e.g., solar photovoltaics or conventional generator) of electricity generation. Using this information, the preferred ability of wind, solar, or petroleum (or combination thereof) for a certain application in a developing country will be concluded.

Chapter II: Wind as an Energy Resource

Nomenclature

A_{plane}	[m^2]	Area across which air is flowing
A_{rotor}	[m^2]	Swept area of the turbine rotor
C_p	[~]	Power coefficient-% of power turbine is able to extract from P_{wind}
e	[J/kg]	Specific energy of wind pertaining to kinetics
E_{prod}	[J]	The energy production of the wind turbine over a given time period
$f(v(t))/PDF$	[~]	Probability density function of the wind blowing at a certain velocity
$F(v(t))/CDF$	[~]	Cumulative probability function of the wind velocity
$\dot{m}$	[kg/s]	Mass flow rate of air
$NAEP$	[kW-hrs]	Net annual energy production of the wind turbine including availability factor
P_{aero}	[W]	Power extracted by the wind turbine at a given wind velocity
P_{elec}	[W]	The electric power produced by the turbine considering system inefficiencies
P_{rated}	[W]	Power which the turbine is rated to produce
P_{wind}	[W]	Kinetic power in the wind
TSR	[~]	Tip speed ratio-ratio between the speed of the blade tip and the prevailing wind
$v_{avg}/\ V_{avg}$	[m/s]	The average annual wind velocity for a given site
$v_{cut\text{-}in}$	[m/s]	Wind velocity at which turbine begins producing power
$v_{cut\text{-}out}$	[m/s]	Wind velocity at which turbine stops producing power (shuts down)
v_{rated}	[m/s]	Wind velocity at which turbine reaches rated power
V_{wind}	[m/s]	Velocity of the wind
η_{gbox}	[~]	Efficiency of the gear box
η_{gen}	[~]	Efficiency of the generator
η_{inv}	[~]	Efficiency of the inverter
η_{syst}	[~]	System efficiency including the generator, gearbox, and inverter
ρ	[kg/m^3]	Density of the air

Wind turbines produce electricity by converting kinetic energy in the wind into mechanical motion. A basic understanding of the power in the wind is presented in this chapter; the analysis follows that presented in Gary Johnson's Wind Energy Explained textbook [27]. The available power in the wind is considered part of the wind flowing normal to some plane of reference and is a function of the mass flow rate of the air along with the kinetic energy density at which the air is moving. The mass flow rate of the air is given by the formula:

$$\dot{m} = \rho A_{plane} V_{wind} \qquad \text{[kg/s]} \tag{2}$$

where ρ is the density of the air, A_{plane} is the area of a given plane normal to the flow of the air, and V_{wind} is the velocity of the air. The kinetic energetic density (e) is simply the intensive kinetic energy of air moving at a given speed:

$$e = \frac{1}{2} V_{wind}^2 \qquad \text{[J/kg]} \tag{3}$$

The power in the wind (P_{wind}) is simply a product of the mass flow rate and the kinetic energy density:

$$P_{wind} = \dot{m}e = \frac{1}{2} \rho A_{plane} V_{wind}^3 \text{ [W]} \tag{4}$$

In terms of wind turbine power production, A_{plane} equals the area of the rotor (A_{rotor}), and Equation (4) illustrates that the available power in the wind is heavily dependent on the prevailing wind speeds and the size of the turbine rotor. In the analysis of turbine power, the wind velocity is the magnitude of the wind speed at the hub height of the rotor normal to the rotor plane, and the area of the plane is the full area that the turbine sweeps as it rotates. The density of the air changes depending on the local temperature and elevation, but for calculation purposes, the power is analyzed here at standard air density.

It is important to note that not all of the power in the wind is extractable by the turbine. Turbine operation is a steady state process in which air moves across the rotor plane from a high-pressure zone to a lower pressure zone. Extracting all of the available power in the wind would require that the final velocity of the air after crossing the rotor plane be zero. This would effectively stop air movement across the rotor and completely halt power production. The concept of aerodynamic efficiency in wind turbines addresses how much of the available power the turbine can extract from the wind. There exists, in theory, a maximum possible amount of the available power that any turbine can extract. This is known as the Betz Limit, and it states that the maximum percent of extractable energy across a turbine is 59%

of the available power in the wind. This value can be considered a physical limit rather than as efficiency, and the aerodynamic efficiency of wind turbines should be analyzed against this value. In wind turbine terminology, the power coefficient (C_p) is the fraction of available power that a turbine is able to extract, and the aerodynamic power (P_{aero}) equals the amount of power extracted by the turbine rotor:

$$P_{aero} = C_p P_{wind} = \frac{1}{2} C_p \rho A_{rotor} V_{wind}^3 \text{ [W]} \tag{5}$$

The aerodynamic power, which affects itself by turning the rotor with a certain torque and angular velocity, is converted into electricity by spinning a shaft inside a generator. The generator has an associated inefficiency (η_{gen}), and depending on the turbine a gearbox might be employed that has also associated inefficiencies (η_{gbox}). Generally, these are the only two system inefficiencies considered in the evaluation of electric power. However, most residential turbines require an inverter to deliver 60 Hz AC signal, and this additionally has an associated inefficiency (η_{inv}). For the analysis of residential wind turbines, these three efficiencies will make up the system inefficiencies of the wind turbine. The total system efficiency is thus equal to:

$$\eta_{syst} = \eta_{gen} \eta_{gbox} \eta_{inv} \qquad \text{[~]} \tag{6}$$

and the electric power(P_{elec}), generated by the turbine is given by the equation:

$$P_{elec} = \frac{1}{2} n_{sys} C_p \rho A_{rotor} V_{wind}^3 \quad \text{[W]} \tag{7}$$

This P_{elec} is the energy rate at which the turbine will deliver energy to the residence. The amount of energy produced by the turbine (E_{prod}) is simply the instantaneous power production integrated over a length of time:

$$E_{prod} = \int P_{elec}(t)dt = \int \frac{1}{2} n_{sys} C_p \rho A_{rotor} V_{wind}^3(t)dt \quad (8)$$

with the air density assumed to remain constant over time.

The Rayleigh Wind Distribution

Electric energy generation is highly dependent on the wind velocity at any given time. Wind velocity is a relatively stochastic phenomenon, and any attempt to predict wind speed at best yields only rough estimations. Nonetheless, analyzing the energy capture of a given wind turbine at a given location requires determining (or estimating) how the wind speed varies over time. Often complicated models for describing the wind resources are developed for a given location, but the general method of approximating the wind profile is to use a Rayleigh distribution [11, 27]. In this distribution, the instantaneous velocity is a function of the average velocity of the location only. The probability density function of the Rayleigh distribution is given as:

$$f\left[v(t)\right] = \frac{\pi}{2} \frac{v(t)}{v_{avg}^2} e^{-\frac{\pi}{4}\left[\frac{v(t)}{v_{avg}}\right]^2} \quad [\sim] \quad (9)$$

where v_{avg} is the average annual velocity of the wind site. This distribution gives the probability of the wind blowing at a certain velocity given an average annual velocity. In wind power analysis, the primary method of analyzing wind speed probabilities and the corresponding power production is to bin the wind speeds in 1 m/s increments. The easiest way to do this is to consider the cumulative distribution density function of the wind speed:

$$F\left[v(t)\right] = \int_0^v f\left[v(t)\right]dt = 1 - e^{-\frac{\pi}{4}\left[\frac{v}{v_{avg}}\right]^2} \quad [\sim] \quad (10)$$

This cumulative density function (CDF) is the probability that at any time the wind speed will be less than a given velocity.

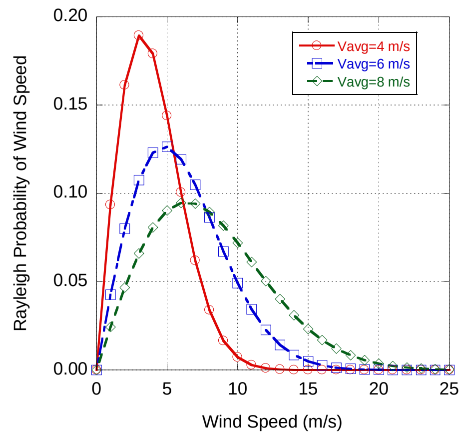


Figure 7: Rayleigh probability density function for different wind speeds

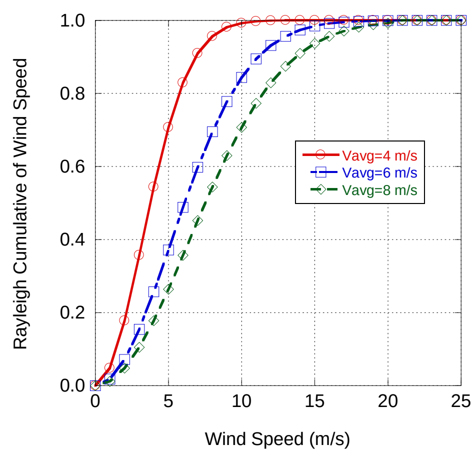


Figure 8: Rayleigh cumulative density function for different wind speeds

Graphically, these functions are represented in Figure 7 and Figure 8 respectively. Both of these graphs illustrate the impact that the average annual wind speed will have on power production. Instantaneous power production varies according to the cube of the wind speed, and sites with higher average velocities spend substantially more time at higher velocities.

As mentioned prior, wind power analysis often bins wind speeds and their associated probabilities into specific ranges. In this analysis, the CDF is binned by 1 m/s increments with bins centered on integer velocities. The velocity distribution of the wind over a period is then determined by analyzing the cumulative probability at these binned integers:

$$T(v) = F(v + \frac{1}{2}\Delta v) - F(v - \frac{1}{2}\Delta v) \tag{11}$$

here Δv is the 1 m/s increment. The corresponding percent time associated with each velocity bin is best represented through tabulation.

Table 1: % Time of operation at different wind speeds for site with 6 m/s average wind speed

Bin Velocity	V_{avg} 4 m/s	V_{avg} 6 m/s	V_{avg} 8 m/s
m/s	% Time	% Time	% Time
0	1.22%	0.54%	0.31%
1	9.24%	4.25%	2.42%
2	15.96%	7.96%	4.66%
3	18.77%	10.71%	6.57%
4	17.80%	12.26%	8.05%
5	14.36%	12.60%	9.01%
6	10.08%	11.91%	9.45%
7	6.25%	10.47%	9.40%
8	3.44%	8.64%	8.94%
9	1.69%	6.71%	8.17%
10	0.74%	4.94%	7.19%
11	0.29%	3.44%	6.12%
12	0.10%	2.28%	5.03%
13	0.03%	1.43%	4.02%
14	0.01%	0.86%	3.11%
15	0.00%	0.49%	2.33%
16	0.00%	0.27%	1.70%
17	0.00%	0.14%	1.21%
18	0.00%	0.07%	0.83%
19	0.00%	0.03%	0.56%
20	0.00%	0.01%	0.36%
21	0.00%	0.01%	0.23%
22	0.00%	0.00%	0.14%
23	0.00%	0.00%	0.09%
24	0.00%	0.00%	0.05%
25	0.00%	0.00%	0.03%
Total	**100.00%**		

Calculation of Energy Capture for Different Sized Turbines and Wind Speeds

Part of the reason for analyzing the wind as a discretized distribution rather than as a continuous function is that usually turbine power coefficients and system efficiencies are characterized in 1 m/s increments as well. Thus, power generation as a function of time is also analyzed as a discrete distribution. At this point, a few terms that need to be introduced that are relevant to a turbine power analysis. The cut-in velocity ($v_{cut\text{-}in}$) is the minimum velocity the turbine must achieve to begin operation. The cut-out velocity ($v_{cut\text{-}out}$) is the maximum velocity that the turbine can encounter before it will shut down. The rated power (P_{rated}) is the electric power at which the turbine is designed to regulate in high winds. The rated velocity (v_{rated}) is the wind speed at which the turbine reaches rated power. The tip speed ratio (TSR) is the ratio between the velocity at the tip of the blade and the wind velocity. The aerodynamic properties of blades are such that the performance coefficient of the blades (or the power coefficient of the turbine) is a function of the TSR. Another way of saying this is that for a given TSR there is a set power coefficient. Thus, turbine performance can be represented as a function of wind speed which lends itself well to the discretization of the power analysis. The optimal TSR is that which yields the highest blade performance, and normally turbines are controlled to operate at the optimal TSR until they reach rated power. At this point, as the wind speed increases, turbines operate off optimal TSR in order to regulate power. The availability factor is the percent time during the year that the turbine is operable. Because turbines will require maintenance or repair, this value is normally less than 100%.

Given the described equations for the electrical power and the distribution for the wind velocities, the energy generation over a set period can be readily calculated for an idealized performance curve and wind distribution. For a given average wind speed and turbine size, the only assumptions that need to be made are those concerning the power coefficients of the turbine, the system efficiency of the turbine, the availability factor of the turbine, and the turbine operating parameters ($v_{cut\text{-}in}$, $v_{cut\text{-}out}$, and P_{rated}). While there is a region of operation below rated at which the turbine operates at optimal TSR, it usually does not operate at optimal TSR until a few m/s above $v_{cut\text{-}in}$ [28, 29] . This analysis will assume a maximum C_p of 0.4 at optimal TSR and then a linear regression from of 0.2 at $v_{cut\text{-}in}$ to 0.4 at 2 m/s above $v_{cut\text{-}in}$. Ozgener [29] measured the performance on a small 1.5

kW turbine, and this study suggests that these are reasonable values to assume. While this results in a slightly idealized operation, these power coefficients are achievable for residential wind turbines. Because most residential turbines are direct drive and do not require a gearbox, the system efficiency is relatively high. For this analysis, it will be assumed to be 0.90; this value is slightly conservative as compared to the results found in study [29]. Residential turbines are also designed to be relatively low maintenance machines, and the assumed availability factor will be 0.95 [30]. The turbine operation will assume $v_{cut\text{-}in}$ to be 4 m/s, $v_{cut\text{-}out}$ to be 25 m/s, and P_{rated} to occur at 10 m/s .

Table 2: Energy analysis for turbine with given parameters

Rotor Diameter	**5**	**m**					
Air Density	**1.225**	**kg/m^3**					
V_{avg}	**6**	**m/s**					
η_{syst}	**0.90**	**~**					
Availability Factor	**0.95**	**~**					
Available Time	**8760**	**hrs**					
P_{rated}	**4.33**	**kW**					
V	V **range**	C_p	P_{wind}	P_{aero}	P_{elec}	**Time in Range**	**Energy Output**
m/s	**m/s**	**~**	**kW**	**kW**	**kW**	**%**	**kW-hrs**
<3.5	0-3.5	0	~	0	0	10.71%	0.0
4	3.5-4.5	0.2	0.770	0.154	0.139	12.26%	141.3
5	4.5-5.5	0.3	1.503	0.451	0.406	12.60%	425.6
6	5.5-6.5	0.4	2.598	1.039	0.935	11.91%	926.5
7	6.5-7.5	0.4	4.125	1.650	1.485	10.47%	1294.0
8	7.5-8.5	0.4	6.158	2.463	2.217	8.64%	1593.3
9	8.5-9.5	0.4	8.767	3.507	3.156	6.71%	1763.6
10	9.5-10.5	0.4	12.026	4.811	4.330	4.94%	1778.6
11	10.5-11.5	0.30	16.007	4.811	4.330	3.44%	1239.5
12	11.5-12.5	0.23	20.782	4.811	4.330	2.28%	820.2
13	12.5-13.5	0.18	26.422	4.811	4.330	1.43%	516.0
14	13.5-14.5	0.15	33.000	4.811	4.330	0.86%	309.0
15	14.5-15.5	0.12	40.589	4.811	4.330	0.49%	176.3
16	15.5-16.5	0.10	49.260	4.811	4.330	0.27%	95.8
17	16.5-17.5	0.08	59.086	4.811	4.330	0.14%	49.7
18	17.5-18.5	0.07	70.138	4.811	4.330	0.07%	24.6
19	18.5-19.5	0.06	82.489	4.811	4.330	0.03%	11.6
>20	19.5+	0.00	~	0.000	0.000	0.01%	0.0
						$NAEP$ **(kW-hrs)**	**11165.7**

Table 3: $NAEP$ varying with rotor size and average wind speeds

	Rotor D=3 m	Rotor D=5 m	Rotor D=7 m
V_{avg} = 4 m/s	1351.7 kW-hrs/yr	3754.8 kW-hrs/yr	7359.5 kW-hrs/yr
V_{avg} = 6 m/s	4019.5 kW-hrs/yr	11165.7 kW-hrs/yr	21884.1 kW-hrs/yr
V_{avg} = 8 m/s	6354.8 kW-hrs/yr	17652.3 kW-hrs/yr	34598.6 kW-hrs/yr

Table 2 provides an illustration for how energy production is evaluated for wind turbines. For most turbine power analysis, the goal is to estimate how much energy the turbine will produce in a year for a given wind site. When this analysis incorporates the availability factor, this amount of energy is referred to as the net annual energy production ($NAEP$). This value is extremely important in determining the cost economics of the wind turbine. Table 3 tabulates the $NAEP$ for three different turbine sizes and three different wind speed locations using the same analysis method and parameters as presented in Table 2. Looking across this table, it can be seen how power production varies significantly with rotor size. Looking down the table, comparisons can be made concerning the energy production for locations with different average annual wind speeds.

Table 2 and Table 3 also illustrate the applicability of wind turbines to provide the electrical needs of residential houses. The turbine in Table 2 was a 5 m turbine with a rated power of 4.33 kW. It produced 11,165 kW-hrs over the course of a year, which is commensurate to the average residential electric consumption as presented in Chapter 1. For residences that consume substantially more or less electricity, these tables indicate the turbine size suited to generating that amount of electricity. It should be noted from Table 3 how little energy is produced at low average wind speed sites. This reinforces the notion that wind turbines are not suited for operation in locations with relatively little wind, and there is a minimum average wind speed per location in order for the turbine to be economically viable.

Chapter III: Current Market Products and their Cost Economics

Nomenclature

BOS	[$]	All costs associated with purchasing and installing the wind turbine other than the turbine and tower costs
C_f	[%]	Capacity factor-ratio of actual energy production to that if operated at rated power 100% of the time
COE	[$/(kW-hr)]	Cost of Energy-price at which turbine will generate electricity
FCR	[%]	Fixed charged rate-annual percentage rate that is being paid back each year
IC	[$]	Installed cost of the wind turbine system including installation
IRR	[%]	Internal rate of return on an investment
MC	[$]	Maintenance cost of turbine, including insurance
NAEP	[kW-hrs]	Net annual energy production of the wind turbine including availability factor
$NC_{turbine}$	[$]	Cost of the turbine normalized to the size of the turbine
NPV	[$]	Net present value of an investment
$v_{cut\text{-}in}$	[m/s]	Wind velocity at which turbine begins producing power
$v_{cut\text{-}out}$	[m/s]	Wind velocity at which turbine stops producing power (shuts down)
v_{rated}	[m/s]	Wind velocity at which turbine reaches rated power
V_{avg}	[m/s]	The average annual velocity of a given location

While there are a number of residential wind turbine products sold in the United States, the number of prominent manufacturers is relatively few. As of 2011, the foremost U.S. manufacturers of small wind turbines were Bergey Windpower, Northern Power Systems, Polaris, and Southwest Windpower [3]. Of those four, only Bergey and Southwest Windpower specialize in residential turbines. The influx of foreign products is slightly increasing, but primarily American made products dominate the U.S. market at 90% of units sold in 2011; this is down from 94% in 2010 [3].

Table 4: Bergey Excel 10 parameters and performance [31]

Diameter	7.0 m		**Average Wind**	***NAEP***
Rated Power	8.9 kW		**m/s**	**kW-hours**
Peak Power	12.6 kW		3.6	4910
v_{rated}	11 m/s		4.5	9850
$v_{cut\text{-}in}$	2.5 m/s		5.5	16530
$v_{cut\text{-}out}$	none		6.4	24330
Furling Speed	14-20 m/s		7.3	32388

Bergey Windpower is small wind turbine manufacturing company headquartered in Norman, Oklahoma. They have been manufacturing turbines since 1977, and are known more for their reliability rather than the technology they employ. They primarily sell one line of product that they name the Excel, and they offer this turbine in four different sizes with the Excel 10 turbine their best selling product. They advertise this system for large rural homes, farms, and small businesses. It is a direct drive three bladed turbine oriented upwind that uses a furling system for power regulation in high winds. The turbine is intended to be grid tied, and the turbine system comes with a 12 kW Powersync II inverter. The manufacturer stated turbine parameters and expected performances are listed in Table 4. A cost quote for this machine has not been received from a dealer, but these turbines are sold for around $29,000 with a 60 foot guyed tower for around $9000 [32].

Table 5: XZERES Skystream 3.7 parameters and performance[33]

Diameter	3.7 m		**Average Wind**	***NAEP***
Rated Power	2.1 kW		**m/s**	**kW-hrs**
Peak Power	2.6 kW		3.5	960
v_{rated}	11 m/s		4.5	2400
$v_{cut\text{-}in}$	3.2 m/s		5.5	4320
$v_{cut\text{-}out}$	none		6.5	6000
			7.5	7440

Southwest Windpower had been the other main manufacturer of residential turbines in the U.S. They were headquartered in Flagstaff, Arizona, and had been producing wind turbines since 1987. Unfortunately, they went out of business in early 2013, and other companies acquired their products. One of their best selling product lines was the Skystream; this line was acquired by a company called XZERES Corporation in July 2013 [34]. XZERES is based out of Seattle, Washington, and the company both manufactures and distributes its products. The two products they currently market are the Skystream 3.7 and the XZERES 442SR. The Skystream 3.7 has been a very popular item, and as of 2008 was the highest selling residential turbine worldwide [34]. It is a smaller turbine, and typical design intent is to use it to supplement the power provided by the local electric grid. It is a three bladed, downwind turbine that uses electronic torque control to regulate speed in high winds. Both grid tied and off-grid versions of the turbine are sold. The manufacturer stated turbine parameters from and expected performances are listed in Table 5. A cost quote for this turbine was received from XZERES. The cost of the turbine including the inverter was $10,931 and the cost of the tower with a foundation kit included was $5921.

These are considered two of the best-selling residential wind turbines on the market. The Excel 10 will represent larger residential turbines intended to provide the entre electrical needs of the residence, and the Skystream 3.7 will represent the smaller residential turbines intended to supplement the electricity coming from the grid. Their respective performance and cost economics is assumed to represent the current residential wind turbine market; analysis of performance and cost economics of turbines sized in between these two turbines will be performed according to a linear interpolation scheme.

Case Studies of the Excel 10 and Skystream 3.7

While the manufacturers state the nominal performance and cost of their turbines, it is important to analyze the "in the field" performance and actual cost of these wind turbine systems. Two case studies are here presented: one of the Bergey Excel 10 and one of the Skystream 3.7.

Table 6: Case Study of six Berge Excel 10 in Pacific Northwest [35]

Site/Location	Total Installed Cost	Expected $NAEP$	Actual $NAEP$	Avg. Recorded Wind Speed	Months of Data
~	~	kW-hrs/yr	kW-hrs/yr	m/s	~
Stanford, MT	$46,817	18,000	11,600	5.95	18
Goldendale, WA	$47,487	13,000	8,800	4.09	7
Peshastin, WA	$59,199	8,000	600*	1.95	15
Goldendale, WA	$53,393	13,000	12,400	5.64	16
Chester, MT	$58,649	10,000	7,400	4.86	15
Browning, MT	$46,153	18,000	8,300	5.73	13
* Turbine was inoperable for large period of time					

NREL performed a study in 2003 through 2005 in order to understand the operation and cost economics of small wind turbines better. They tracked six newly installed Bergey 10 kW turbines at six different locations in the Pacific Northwest. At each Bergey site, they recorded the cost of installation, the energy generation of the turbine and the average wind speed for each of the turbines. Based on the local wind resources as evaluated by using state wind profile map, and a given tower height at each location an expected net annual energy production ($NAEP$) was calculated. Table 6 lists the above data for each of the six turbine installations. The total installed cost (IC) includes all of the costs associated with installing the turbine: turbine cost, tower cost, fees, permits, site preparation, and miscellaneous costs.

As is evident for each of the six turbines, the actual performance is much lower than the expected performance. It is not obvious what is responsible for the poorer than expected performance; three of these case studies report some sort of inverter failure and one reports a furling issue. In the lessons learned section of the report, it is stated that wind maps should only be used as a guide for site evaluations, and that actual measuring of the local wind resources at the site need to be made to make an accurate estimation of the local wind resources. A significant reason for the low $NAEP$s are the relatively low average wind speeds, but it has to be questioned how efficient these turbines actually are during operation. Also apparent from the study is the fact that the installed cost is substantially higher than just that of the tower and turbine. In the study, the balance of station (BOS) which includes all of the costs other than the tower and turbine was over $13,000 on an average.

Of importance, Bergey does not release the details of their blade design or operational power coefficients. Furthermore, it is not possible to estimate the availability factor of these turbines from the captured data. Instead, another method to analyze turbine performance is to consider the capacity factor (C_f). The capacity factor is relates the amount of actual energy produced by the turbine in a given amount of time compared to how much electricity the turbine would produce if continually operated in that time period at its rated power. As an example, a 1 kW rated wind turbine which produces 2190 kW-hours over the course of a year would have a capacity factor of 25% (8760 hours per year). Essentially it is a measure of two things: the available wind resources and the turbine operational efficiency. While this method does not draw any firm conclusions concerning the efficiency of the turbine, it is useful for analyzing the cost economics of the turbine. For the tested six turbines, the capacity factor ranges from 9% to 16% not including the turbine installed in Peshatin.

Table 7: Case study of SouthWest Skystream in Kansas

Site/Location	Total Installed Cost	Expected AEP	Actual AEP	Avg. Recorded Speed	Months of Data
~	~	kW-hrs/yr	kW-hrs/yr	m/s	~
Perry, KS	$12,500	3,400	957	*not recorded	24

Jim King is a homeowner in Perry, KS who had a SouthWest Windpower Skystream 3.7 turbine installed on his property. His house is located on the east side of highway 59 one mile north of highway 24. The location has a fair amount of tress to the north and east, but the turbine is mounted on a 60-foot tower that places the turbine in an estimated decent spot. Table 7 lists the cost and performance of the turbine over a two-year period. The turbine itself cost $10,000, the tower and balance of station cost $2,000, and the electric cooperative (LJEC) charged $500 for connecting into the grid. Jim was able to arrange a net metering policy with LJEC such that he is credited with all of the excess electricity that is put back onto the grid. Over the years 2011 and 2012, the turbine produced 1915 kW-hours. This results in a capacity factor of 5.2% over that time. Jim's opinion on the poor performance is twofold: first, the turbine is very inefficient, and second the surrounding trees are substantially interfering with the airflow across the generator and a higher tower is needed. He has had minimal maintenance performed on the turbine, and he estimated the availability factor was close to 100%.

Cost Economics of Turbines

Consumers purchase wind turbines primarily because they provide a better means of generating electricity compared to the conventional method of buying from the grid. While "better" is not entirely encompassed by economic concerns, purchasing a wind turbine is approached from a financial standpoint, and as such needs to be analyzed as an economic investment. There are number of different methods to analyze the economics of purchasing a wind turbine. One method already described is to consider the cost of energy as described in Equation (1). Assuming nominal annual energy production, nominal turbine and tower costs and a BOS cost of 20% (likely low), Table 8 lists the cost of energy (COE) for the Excel 10 and the Skystream 3.7.

Table 8: COE analysis for Excel 10 and Skystream 3.7 for a 6.5 m/s wind site

Excel 10			SkyStream		
IC	45,600	$	IC	20,222	$
V_{avg}	6.5	m/s	V_{avg}	6.5	m/s
$NAEP$	24,330	kW-hrs	$NAEP$	6,000	kW-hrs
MC	0.02	$/kW-hr	MC	0.02	$/kW-hr
FCR	10%	~	FCR	10%	~
COE	0.207	$/kW-hr	COE	0.357	$/kW-hr
IC			IC		
Turbine	29000	$	Turbine	10931	$
Tower	9000	$	Tower	5921	$
BOS	7600	$	BOS	3370.4	$
Total	**45600**	$	**Total**	**20222.4**	**$**

Table 8 indicates how the economics of scale influence the cost economics of these turbines. The Excel 10 is roughly twice the size of the Skystream, and all else being equal would produce four times the $NAEP$. However, the corresponding cost of the Skystream is much greater than one-fourth that of the Excel, and the COE of the Skystream is correspondingly much higher.

While this method is reasonable for comparing different forms of energy and their associated costs, it is not meant to be used to evaluate whether or not one's money would be better spent investing in a wind turbine rather than elsewhere. A better method to determine this is to consider a yearly cash flow associated with the turbine investment and then analyze the internal rate of return (IRR) on the investment. The IRR is the discount rate that an investment would have to possess in order to yield a net present value (NPV) of zero dollars on the investment. The discount rate is essentially the rate of return that one would expect to receive on an investment if the money was put somewhere else, and is in general a good measure of "is it worth it" to the investor. The NPV is the value in dollars that a current investment possesses at the present time of investment. At a certain discount rate, the investment would be worthwhile if the NPV is greater than zero and not if the NPV is less than zero. Like any traditional investment, there are costs and profits associated with the venture. The costs are the installed cost of the turbine, interest on financing from the bank, operating and maintenance expenditures, and expenses due to general inflation. The profits are revenue generated by the turbine and the value associated with a utility rate escalation.

One other profit that is not often considered is that the money that would have been spent to buy the electricity comes from taxable income. In order to purchase a given amount of electricity one has to make some percentage more than that depending on one's tax bracket, and thus not having to buy electricity has added value. This economic consideration is consistent with an economic analysis performed by Gipe[11]. Depending on one's tax bracket, this can substantially increase the value of the electricity being generated by the turbine. Other profits that could be considered are state or federal incentives; however, these will not be considered in this analysis.

Table 9: 20-year cash flow analysis for Excel 10

Assumptions: No tax credits, 100% energy generated has full value							
Rotor Diameter	7	meter	Retail Rate	0.11	$/kW-hr	Utility Rate Escalation	5%
Avg. Wind Speed	6.4	m/s	Feed in Tariff	0.02	$/kW-hr	Inflation Rate	3%
NAEP	24,330	kW-hrs	% @ Retail Rate	100.00%	~	Down Payment	20%
Installed Cost	45600	$	Tax Credit Rate	0%	~	Loan Term	10
O&M	0.02	$/kW-hr	% Tax Credit Used	0%	~	Loan Interest Rate	5%
			Tax Bracket	30.00%	~	**Discount Rate**	**11.6%**
Year	**Gross Revenue ($)**	**O&M($)**	**Loan Interest($)**	**Loan Principal($)**	**Tax Value (Revenue) ($)**	**Revenue (Loss) ($)**	**Cumulative($)**
0	-9120	0	0	0	0	-9120	-9120
1	2676	-486	-1824	-2900	3822	-1388	-10508
2	2810	-501	-1679	-3045	4014	-1212	-11720
3	2950	-516	-1527	-3198	4214	-1026	-12746
4	3097	-532	-1367	-3357	4425	-831	-13577
5	3252	-548	-1199	-3525	4646	-626	-14203
6	3415	-564	-1023	-3702	4879	-410	-14613
7	3586	-581	-838	-3887	5122	-183	-14796
8	3765	-598	-643	-4081	5379	56	-14740
9	3953	-616	-439	-4285	5648	307	-14433
10	4151	-635	-225	-4499	5930	571	-13862
11	4358	-654	0	0	6226	5573	-8289
12	4576	-673	0	0	6538	5864	-2425
13	4805	-694	0	0	6865	6171	3746
14	5045	-714	0	0	7208	6493	10239
15	5298	-736	0	0	7568	6832	17072
16	5563	-758	0	0	7947	7189	24260
17	5841	-781	0	0	8344	7563	31824
18	6133	-804	0	0	8761	7957	39781
19	6439	-828	0	0	9199	8371	48152
20	6761	-853	0	0	9659	8806	56958
						$56,958	
					NPV	$0.00	

Table 10: *IRR* for Excel and Skystream given nominal IC and *NAEP*

Excel 10				Skystream 3.7			
Wind speed	Nominal NAEP	C_f	*IRR*	Wind speed	Nominal *NAEP*	C_f	*IRR*
m/s	kW-hrs/yr	~	~	m/s	kW-hrs/yr	~	~
3.6	4910	6.3%	-10.5%	3.5	960	5.2%	-17.8%
4.5	9850	12.6%	-3.1%	4.5	2400	13.0%	-9.5%
5.5	16530	21.2%	3.9%	5.5	4320	23.5%	-3.2%
6.4	24330	31.2%	10.8%	6.5	6000	32.6%	1.0%
7.3	32388	41.5%	17.9%	7.5	7440	40.4%	4.1%
				8.5	8640	47.0%	6.6%

Table 9 illustrates the cash flow of a twenty year investment for a given turbine. Table 10 lists the results of the twenty year cash flow analysis (using the method shown in Table 9) for the Excel 10 and Skystream 3.7 turbines. Twenty years is the general amount of time for which turbines are expected to operate [36]. The installed cost (*IC)*, maintenance cost (*MC)*, and *NAEP* are the nominal values as presented in Table 8. It is assumed that 80% of the *IC* is borrowed from the bank at an interest rate of 5% with a 10-year term. The tax bracket is set at 30%, and the general inflation rate analyzed at 3% while the utility rate inflation is analyzed at 5%[11]. For this analysis, it is assumed that all of the electricity generated has a value equal to the cost that the customer would be purchasing it from the utility company, which initially is valued at 0.11$/kW-hr. As can be seen, at a calibrated discount rate of 11.6%, the *NPV* of the investment is $0.00, and the investment thus has an IRR of 11.6%. Table 10 calculates the *IRR* for the two turbines for different wind speeds and nominal *NAEP*s. The nominal *NAEP*s equate to a corresponding capacity factor of the turbine.

As is quite evident and expected, the Excel has much better investment prospects than the Skystream; this is due to economics of scale. The analysis also begins to clarify at what point investing in a turbine is simply not worth it due to the relatively low local wind resources. There are obviously a number of factors which if altered would affect the *IRR*. Most likely to vary substantially is the cost of electricity from the local utility company. Locations that have a substantially higher cost of electricity, like many parts of western Kansas, will see a much higher IRR. This will also be true if the utility electric inflation is higher than the assumed 5%. Even though some factors will be changed depending on local circumstances, the trends shown in this analysis will remain accurate.

Table 11: IRR for Excel and Skystream Case Studies

Excel 10				Skystream 3.7			
Location	**$NAEP$**	**C_f**	**IRR**	**Location**	**$NAEP$**	**C_f**	**IRR**
~	**kW-hrs/yr**	~	~	~	**kW-hrs/yr**	~	~
Stanford, MT	11600	15%	-1.4%	Perry, KS	957.5	5.2%	-13.6%
Goldendale, WA	8,800	11%	-4.9%				
Peshastin, WA	600	1%	~				
Goldendale, WA	12,400	16%	-2.2%				
Chester, MT	7,400	9%	-8.9%				
Browning, MT	8,300	11%	-5.2%				

The performance of the turbines in the case studies are evaluated using the same strategy, and the results are given in Table 11. Given that the nominal $NAEP$ assumes an availability factor of 100%, it is not surprising that the IRR of the actual turbines are lower than the nominal analysis. It is surprising though how poor of a return these turbines are actually producing. It is possible that the owners of these turbines, while disappointed with the performance, were not unhappy with the purchase of the turbine and would make the same investment again. However, in order for wind turbines to gain prominence they need to represent an economically sound investment. There is certainly value in being "self-sufficient" and "green" that for many people breaking even economically might warrant investment, but there is also a bit of risk associated with installing a turbine, especially larger ones which are costing upwards of $45,000, and there does need to be a decent economic incentive to invest in these turbines.

What value of IRR justifies investing in a turbine is partly a matter of personal preference. For homeowners, it would seem like any IRR less than the rate on which money is being borrowed from the bank is too low. If one is going to borrow money from the bank to finance an investment, it seems reasonable that the return on the investment be at least equal to the rate at which that money is being financed. Given an IRR being equal to the rate at which money is borrowed from the bank, it appears that all six of the Excel 10s installed in the Pacific Northwest are poor economic investments thus far. The best IRR among all of them was -1.4%. If that customer had valued his money at a discount rate of 5%, that investment would have had an NPV of -$11,662. As far as investments go, this means that when he invested in the turbine he essentially lost that amount of money. Now perhaps the $NAEP$ has since increased, but it seems quite evident why the market for residential wind turbines is struggling.

Normative Cost Economics of Wind Turbines

The analysis of the cost economics of wind turbines now proceeds to the performance to cost ratio that turbines need to possess in order to be economically feasible. There are a number of ways to classify turbine performance and cost. Turbine performance is primarily measured by $NAEP$, but this $NAEP$ is dependent on wind speeds, turbine efficiency, and availability factors all of which vary with different turbines and different location. Rather than specifying normative values for these three parameters, a simpler method to normalize performance is to consider the capacity factor. While for some turbines this is not the best analysis, the C_f is a reasonable method of specifying how well a turbine needs to perform to be cost effective. With this rubric for performance, it also makes sense to specify the cost of the turbine based on rated power. Thus, the cost will be analyzed according to price per turbine rated power; this will be referred to as the normalized cost. Using the nominal cost of the Excel 10 and the Skystream 3.7 as given in Table 8 and the rated power of the turbines as given in Table 4 and Table 5, the current market costs of the turbines are $5124/kW and $9628/kW for the Excel 10 and Skystream 3.7, respectively. As mentioned above, these two turbines are intended to represent the current market for residential turbines on the larger and smaller ends, and the cost per kW of other sized turbines will be calculated by linearly interpolating between these two turbines. While this linear interpolation would not provide accurate results for much larger turbines, for such a small interval in turbine sizes it seems reasonable that costs per kW would scale linearly between. The method for determining the cost of a turbine is given as follows via the gradient of the normalized cost (∇NC) and normalized turbine cost ($NC_{Turbine}$), respectively:

$$\nabla NC = \frac{IC_{Excel} - IC_{Skystr}}{P_{Excel} - P_{Skystr}} \text{ [\$/kW]} \tag{12}$$

$$NC_{Turbine} = IC_{Skystr} + (P_{Turbine} - P_{Skystr})\nabla NC \text{ [\$]} \tag{13}$$

It is assumed that the cost of these turbines is fixed, and the two parameters, which can be varied to achieve economic viability, are the capacity factors of the turbine and the discount rate of the investment (equal to the interest rate at which the investment is being financed).

Table 12: C_f vs IRR for given turbine

Rated Power	IRR=10%	IRR=6%	IRR=5%	IRR=4%
kW	C_f	C_f	C_f	C_f
8.9	34.5%	24.3%	21.9%	19.7%
8	35.6%	24.9%	22.5%	20.3%
7	37.1%	25.9%	23.5%	21.2%
6	39.1%	27.3%	24.7%	22.3%
5	41.8%	29.3%	26.5%	23.9%
4	46.0%	32.2%	29.2%	26.3%
3	53.0%	37.1%	33.6%	30.3%
2.1	64.9%	45.4%	41.1%	37.1%

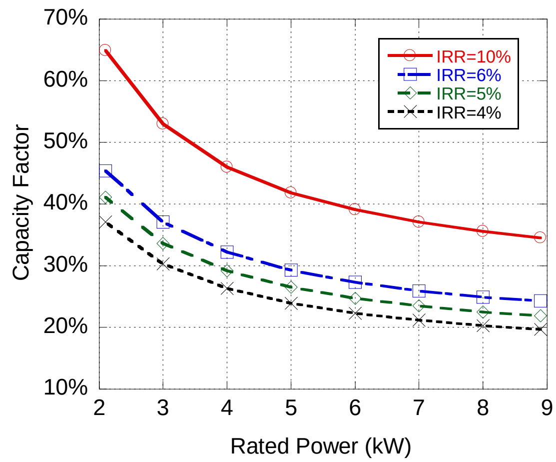


Figure 9: Required C_f for different sized turbines to achieve given IRR

Using the same analysis as presented in Table 9 and the scheme presented in Equations (12) and (13) for determining the IC of different turbines, a capacity factor based on IRR was calculated, and the results are tabulated in Table 12 and displayed in Figure 9. It is quite evident from the information how dependent economic viability is on both the size of the turbine and the IRR. Figure 9 shows how consistent the trends are across the range of turbine sizes for a given IRR. Though not impossible, it is quite unlikely that at an IRR of 10% will ever possess economic viability. As seen from the case studies, capacity factors are not near what that high of a discount rate would require even for the larger sized turbines. A much more feasible IRR is 5%. This is at or slightly higher than current interest rates. While it still results in rather high capacity factors for the smaller turbines, a well-designed turbine in a good wind site could certainly achieve those factors.

Table 13: $NAEP$ for given turbine size at IRR=5%

Rated Power	C_f	$NAEP$	IC
kW	~	kW-hrs/yr	~
8.9	21.9%	17,074	$45,600
8	22.5%	15,768	$42,241
7	23.5%	14,410	$38,509
6	24.7%	12,982	$34,777
5	26.5%	11,607	$31,045
4	29.2%	10,232	$27,313
3	33.6%	8,830	$23,581
2.1	41.1%	7,561	$20,222

Table 13 presents the normative production that a residential wind turbine needs to generate in order for the turbine to be economically viable for a given IC and IRR of 5%. Whether wind turbines achieve the required C_f via higher operational efficiency, high availability factors, or installations in high wind speed sites is subsidiary to the requirement that wind turbines achieve the specified C_f.

Chapter IV: Economic Viability and the Integration of Heat Pumps

Nomenclature-General

BER	[~]	Ratio of monthly thermal load storage (auxiliary loads) to monthly generated electricity
BLR	[~]	Ratio of the battery storage capacity to daily load
BLR'	[~]	Ratio of battery storage capacity to daily generated load
C_f	[~]	Capacity factor-ratio of actual energy production to that if operated at rated power 100% of the time
$CESS$	[~]	Conventional energy storage system-use of battery bank to store energy
COE	[$/(kW-hr)]	Cost of Energy-price at which turbine will generate electricity
COP	[~]	Coefficient of performance of heat pump
EER	[~]	Ratio of monthly generated electricity to monthly normal load
ELR	[~]	Ratio of the daily generated electricity to daily load
HES	[~]	Home energy system
$HSPF$	[BTU/W-hr]	Heating season performance factor-ratio of heating capacity in BTUs to the input electricity in W-hrs
$SEER$	[BTU/W-hr]	Seasonal energy efficiency rating-ratio of cooling capacity in BTUs to the input electricity in W-hrs
X_{sys}	[~]	System performance of the HES

Nomenclature - Heat Transfer Analysis

A	[m^2]	Area of a surface perpendicular to direction of heat flow
A_{crack}	[m^2]	Effective area of a crack around a door or window
c_{p-air}	[kJ/(kg-K]	Specific heat of air at constant pressure
C	[~]	Crack flow coefficient
C_{pe}	[~]	External pressure coefficient
F_E	[~]	Emissivity factor
$F_{surface-i}$	[~]	Shade factor between the surface and the surrounding object i
G_b	[W/m^2]	Intensity of the beam radiation
G_d	[W/m^2]	Intensity of the diffuse radiation
G_h	[W/m^2]	Solar intensity of the radiation
$G_{o,h}$	[W/m^2]	Total amount of radiation on a horizontal surface outside the atmosphere
G_{sc}	[W/m^2]	Solar constant, the amount of energy per unit area on a surface outside the earth's atmosphere perpendicular to the beam propagation
G_{solar}	[W/m^2]	Solar irradiation on a surface
h_c	[W/(m^2-K)]	Heat convection coefficient
h_{fg}	[kJ/(kg-K]	Latent heat of vaporization at constant temperature
K	~	Variable determining quality of windows and doors
k_T	~	Hourly clearness index
k_x	[W/(m-k)]	Thermal conductivity of a material

l	[mm,m]	Thickness of material that is part of wall membrane
L	[m^4]	Four times the ratio of the area of the surface divided by the perimeter
m	[~]	Exponent representing crack severity
n	[~]	Day number of the year
P_{stag}	[Pa]	Stagnation pressure
$\dot{q}_{cond,x}$	[W/m^2]	Heat flux via conduction in the x direction across the wall membrane
$\dot{q}_{conv}$	[W/m^2]	Heat flux via convection
$\dot{q}_{rad,net}$	[W/m^2]	The net radiative heat flux to a surface
$\dot{Q}_{conv,o}$	[W]	Heat convected to or away from the outside wall surface
$\dot{Q}_{HeatPump}$	[W]	Heat transferred into the conditioned space by the heat pump
$\dot{Q}_{L-Airexchar}$	[W]	Latent heat exchange due to air infiltration and leakage through the wall membrane
$\dot{Q}_{L-Internal}$	[W]	Latent heat exchange due to people and appliances operating in the conditioned space
$\dot{Q}_{Membrane}$	[W]	Heat transfer through the building membrane excluding transmitted radiation
$\dot{Q}_{S-Airexchar}$	[W]	Sensible heat exchange due to air infiltration and leakage through the wall membrane
$\dot{Q}_{S-Internal}$	[W]	Sensible heat exchange due to people and appliances operating in the conditioned space
$\dot{Q}_{surface}$	[W]	Total heat transferred to or from the exterior surface
$\dot{Q}_{radiation-su}$	[W]	Heat transferred to the outside surface via radiation
$\dot{Q}_{Total}$	[W]	The total heat transfer into the conditioned space
$\dot{Q}_{Transmitted}$	[W]	Heat transfer through the wall membrane via transmitted radiation
R	[m^2-K/W]	Thermal resistance of a given material
R_b	[m^2-K/W]	Ratio of the amount of beam radiation on a tilted surface to that on a horizontal surface
T	[C,K]	Temperature of a given entity
$\dot{V}_{air}$	[m^3/s]	Volumetric flow rate of air
V_{wind}	[m/s]	Velocity of the wind
U	[W/(m^2-K)	Overall heat transfer coefficient
α	[~]	Absorptivity of given enitity
B	[~]	Heat pump cooling coefficient of performance
β	[^{o}]	Slope of a surface from the horizontal
δ	[^{o}]	Declination angle of the sun
ΔP_b	[Pa]	Pressure difference inside a building due building pressurization
ΔP_s	[Pa]	Pressure difference inside a building due to the stack effect

ΔP_{total}	[Pa]	Total pressure difference in a building
ΔP_w	[Pa]	Pressure difference inside a building due to the wind effect
ΔW	[~]	Difference in the humidity ratios between the inside and outside air
ϵ	[~]	Emissivity of given surface
γ	[^{o}]	Surface azimuth angle of a surface with a value of zero degrees representing true south
Υ	[~]	Heat pump heating coefficient of performance
ρ_{air}	[kg/m^3]	Density of the air
ρ_g	[~]	Reflectivity coefficient of surroundings
ϕ	[^{o}]	Latitude of the building location

Introduction

The previous chapter analyzed the cost economics of different wind turbines, and specified the performance in terms of capacity factors that a turbine would have to realize in order to be economically viable for a given internal rate of return (IRR). However, the analysis assumed that all of the electricity generated by the wind turbine had a value equal to the cost of the electricity that was displaced by the turbine. In other words, it assumed that all of the electricity was utilized at full value in some manner. For applications in which a net metering program is in place or in which the buy-back rate is equal to the cost of grid electricity this is a valid assumption. However, for off-grid applications or on-grid applications without a net metering system and a relatively low buy back rate, this assumption is not valid. For these applications, this would require that all of the electricity generated by the turbine is utilized in the house or property at full value and no electricity is 'dumped'. This is not valid because there exists an imbalance between the electricity generated by the turbine and the electric load of the house. At times, the wind turbine will generate more electricity than the house is currently consuming, and by definition, this excess electricity must be dumped. Dumped electricity has a reduced value, and the more electricity that is unused, the less economically viable the investment becomes. In order for the investment to make economic sense, there needs to be as minimal an amount of dumped electricity as possible. To accomplish this requires system integration of the turbine such that all or nearly all of excess electricity is utilized. Thus, the focus of the chapter is to identify and analyze two systems through which the wind turbine can be integrated in such a manner as to make the investment economically viable.

One of the traditional methods for utilizing excess electricity has been to employ a conventional energy storage system ($CESS$). This method is fairly practical and efficient and can certainly provide an effective means of utilizing excess electricity. However, while battery technology has seen substantial improvements in recent years, the cost associated with this method of energy storage is still quite high [37], and the primary downside of the $CESS$ is the added cost coupled to the wind turbine system. This added cost reduces the economic viability of the investment. The added cost of this $CESS$ and its impact on economic viability will be analyzed in this chapter.

As was shown in Chapter 3, the installed cost of the wind energy system is already high enough to make investing in wind turbines prohibitive in many applications. A system that integrates a wind turbine needs to accomplish two things in order to be economically viable, utilize all excess electricity and maintain a relatively low added cost to the wind energy system. One system that has the potential to integrate the wind turbine successfully is through a heat pump. Throughout the course of the year, a substantial amount of energy is used in homes to provide the heating and cooling needs of the house. An electric heat pump would allow excess electricity to be utilized by essentially storing energy inside the house and, thereby, offsetting the amount of purchased energy. Heat pumps are used to provide both heating and cooling loads, and it is assumed that this use of electricity would be utilized in a house that already has an electric heat pump, subsequently making the added cost to the wind turbine system negligible. Integrating the heat pump as an auxiliary load will substantially increase the total electric load on the house, and the impact of this will be considered.

The analysis of the economic viability of the *CESS* and the heat pump system will require characterizing a number of elements in order to determine economic viability. These include descriptions of the electric load in a house, temporal variations in the wind speed, and an analysis of the heat transfer in a house. All of these are quite varying in nature, and an accurate analysis for a given application would require considering the specific profiles of the given application. However, as the attempt is to understand the general viability of the integration of the heat pump, the portrayals of the indicated elements will be simplified to make such generalizations possible. These abridged assumptions will be identified for each of the above characterizations.

Characterizing Load Imbalance in the HES

Load imbalance, defined as the difference between the turbine generated power and the electric consumption in the house at the time of consumption, has a large impact on the viability of integrating the turbine into the home energy system (*HES*). It affects both the sizing of the wind turbine, the sizing of the energy storage system, and the amount of generated excess electricity. Ideally, energy consumption and production would match each other, and there would not be excess electricity generated by the turbine. Since both the electric loads and the generated wind power independently fluctuate over time, load imbalance will always exist in a wind turbine system. As mentioned prior, methods of utilizing excess electricity at full value need to be implemented to cope with the load imbalance present in the system. Analyzing the suitability of different methods requires characterizing the electric loads in a house and the available power in the wind at given times.

Characterizing the electrical load in a house is not an exact science. Electrical consumption depends on many factors including the size of the residence, number and lifestyle of occupants, the number and efficiency of appliances, and consumption varies temporally with the season, day of the week, and time of the day. Both the amount of electricity consumed and the timing of that consumption are significant aspects of electricity use in residences. “Bottom-up” models are used to generate synthetic models that characterize residential electric consumption, but it is generally agreed upon that these models require an extensive understanding of the local household, appliances, and consumption patterns [38]. The other method to characterize electric loads is to perform numerous case studies on different residences. One notable study was performed on twelve homes in Canada [39] which logged the power consumption in these homes on one minute intervals. While there was definitively shown to be a general trend for large periods of the day, over the course of the year there was substantial deviation between the hourly and mean electric consumption. The study also compared its findings to what a bottom-up model would have predicted for the given houses. While it was found that the bottom-up model made relatively accurate predictions in terms of power peaks and total consumption, the model did not accurately capture the temporal variations in the electric loading.

The wind distribution has already been characterized in Chapter 2 by a Rayleigh distribution. While that distribution identifies the respective percentage of time that the wind will blow at a certain speed for a given annual average velocity, it does not describe the temporal variation of the wind speed over a course of time. It can be expected that in a day, the wind will blow at a certain speed for a given amount of time, but when during the day it blows at that speed is an extremely unpredictable and stochastic event. Sometimes there exists a correlation between the time of the day and expected wind speed, but normally an attempt to model the wind speed in a non-random manner is not warranted. Another issue with modeling the wind is the period over which the Rayleigh distribution is valid. In Chapter 2, the Rayleigh distribution was employed to estimate the energy capture over the course of the year. It is generally admitted that in that period the wind speed resources are relatively well modeled by the Rayleigh distribution [11]. However, the shorter the period, the less likely it is that the Rayleigh distribution accurately models the distribution of the wind.

Thus, there is significant difficulty in characterizing electric and wind profiles in a non-trivial manner. For specific installations in which the load profile and local wind resources can be accurately predicted, a model that analyzes the load imbalance over a short period of time (such as an hourly basis) can yield reasonable estimations for the load imbalance and associated required size of an energy storage system [40-42]. Without specific electric load and wind resource information, a more generalized approach to analyzing load imbalance is required.

Hence, the method proposed will consider analyzing the average electric load consumption and average generated electricity for a given month; [43] suggests this as a reasonable approach for analysis. For most homeowners, the monthly electrical consumption of the residence is a known quantity. One assumption made in the analysis is that the amount of electricity generated by the turbine is a known quantity via the capacity factor (C_f). This assumption is more or less valid over longer or shorter periods. Because the installation of a wind turbine is not meant to provide an autonomous system but rather an economically viable means of generating electricity, *the important aspect is minimizing the amount of excess electricity generated by the turbine* (optimized according to cost economics). Whether this is accomplished through immediate consumption or through storage for use later, what is to be avoided is selling electricity back onto the grid. Thus, important for the analysis is not a minute-to-minute tabulation of the energy flow in the system, but rather a larger picture of the conditions that will generate excess electricity. Of note, there exists a strong correlation between the size of the energy storage system and the amount of excess electricity generated [42], and the analysis progresses to how large does the energy storage system need to be for a given sized wind turbine system.

A common way to size the energy storage system is by considering the amount of time that it is desirable to run the system autonomously [44]. While this method is suitable for off-grid applications that need a certain amount of backup power for times when the turbine is not producing any electricity, it is not as suitable for this analysis in which the important issue is not that of running out of electricity, but that of not producing excess electricity. What is needed is a relationship between the size of the energy storage system and an amount of excess electricity generated. This method of analysis is not as prevalent in the current renewable energy system dialogue, but one notable report by Celik [45] attempts to discern this relationship for small wind turbines. The report presents a simplified algorithm for estimating the performance of small-scale wind energy systems which have battery storage given know wind distribution data. Hour-by-hour wind speed data is taken from five locations over an eight year period. The data is used to simulate the performance of a system of three small wind turbines, lead acid batteries, and a load. The report defines the system performance (X_{sys}) in terms of the percentage of time that the turbine system is able to deliver the demanded load. The performance is analyzed according to the available wind resources, the ratio of the monthly produced wind energy to total load demand during the month (ELR, ideally equal to unity), and the ratio of the battery capacity in days to daily load (BLR, aka the $CESS$).The available wind resources are described by a Weibull distribution. The study used four different BLRs of 1.00, 1.25, 1.50, and 2.00, and calculated the respective performance as a function of wind speed data and the ELR. The result of the study is a mathematical relationship expressing the system autonomy (i.e., performance) for the above mentioned BLRs in terms of the ELR and for a given wind speed distribution. The analysis in [45] is similar to the type of analysis needed for determining the size of an energy storage system that optimizes the economics of the system. The data taken from Celik was generated assuming a Weibull wind speed distribution with a scale factor of 5.5 m/s and a shape factor of 2. The scale factor is a measure of the average wind velocity, and the shape factor is a measure of the variability in the wind. A scale factor of 5.5 m/s was chosen because that correlates to a capacity factor in the range of 20-25%[46, 47]. The case studies and performance reports of small wind turbines presented prior suggest that this value is high; however, as presented in Table 12, given current turbine costs, a capacity factor of 20% is about the minimum a turbine can achieve and still maintaining viability (for larger turbines). A capacity factor of 20-25% tries to compromise the actual turbine performance with what needs to be achieved. A shape factor of 2 was chosen because that is the default value for a general analysis[47].

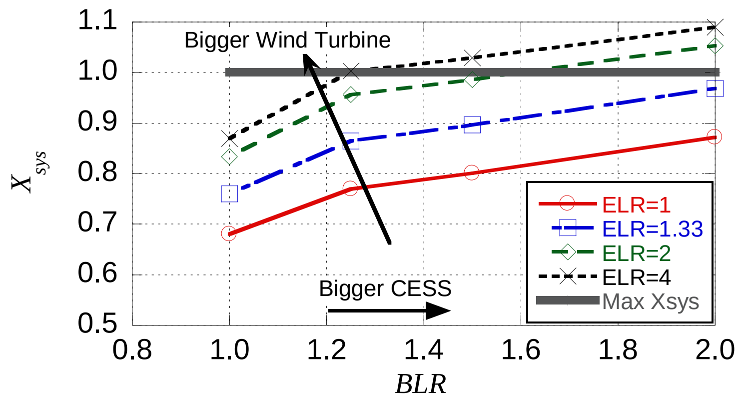


Figure 10: Performance analysis of wind turbine system taken Celik [45]

Figure 10 depicts the results of the report. The performance is the amount of electricity that is utilized at full value (ideally equal to unity for maximizing *IRR*), and the *BLR* is the amount of energy storage space associated with the performance (ideally equal to zero; hence, no incurred cost for the *CESS*). Data for four different *ELR*s (1.00, 1.33, 2.00, and 4.00) is shown. As can be seen, as the *BLR* increases so does the system performance. Also, as the system *ELR* increases, so does the system performance. The system with an *ELR* of 4.00 reaches a system performance of one at a *BLR* of 1.25, while the system with an *ELR* of 1.00 never quite reaches full system performance, though with *BLR*s higher than 2.00 it inevitably would. This makes sense because this report analyzes performance in terms of the percentage of loads that are being met. Thus, an increase in the ratio of the generated electricity to the consumed electricity will result in a higher likelihood that the system will be able to supply the load consumption. Of note, certain configurations appear to yield system performance values greater than one. This is the result of the mathematical modeling; the purpose for presenting those values is that they are used in evaluating a linear regression analysis of the data (discussed following).

The main difference between Celik and the present analysis is that in the present analysis the outcomes are measured in terms of the percentage of generated electricity that is utilized at full value (i.e., minimizing excess electricity). For Celik's efforts, a higher ELR (and bigger wind turbine) results in greater system performance; whereas, for the present analysis, operating at a lower ELR would result in better system implementation (less potential for wasted generated electricity). Applications in which the turbine is sized smaller than the household consumption would require smaller energy storage systems in order to minimize excess electricity generation. For the case where the ELR equals one, the discrepancy between the two analyses does not exist. Given that the current analysis measures success in a reverse context to the Celik, the efficiencies associated with varying ELRs in this report are assumed to be equivalent to the efficiencies associated with the inverse of the ELR for Celik. Thus Celik's ELRs of 4.00, 2.00, 1.33, and 1.00 and the associated performances are equivalent to ELRs of 0.25, 0.50, 0.75, and 1.00 in this report. Granting this assumption, BLR' will take on the new definition of being the ratio between the battery capacity and the daily-generated electricity. The revised Celik data results in 16 data points all within a BLR' range of 1.00 to 2.00. In terms of optimizing the cost economics of the turbine investment, the range of the BLR' values and associated system performance values needs to be extended from a minimum (BLR'=0.00) to a maximum (BLR'=3, approximate value for which ELR=1.00 result in X_{sys} of 1.00). The best method for extrapolating this data is debatable; a linear regression analysis of the four data points for each ELR value as shown in Figure 10 resulted in R^2 values of 0.84, 0.87, 0.91, and 0.94 for ELRs of 0.25, 0.50, 0.75, and 1.00. Given that the mathematical relationship between the BLR and ELR determined by Celik was derived from data quite varying in nature, these levels of variance in the linear regression are thought to be low enough to warrant a linear extrapolation of the data.

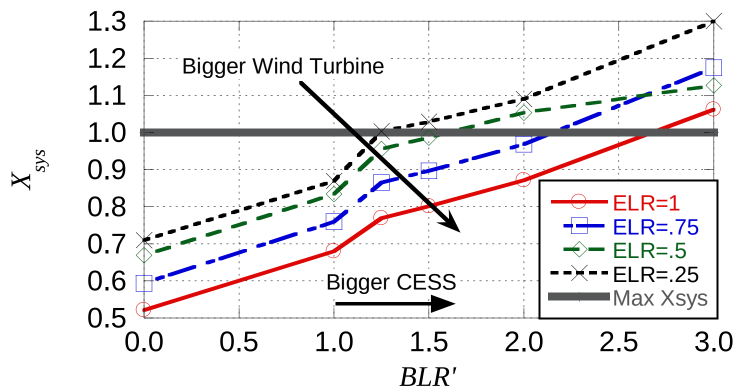


Figure 11: Revised system performance including extrapolated data

Figure 11 displays the system performance values associated with the different *BLR*'s assuming the inverted *ELR*s of 1.00, 0.75, 0.50, and 0.25. The performance values associated with a *BLR*’ of 0.00 and 3.00 are the results of a linear extrapolation of the performance values at *BLR’*s of 1.00, 1.25, 1.50, 2.00. As can be seen, a smaller *ELR* results in a smaller associated *BLR’* to achieve full system performance. All of the *ELR*s reach full system performance before a *BLR’* of 3.00 is required. On the small end, a system with an *ELR* of 0.25 reaches full system performance at a *BLR’* of 1.25, and on the large end a system with an *ELR* of 1.00 reaches full system performance at a *BLR’* of 2.66. In terms of application, this means that a wind turbine system designed to generate all of the household electric consumption would require battery storage of 2.67 times the generated amount in order to utilize all of the electricity at full value (i.e . not waste any or sell back to the grid); a wind turbine designed to produce one-fourth the household electric consumption would require battery storage of 1.25 times the generated amount for the same (for a given location which can expect capacity factors of 20-25%, or an average velocity around 5.5 m/s).

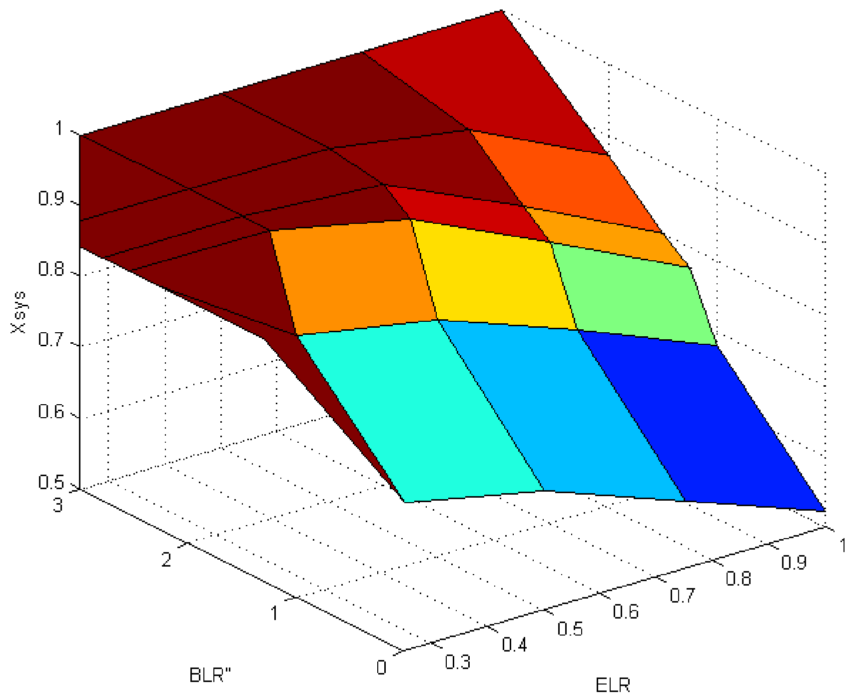


Figure 12: Surface plot of ELR, BLR', and X_{sys} data

Figure 12 is a 3D contour plot of the data presented in Figure 11; the plot was generated by a linear interpolation of the data points shown in Figure 11 using MATLAB 2009a software. The surface plot maps the system performance for every combination of the ELR and BLR' (in the ranges of 0.00 to 1.00 for the ELR and 0.00 to 3.00 for the BLR'). Maximum performance values are capped at 1.00. A system with an ELR of 0.00 indicates that zero energy is being generated, and the associated system performance value is assigned to be 1.00 for all values of BLR'. Because the utility buy-back rate is assumed low, it does not make sense to produce more electricity than can be consumed over a large period and ELRs greater than 1.00 were not considered. Figure 12 maps the system performance for every combination of ELR and BLR' for the given ranges, and this data will be used to optimize the size of the wind turbine and the energy storage for a given household electric consumption according to the 20 year cost economics analysis presented in Chapter 3.

Analyzing the Economic Viability of the *CESS*

For wind turbines producing electricity in a location without a net metering policy, some form of energy storage needs to be integrated into the *HES* in order to utilize the electricity at full value. To illustrate this point, consider the 20-year cash flow analysis presented in Table 9, but now assume that all excess electricity is sold back to the utility company at an avoided cost value of \$0.03/kW-hr. Without any form of energy storage, the BLR' of the system is 0, and the corresponding X_{sys} is 52% (i.e., 52% of the generated electricity is utilized at full value) for the system with an *ELR* of 1. The original results for a given turbine size and capacity factor yielding a specified *IRR* of 5% were listed in Table 13 (the *IRR* of 5% corresponds to the discount rate which results in a *NPV* of \$0.00 on the investment).

Table 14: *NPV* for investment on a turbine assuming only 52% of electricity is utilized at full value

Discount Rate=5%		
Rated Power	C_f	***NPV***
kW	~	~
8.9	21.9%	(\$18,983.00)
8	22.5%	(\$17,655.00)
7	23.5%	(\$16,044.00)
6	24.7%	(\$14,534.00)
5	26.5%	(\$12,949.00)
4	29.2%	(\$11,364.00)
3	33.6%	(\$9,816.00)
2.1	41.1%	(\$8,434.00)

Table 14 shows the *NPV* of the different turbine systems when a substantial portion of the generated electricity is excess and sold back to the grid at the avoided cost rate. It considers the same turbine size, capacity factor, and discount rate as in Table 12 which resulted in *NPV* values of \$0.00. At a discount rate of 5%, all of the turbines possess a substantially negative *NPV*. Interesting to note is that under these conditions the smaller turbines now appear to offer a relatively better investment because the value of the produced electricity has dropped such that purchasing a larger turbine is not worth the added cost, even considering the economics of scale. The purpose of Table 14 is to clarify the importance of minimizing excess electricity on the economic viability of the wind turbine.

Employing a *CESS* is one method of minimizing this excess electricity. The *CESS* utilizes batteries to store electricity produced by the wind turbine that is not immediately consumed in the house. Four battery types that are most suitable for small-scale renewable energy systems are lead-acid, nickel cadmium, nickel metal hydride and lithium-ion [37]. Lead-acid batteries account for 79% of the rechargeable battery market share as of 2008 [48], and they continue to offer the most cost effective means of energy storage [37, 48]. In terms of cost economics, three important considerations for choosing a battery type are cost per kW-hr of storage, depth-of-discharge, and cycle life. Deep cycle lead-acid batteries have relatively high rates of depth of discharge, up to 80%, and the cost of energy storage is well below the other three battery types [48]. The main downside to lead acid batteries is their relatively low cycle life. Given a 20-year turbine cycle life, battery cycle life is a significantly important consideration for a battery storage system. Even with a low cycle life, based on economic considerations, lead acid batteries still offer the most cost effective means of storing electricity [37].

Deep cycle lead acid batteries cost on average $200 per kW-hr of storage [48]. Depending on the size of the battery bank utilized, this represents a significant portion of the initial investment. The operating life of these batteries is largely dependent on the charge and discharge operational characteristics. Of note, batteries that are discharged at higher current rates (C-rating) and to higher levels of discharge will have a reduced battery life as compared to batteries that are discharged at lower C-rates and lower levels of discharge; however, this is difficult to quantify and not considered as part of this analysis. Instead, a simple assumption that deep cycle batteries can withstand upwards of 2000 cycles under proper care is employed. In a renewable energy system this translates to an operating life of roughly 10 years, and it is expected that the battery bank be replaced once over the 20-year life of the turbine. The cost analysis will account for this by assuming a battery operating and maintenance cost that over the course of 20 years adds to the initial cost of the battery pack. Given that battery technology is increasing and battery costs are reducing, it will be assumed that the price reduction in battery costs is equal to the current inflation rate. The initial cost of the battery pack will be added to the initial cost of the wind turbine.

Optimization of the Wind Turbine System using a *CESS*

Optimizing the cost economics of a wind turbine system that utilizes a *CESS* requires that both the amount of electric consumption in a given time period and the wind energy resources be known. Given that most consumers receive a monthly electric bill, a monthly electric consumption that is constant over the course of the year will be considered. The wind resources are important for determining the capacity factor one could expect to achieve. As mentioned prior, this analysis will assume that wind speeds are such to achieve a capacity factor of 20-25%. Reiterating, the small turbine case studies and performance reports suggest that this value is optimistic, but the economic results presented in Table 12 require this level of performance or higher. The discount rate will be analyzed at 5%, and the turbine systems will be optimized to achieve a maximum NPV. The optimization was achieved using the same analysis as presented in Table 9, but assuming a $NAEP$ and battery storage cost according to the system BLR' and ELR. X_{sys} is determined from the MatLab surface plot of Figure 12 for a given ELR and BLR', and its value determines the percentage of the generated electricity sold at full value ($0.11/kW-hour) and the percentage sold at avoided cost ($0.03/kW-hour).

Table 15: Optimal NPV for $CESS$ with turbine capacity factor of 20%

Consumption	ELR	BLR'	X_{sys}	Turbine Size	NPV
kW-hrs/month	~	~	~	kW	~
500.00	0.11	0.00	0.87	0.38	(12206.06)
1000.00	0.11	0.00	0.87	0.76	(12027.45)
1500.00	0.11	0.00	0.87	1.15	(11848.83)
2000.00	0.11	0.00	0.87	1.53	(11670.22)
2500.00	0.11	0.00	0.87	1.91	(11491.61)
3000.00	0.11	0.00	0.87	2.29	(11312.99)
3500.00	0.11	0.00	0.87	2.67	(11134.38)
4000.00	0.11	0.00	0.87	3.06	(10955.76)

Table 15 lists the optimal ELR and BLR' configurations for varying levels of residential electric consumption assuming a capacity factor of 20% and a discount rate of 5%. The first thing to note is that the values of BLR' for all configurations are zero. This means that at current battery pricing and performance (in terms of cycle life) it does not make any economic sense to use batteries to store electricity, and a consumer would be better off selling excess electricity back to the grid rather than trying to store it in batteries. Without any form of energy storage, it is evident that utilizing a system with a lower ELR results in a better economic return. Wind turbine systems that generate less electricity compared to the household consumption will utilize a higher percentage at full value. The cost economics are optimized in Table 15 at ELR values of 0.11. Essentially, the capacity factor is too low to make investing in a turbine worthwhile, and it is economically more profitable to focus on higher system efficiency than a higher $NAEP$.

Table 16: Optimal NPV for $CESS$ with turbine capacity factor of 25%

Consumption	ELR	BLR'	X_{sys}	Turbine Size	NPV
kW-hrs/month	~	~	~	kW	~
500.00	0.50	0.00	0.67	1.39	(11629.94)
1000.00	0.50	0.00	0.67	2.78	(10875.20)
1500.00	0.50	0.00	0.67	4.17	(10120.47)
2000.00	0.50	0.00	0.67	5.56	(9365.73)
2500.00	0.50	0.00	0.67	6.94	(8611.00)
3000.00	0.50	0.00	0.67	8.33	(7856.26)
3500.00	0.50	0.00	0.67	9.72	(7101.52)
4000.00*	0.45	0.00	0.68	10.00	(6545.35)
*Sized to stay within residential turbine bounds 1-10 kW					

Table 16 performs the exact same analysis as previously presented except now a capacity factor of 25% is assumed. The result is substantially different. While the cost of energy storage in batteries is still too prohibitive to make it viable, the system is optimized with much larger turbines. The size of turbine is capped at 10.00 kW; this is the upper end of the range of small-scale wind turbines. Of note, the system performances in Table 16 are lower than in Table 15. This suggests that the economics of scale associated with purchasing larger turbines has a significant impact on the overall economic viability of the turbine.

Table 17: Optimal NPV analysis with reduced battery costs and capacity factor of 20%

Consumption	ELR	BLR'	X_{sys}	Turbine Size	NPV
kW-hrs/month	~	~	~	kW	~
500.00	0.38	1.26	0.98	1.32	(12027.56)
1000.00	0.38	1.26	0.98	2.64	(11670.44)
1500.00	0.38	1.26	0.98	3.96	(11313.31)
2000.00	0.38	1.26	0.98	5.28	(10956.19)
2500.00	0.38	1.26	0.98	6.60	(10599.07)
3000.00	0.38	1.26	0.98	7.92	(10241.95)
3500.00	0.38	1.26	0.98	9.24	(9884.83)
4000.00*	0.36	1.26	0.98	10.00	(9536.11
*Sized to stay within residential turbine bounds 1-10 kW					

Table 15 and Table 16 illustrate that relying on batteries for storing excess electricity is not an economically viable option. At $200/kW-hr and a 10-year cycle life, the initial cost and eventual replacement of the batteries results in a substantially negative NPV on the investment. If the initial cost of these batteries could be reduced, or the cycle life extended, they could potentially provide an economically viable means of storing energy. Table 17 performs the same analysis as previously except it now assumes that the battery costs are halved and the battery life is doubled. This cost reduction and performance improvement is shown to impact the design of the system in terms of utilizing battery storage and a larger turbine, but the impact on the NPV is not large. The system performance is higher than in Table 15 by over 10% and the turbine size is three times larger, but the cost associated with the utilizing battery storage as compared to the revenue generated by the $NAEP$ render it too high to really affect the economic viability.

Table 18: Optimal NPV analysis with reduced battery costs and capacity factor of 25%

Consumption	ELR	BLR'	X_{sys}	Turbine Size	NPV
kW-hrs/month	~	~	~	kW	$
500.00	0.77	2.19	1.00	2.14	(10655.69)
1000.00	0.77	2.19	1.00	4.28	(8926.70)
1500.00	0.77	2.19	1.00	6.42	(7197.71)
2000.00	0.77	2.19	1.00	8.56	(5468.72)
2500.00*	0.72	2.10	1.00	10.00	(3746.82)
3000.00*	0.60	1.86	1.00	10.00	(2347.39)
3500.00*	0.52	1.26	0.95	10.00	(999.18)
4000.00*	0.45	1.26	0.97	10.00	(292.40)
*Sized to stay within residential turbine bounds 1-10 kW					

Table 18 displays the results associated with a capacity factor of 25% coupled with lower battery storage costs. As can be seen, a higher capacity factor dramatically affects the economic viability of small wind turbines. Given this capacity factor and associated $NAEP$, the revenue generated by the turbine is enough to warrant investing in a large enough energy storage system to render a system performance of 1.00. For the higher consumption months, a maximum sized turbine is employed to optimize the cost economics. For these entries, as the consumption increases the ELR decreases, resulting in a reduction of the size of energy storage needed to optimize the system performance. This results in a lower cost and higher NPV. Operating at this higher capacity factor and these reduced battery costs is close to yielding a non-negative NPVs for the large turbines when utilized in residences that have higher consumption.

The Integration of Wind Turbines into the HES via Electric Heat Pumps

In order for residential wind turbines to provide an economically viable means of generating electricity for applications without a net-metering arrangement, they need to be integrated into the HES in such a way that electricity can be stored in a cost effective manner. As seen from the prior analysis, current battery technology does not allow this to happen. One technology that has the potential to allow for successful integration of the wind turbine into the HES is that of electric heat pumps. The heat pump functions as an auxiliary load that utilizes excess electricity by storing it in the form of energy inside the house. There are a number of features of this integration that make it suitable for wind turbines. Foremost is that this method of energy storage is essentially free (as it is assumed that the heat pump already exists as part of the HES) removing additional capital from the investment. Also of importance is that heat pumps are able to provide both the heating and cooling loads in a residence. From Figure 2, the space heating and cooling loads account for roughly 50% of the energy consumed in homes. This implies that this auxiliary load is large enough that storing excess electricity in the form of energy will retain the full value of the electricity. Finally, there is a direct correlation between the heating and cooling load on the house and the wind speed of the outdoor air [49]. Using a wind turbine to provide heating and cooling loads thus represents in some sense a synergistic integration of the wind turbine into the HES.

This section analyzes the effect that electric heat pumps can have on the cost economics of wind turbines. Through an elementary residential heat transfer analysis, it considers the effect of the wind speed on the heating and cooling loads of the residence. It also considers the conditions under which storing energy in the house is not valuable and the excess electricity utilized by the heat pump does not retain the full value of the electricity. Also, given that using an electric heat pump to provide heating and cooling loads substantially increases the total electric load on the house, the effect of considering the heat pump as a normal load rather than an auxiliary load on the cost economics of the wind turbine will be considered (i.e., sizing the turbine to supply all or part of the electric heat pump load).

Heat Pump Technology

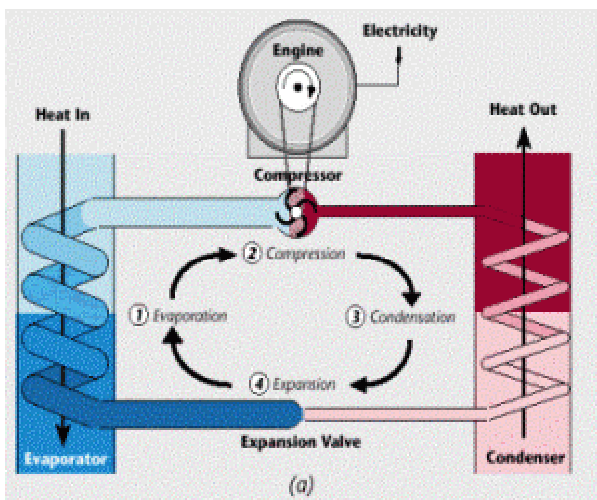


Figure 13: Heat pump cycle illustrating operation [50]

Heat pumps use refrigeration and heat pump cycles to transfer heat from one location to another. Their fundamental operation centers on powering a compressor to either heat or cool a refrigerant fluid that extracts heat from air (or provides heat) inside a conditioned space. Figure 13 depicts the basic operating principles of the heat pump cycle. Heat pumps employ reverse valve technology that allow both vapor-compression refrigeration cycles and vapor-compression heating cycles to take place, meaning that heat pumps can be as used to provide for both the heating and cooling loads in a residence. This is unlike a normal HVAC (Heating, Ventilation, and Air Conditioning) system that uses different appliances for heating and cooling, and typically uses some form of energy other than electricity for heating.

In the cooling cycle, cold liquid refrigerant (colder than the ambient air) is pumped through evaporator coils inside the house over which a fan blows air. The refrigerant extracts heat from the air that increases the temperature of the refrigerant and causes it to evaporative. The refrigerant is then sent through the compressor that pressurizes the fluid and causes a substantial increase in temperature. The fluid then moves through condenser coils outside the house by which heat is extracted from the refrigerant fluid. The loss of heat results in condensation and the refrigerant leaves the condensing unit as a warm liquid. The refrigerant is now sent through an expansion valve that depressurizes the liquid and reduces its temperature and the cycle is completed. The heating cycle is very similar to the cooling cycle, except the reverse valve causes a reverse of the process. The refrigerant absorbs heat from the outside the house, and transfers into the inside air of the house. Now, the coils inside the house form the condensing unit and the coils outside the house form the evaporating unit.

The coefficient of performance (COP) of the heat pump is a measure of the desirable heat transfer to the amount of work input. For cooling, the heat output is the amount of heat extracted from the inside air; for heating, it is the amount of heat extracted by the inside air. The work input is primarily the amount of energy used by the compressor in the cycle, but it also includes the energy used to operate the fans used for aiding the convective heat transfer. Theoretical limits for cooling COP (B) and heating COP (Υ) are given, respectively, in the following expressions [51]:

$$B_{max} = \frac{T_{inside}}{T_{outside} - T_{inside}} \; [\sim] \tag{14}$$

$$\Upsilon_{max} = \frac{T_{inside}}{T_{inside} - T_{outside}} \; [\sim] \tag{15}$$

These equations are the maximum theoretical efficiencies that the heat pump is able to achieve. As is evident from the equations, the greater the temperature difference between the inside air and outside cooling/heating source, the less efficient is the heat pump.

In current residential use, there are two primary types of heat pumps; air source heat pumps and ground source heat pumps [52]. Air source heat pumps use the outside air as the sink and source for the heat exchange with the air inside the house. Ground source heat pumps use the ground itself as the sink and source for the heat exchange with the air inside the house. Typically, water is circulated in tubes through the ground, and the refrigeration fluid exchanges heat with this water. The majority of heat pumps installed for residential units in the U.S. are air-source heat pumps. The main disadvantage of air source heat pumps is that at low outside air temperatures these units are relatively inefficient, and depending on the climate a supplemental heat source is necessary [52]. Because the ground maintains a constant temperature of around 50°F during the heating season, ground source heat pumps generate heat much more efficiently in colder climates than air source heat pumps do, and these units would not require a supplemental heating system [52].

In the market, heat pump efficiency related to the cooling cycle is most often measured in seasonal energy efficiency ratio (SEER). SEER is the ratio of the seasonal cooling capacity in BTUs to the amount of electricity used in watt-hours. It is calculated based on averaging the performance of the heat pump under a number of different conditions. For an air source heat pump, it was found that a heat pump with a SEER rating of 13 resulted in B equaling 3.17 [53]. Heat pump efficiency related to the heating cycle is most often measured in heating season performance factor (HSPF), and it is also a measure of the seasonal heating capacity in BTU per watt-hour of electricity supplied. A report studying the operation of two heat pumps in Washington state with HSPFs of 8.2 and 7.2 resulted in ϒ values of 2.7 and 2.2, respectively [54].

Heat Transfer in a Residence

One of the primary functions of a residence is to provide an enclosure that separates an interior space from the outdoor environment. This enclosure regulates a number of factors such as temperature, moisture, air flow, and air quality so that a comfortable living environment can be maintained. Due to this separation from the outdoor environment, a substantial amount of thermal loading results from regulating the indoor air temperature and humidity at desirable levels. From the vantage point of the conditioned space, thermal loading resulting in heat transfer into or out of the building enclosure occurs in the following primary ways:

- Heat conduction across the wall membrane between the indoor and outdoor environment (sensible heat)
- Heat convection from wall surfaces to the indoor air (sensible heat)
- Radiative heat transfer transmitted into and out of the building enclosure (sensible heat)
- Sensible and latent heat loss or gain from outside air entering the enclosure
- Sensible and latent heat generated by people and appliances inside the enclosure

These different methods of heat transfer result in a substantial amount of energy being used to maintain or regulate a comfortable living environment. Both sensible and latent heat transfers contribute to the thermal loading on the residence. The purpose of the heating and cooling system is to keep the interior of the residence at a determined temperature and humidity. As heat flows into or out of the residence, the heat pump has to deliver or take out certain amounts of heat. The following understanding of heat transfer in a residence is primarily taken from Building Science for Building Enclosures by Straube and Burnett [49].

The total heat flow into or out of the interior conditioned space is given by:

$$\dot{Q}_{Total} = \dot{Q}_{Membrane} + \dot{Q}_{Transmitted} + \dot{Q}_{S-Airexchange} + \dot{Q}_{L-Airexchange} + \dot{Q}_{S-Internal} + \dot{Q}_{L-Internal} + \dot{Q}_{HeatPump} \tag{16}$$

where S/L represent sensible or latent heat flows, $\dot{Q}_{Membrane}$ is the heat exchange that takes place across the wall membrane of the building (exterior walls, windows, roof, and floor) excluding transmitted radiation, $\dot{Q}_{Transmitted}$ is the radiated heat directly transmitted through the wall membrane via glazing, $\dot{Q}_{Airexchange}$ is the heat exchange resulting from exterior air entering the building through the building surface, $\dot{Q}_{Internal}$ is the heat exchange generated inside the residence primarily by people and appliances, and $\dot{Q}_{HeatPump}$ is the heat exchange provided by the heat pump. For a residence maintaining a constant temperature and humidity, $\dot{Q}_{Total}$ will be equal to zero and the thermal load on the heat pump can be analyzed by considering the various other heat exchanges taking place in the residence. The analysis proceeds to determining the governing equations used to analyze the magnitude of each of these components.

Membrane Heat Transfer

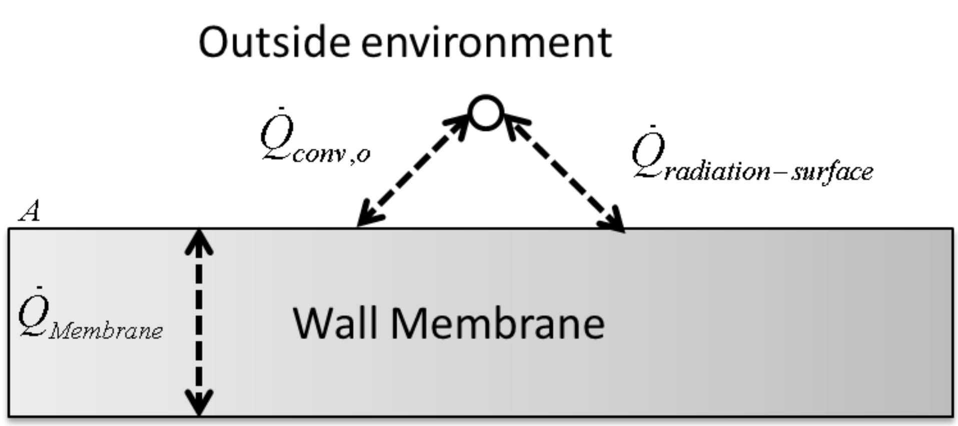


Figure 14: Heat transfer across an exterior building surface

In order to determine the magnitude of $\dot{Q}_{Membrane}$, the surface temperature of the exterior wall needs to be calculated. This is achieved by performing an energy balance on the exterior wall surface; Figure 14 illustrates the different heat transfer interactions taking place on the outside building surface with given area A. The outside building surface absorbs, reflects (and transmits, though not included in the surface energy balance) shortwave radiation from the sun, emits long wave radiation to the environment, and heat is convected and conducted away from or onto the surface. The total heat transfer to the exterior surface is given by the expression:

$$\dot{Q}_{surface} = \dot{Q}_{Membrane} + \dot{Q}_{conv,o} + \dot{Q}_{radiation-surface} \text{ [W]} \tag{17}$$

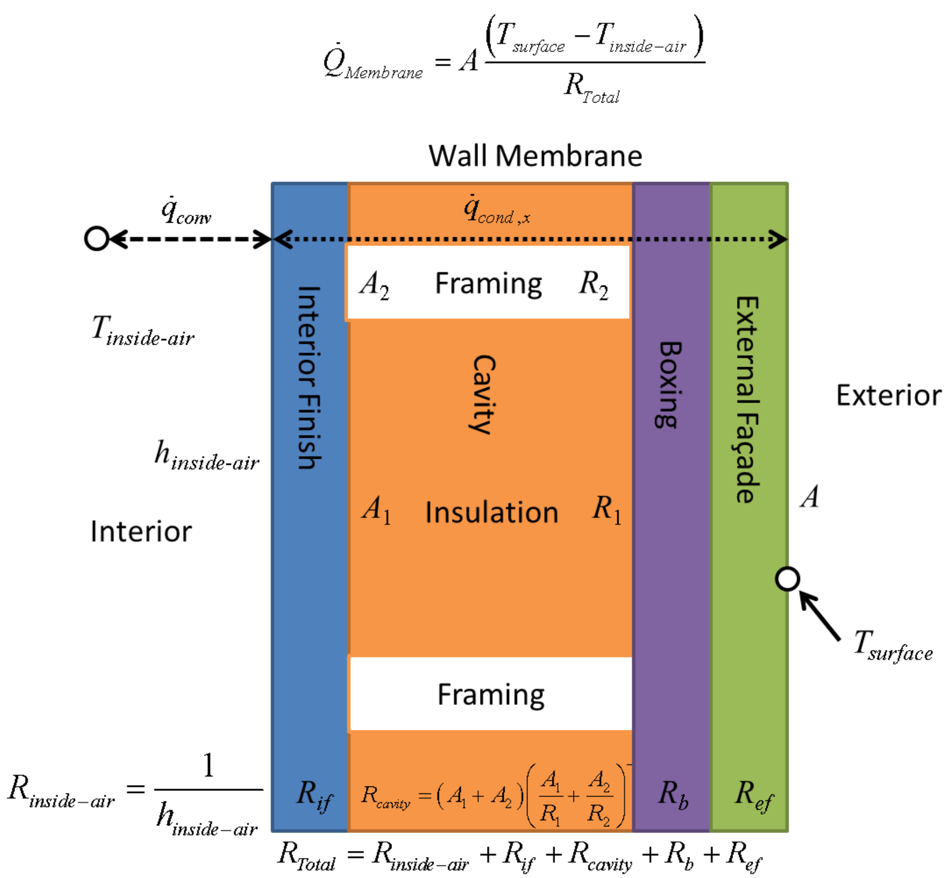


Figure 15: Heat flux through the membrane via wall conduction and inside convection

Figure 15 illustrates the $\dot{Q}_{Membrane}$ portion of the heat transfer from Equation (17). The bulk of $\dot{Q}_{Membrane}$ is made up by heat conduction towards or from the exterior surface. Heat transfer by conduction is governed by Fourier's heat conduction law; for one dimensional heat transfer, the conductive heat flux is given by the expression

$$\dot{q}_{cond,x} = -k_x \frac{dT}{dx} \text{ [W/m}^2\text{]} \tag{18}$$

Equation (18) is negative to denote that heat flows from higher to lower temperature surfaces. The coefficient k_x is thermal conductivity of a material; the units of thermal conductivity are W/(m-K). In building materials this property is considered to be constant with regards to temperature and material thickness [49], and Equation (18) can be rearranged and integrated to yield the following expression:

$$\dot{q}_{cond,x} = \frac{-k_x}{l}\left(T_2 - T_1\right) = \frac{\left(T_1 - T_2\right)}{R} \text{ [W/m}^2\text{]} \tag{19}$$

where l is the thickness of the material parallel to the direction of heat flow, and R is called the thermal resistance or R-value of a building material, with T_1 and T_2 representing arbitrary temperatures of two surfaces between which exists thermal resistance R. In residential construction, the wall separating the inside air from the outside air is constructed of several different layers of material.

These layers include an interior finish (*if*), wall cavity (*cavity*), boxing (*b*), and external façade (*ef*) The total resistance to conductive heat transfer across the wall is equal to the summation of the resistance of each individual layer. Certain layers, such as the wall cavity or a hollow concrete block, are composed of multiple materials integrated together. Total resistance of the layer to conductive heat transfer depends on several factors including the geometry, and the total resistance is not straightforward to calculate. For the case of the wall cavity, which consists primarily of framing members and insulating material (e.g., fiberglass), the total resistance can be calculated by the following:

$$R_{cavity} = (A_1 + A_2)\left(\frac{A_1}{R_1} + \frac{A_2}{R_2}\right)^{-1} \quad [\text{m}^2\text{-K/W}] \tag{20}$$

Here A_1 and A_2 are the surface areas perpendicular to direction of heat transfer of the respective materials inside the layer, and R_1 and R_2 are the thermal resistances of the respective layers.

Heat is also transferred from the interior wall surface to the interior air. Heat flux by convection of a fluid over a plate is governed by Newton's law of cooling which is usually written as:

$$\dot{q}_{conv} = h_c(T_{fluid} - T_{plate}) \qquad [\text{W/m}^2] \tag{21}$$

where h_c is the convective heat transfer coefficient and has units of W/(m^2-K). Recall that it is the indoor air temperature and not the wall surface temperature that determines comfort level (and is regulated). Therefore, it is convenient to include the convection coefficient from the inside surface to the air as part of the total thermal resistance between the outdoor surface ($T_{surface}$) and air the indoor temperature ($T_{inside\text{-}air}$) for which the thermal resistance associated with the convection is equal to:

$$R_{inside-air} = \frac{1}{h_{inside-air}} \qquad [\text{m}^2\text{-K/W}] \tag{22}$$

When done so, the total thermal resistance can be calculated as:

$$R_{Total} = R_{inside-air} + R_{if} + R_{cavity} + R_b + R_{ef} \quad [\text{m}^2\text{-K/W}] \tag{23}$$

and the equation for the heat transfer across the wall membrane (inside air resistance, interior finish, wall cavity, boxing, and external façade) takes the form:

$$\dot{Q}_{Membrane} = A\frac{\left(T_{surface} - T_{inside-air}\right)}{R_{Total}} \quad [\text{W}] \tag{24}$$

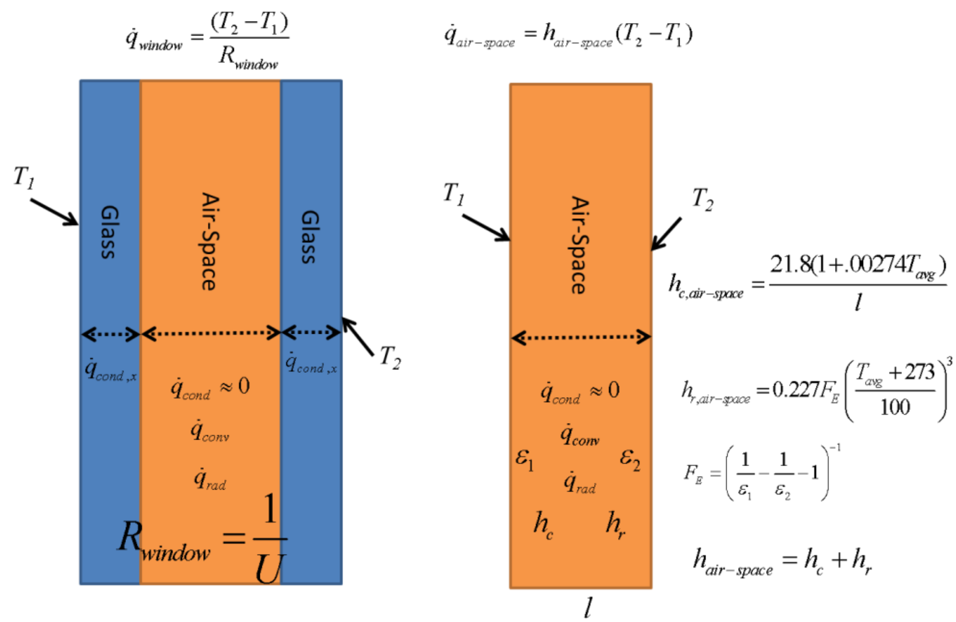


Figure 16: Heat flux across plane air spaces inside of wall; of note, these two schematics become part of the wall membrane of Figure 13 in the analysis when plane air spaces are employed

Equation (24) adequately describes the heat exchange that takes place across walls that do not have plane air spaces inside of them. For walls with plane air layers, a significant contribution by radiation and convection transports heat at a higher rate across the wall. Figure 16 depicts the heat flux across a plane air space inside a wall. For most residential construction efforts, the primary contributions like this are from windows. Most modern windows have multiple panes of glass between that are small sealed spaces filled with a gas. Heat is transferred through the glass primarily by conduction; whereas, the sealed space transmits heat via conduction, convection, and radiation. Most window manufacturers list an overall heat transfer coefficient (U) for the window that considers the contribution from all three modes of heat transfer.

Some residences are constructed so that there is a plane air space in part of the wall itself for insulating purposes. For these layers, typically a convection-radiation coefficient that considers the contributions of both convection and radiation to the heat transfer is calculated. For horizontal heat flow across vertical spaces that are less than 13 mm thick, the following conduction-convection coefficient can be used with reasonable accuracy [55]:

$$h_{c,air-space} = \frac{21.8(1+.00274T_{avg})}{l} \text{ [W/(m}^2\text{-K)]} \tag{25}$$

where T_{avg} is the average temperature of the two surfaces (T_1 and T_2) in Celsius and l is again the thickness of the material (i.e., distance between the two surfaces) except this time in millimeters.

The radiative heat transfer between the air space depends primarily on surface emissivity and temperature. For simple analysis the following radiation heat transfer coefficient can be used with reasonable accuracy[55]:

$$h_{r,air-space} = 0.227F_E\left(\frac{T_{avg}+273}{100}\right)^3 \text{ [W/(m}^2\text{-K)]} \tag{26}$$

where F_E is the emissivity factor and is equal to:

$$F_E = \left(\frac{1}{\varepsilon_1} - \frac{1}{\varepsilon_2} - 1\right)^{-1} \qquad \text{[-]} \tag{27}$$

resulting in:

$$h_{air-space} = h_{c,air-space} + h_{r,air-space} \text{ [W/(m}^2\text{-K)]} \tag{28}$$

This coefficient of heat transfer across the plane air space can be used to calculate the heat flux across the air space.

$$\dot{q}_{air-space} = h_{air-space}\Delta T_{air-space} \text{ [W/m}^2\text{]} \tag{29}$$

The total conductive heat transfer across the membrane of the wall is calculated by summing Equation (24) for each part of the wall membrane that has either a different total thermal resistance or surface temperature.

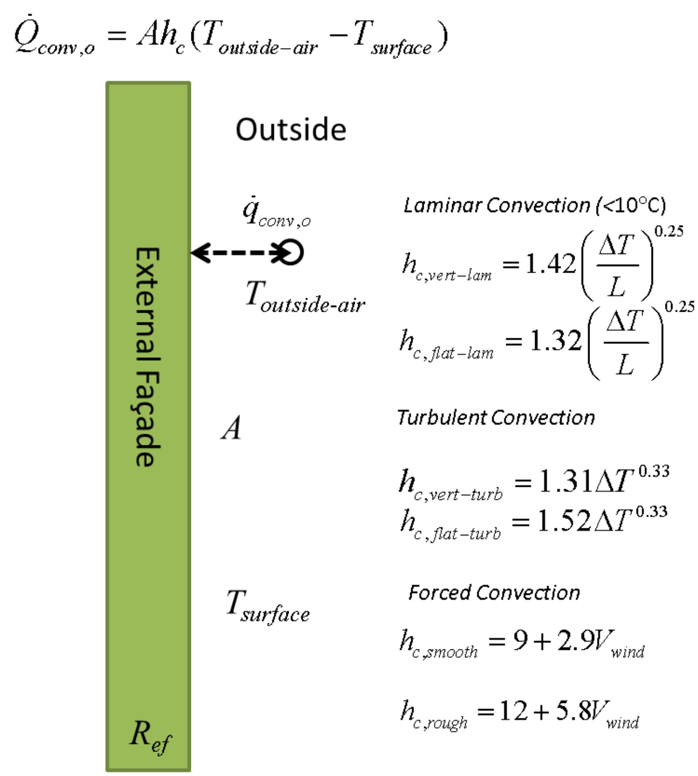


Figure 17: Convection from the exterior surface to the outside air

As can be seen in Figure 14, heat transfer also leaves the exterior surface of the building by convection. Figure 17 illustrates the convective heat exchange between the outside surface and the outside air. As mentioned prior, heat flux by convection is governed by Newton's law of cooling given in Equation(21). The value of the convection coefficient depends primarily on whether the airflow over the surface is natural or forced. If the flow is natural, then the flow of the fluid is primarily temperature dependent, and the orientation and temperature of the surface influences the convective heat transfer. ASHRAE has determined convection coefficient values for different scenarios [55]. For small temperature differences (<10°C) between the surface and air resulting in laminar airflow, the convection coefficient for vertical walls is given by the two following expressions for vertical walls and flat roofs, respectively.

$$h_{c,vert-lam} = 1.42\left(\frac{\Delta T}{L}\right)^{0.25} \text{ [W/(m}^2\text{-K)]} \tag{30}$$

$$h_{c,flat-lam} = 1.32\left(\frac{\Delta T}{L}\right)^{0.25} \text{ [W/(m}^2\text{-K)]} \tag{31}$$

where ΔT is the temperature difference between the surface and the air, and L is four times the ratio of the area of the surface divided by the perimeter.

For larger temperature differences resulting in turbulent flow, the heat transfer coefficients for vertical walls and roofs are given by the following expressions, respectively.

$$h_{c,vert-turb} = 1.31\Delta T^{0.33} \text{ [W/(m}^2\text{-K)]} \tag{32}$$

$$h_{c,flat-turb} = 1.52(\Delta T)^{0.33} \text{ [W/(m}^2\text{-K)]} \tag{33}$$

Forced convection occurs when the air is driven by some external means such as a prevailing wind or fan. Exterior surfaces more commonly undergo this type of convection. The value of the convection coefficient is primarily dependent on the wind speed of the air; it is also dependent on the roughness of the surface finish. Based on wind tunnel testing in small surfaces, a recommended value for smooth surfaces is given by the expression [49]:

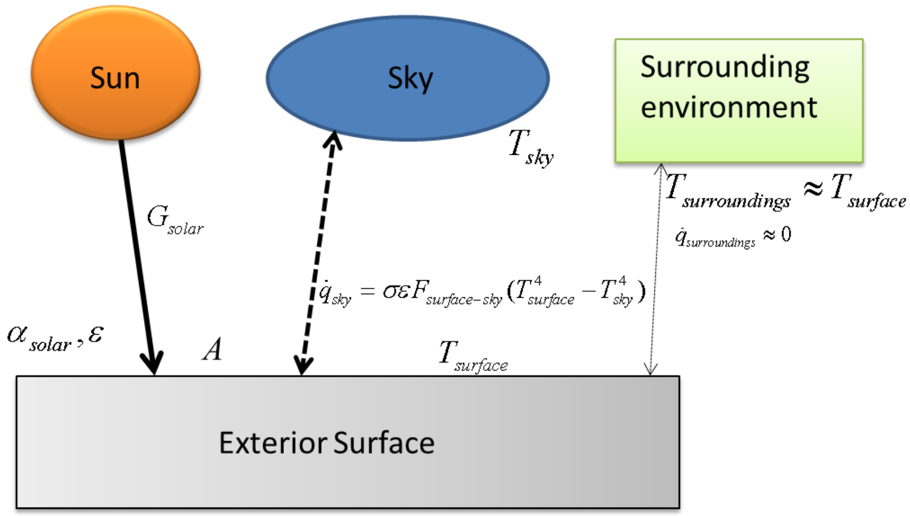
$$h_{c,smooth} = 9 + 2.9V_{wind} \qquad \{V_{wind} = 1 - 15m/s\} \text{ [W/(m}^2\text{-K)]} \tag{34}$$

and for very rough surfaces by the expression:

$$h_{c,rough} = 12 + 5.8V_{wind} \qquad \{V_{wind} = 1 - 12m/s\} \text{ [W/(m}^2\text{-K)]} \tag{35}$$

Smooth surfaces would include glass, metal, and painted wood; whereas, rough surfaces would include stucco and plaster. Using the appropriate convection coefficient, the equation for the heat transfer across the building surface via convection is

$$\dot{Q}_{conv,o} = Ah_c(T_{outside-air} - T_{surface}) \quad \text{[W]} \tag{36}$$



$$\dot{Q}_{radiation-surface} = A\left[\alpha_{solar}G_{solar} + \sigma\varepsilon F_{surface-sky}(T_{surface}^4 - T_{Sky}^4)\right]$$

Figure 18: Radiative heat exchanges occurring at a building surface

As seen in Figure 14, radiative heat transfer also occurs on the exterior surface. The radiative heat exchanges at the surface of the building are the most complicated to accurately analyze accurately. Figure 18 depicts a simplified illustration of the radiated heat exchange. The surface absorbs, reflects, and transmits energy that it receives from the sun and the surrounding environment, and it emits energy back to the surrounding environment. The energy that the surface absorbs from the sun is referred to as the solar irradiation, and the energy that the surface receives from the sky and surroundings are referred to as the sky irradiation. The surface receives energy from the sun based on the solar absorptivity properties of the material (α_{solar}) and the irradiation intensity of the sun (G_{solar}). The environment also reflects solar radiation onto the wall surface according to a net surrounding reflectivity coefficient ρ_g. Certain parts of the surface, such as windows, transmit solar irradiation according to the solar transmissivity (τ_{solar}) properties of the material. The surface also receives energy from the sky and surroundings based on sky absorptivity properties (α_{sky}) of the material and the temperature on the sky and environment. Due to the temperature difference and type of radiation being emitted by the sun and sky, the solar and sky absorptivity properties of the surface are not equivalent. The surface also emits energy to the sky and surrounding environment according to the surface emissivity (ε) of the material and the material temperature.

According to Kirchoff, for a material surface and external source that have temperatures the same order of magnitude, the emissive and absorptive properties of the surface material will be equivalent. This means that the net radiative heat transfer between the surface and the surroundings can be determined by only considering the emissivity of the surface material along with the temperatures of the surface and surroundings. Including the effects of surrounding solar surface reflectivity into the value of G_{solar}, this results in the following expression for the net radiative heat transfer to a surface:

$$\dot{Q}_{radiation-surface} = A\left[\alpha_{solar}G_{solar} + \sigma\varepsilon\sum_{i=1}^{n}F_{surface-i}\left(T_{surface}^{4} - T_{i}^{4}\right)\right] \text{ [W]} \tag{37}$$

where $F_{surface-i}$ is the shade factor between the surface and the surrounding object and the summation of them adds to unity, and σ is the Stefan-Boltzmann constant.

Furthermore, assuming that the locally surrounding environment is at the same temperature as the surface, and that the only surrounding environment over which a net radiative transfer occurs is the sky, the equation can be reduced to:

$$\dot{Q}_{radiation-surface} = A\left[\alpha_{solar}G_{solar} + \sigma\varepsilon F_{surface-sky}(T_{surface}^{4} - T_{Sky}^{4})\right] \text{ [W]} \tag{38}$$

The value of $F_{surface-sky}$ can be assumed to be 1 for roofs and 0.5 for the walls [49].

The parameter G_{solar} is the incident amount of radiation on the surface, both beam and diffuse, and it depends on a number of factors. Primary among these are the angle of incidence (θ) which is calculated, the total intensity of the solar radiation (G_h) which is a measured quantity, the intensity of the beam (G_b) and diffuse (G_d) radiation which are calculated, and the surrounding diffuse reflectance (ρ_g) which is measured. The expression for G_{solar} is [49] :

$$G_{solar} = G_b R_b + G_d \left(\frac{1+\cos\beta}{2}\right) + G_h \rho_g \left(\frac{1-\cos\beta}{2}\right) \text{ [W/m}^2\text{]} \tag{39}$$

where β is the slope of the roof measured from the horizontal and for which values greater than 90 degrees indicate that the surface is facing down, and R_b is the ratio of the amount of beam radiation on a tilted surface to that on a horizontal surface. It is calculated using the angle of incidence by the following [49]:

$$R_b = \frac{\cos\theta}{\cos\theta, \beta = 0} \text{ [~]} \tag{40}$$

where θ is the angle of incidence and is calculated from a number of quantities dependent on the location and orientation of the surface, as well as the time of day and the date. It measures the angle between the beam radiation on a surface and normal to that surface. The expression for the angle of incidence is [49]:

$$\theta = \cos^{-1}\begin{bmatrix} \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\lambda + \cos\delta\cos\phi\cos\beta \\ \cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \end{bmatrix} \text{ [°]} \tag{41}$$

where δ is the declination angle of the sun. It is measured by determining the angular position of the sun at solar noon, ϕ is the latitude of the building location, γ is the surface azimuth angle of the surface with a value of zero degrees representing true south, and ω is the angular displacement of the sun with respect to solar noon; forenoon times have negative values and afternoon times have positive values.

The declination angle of the sun is given by the expression[49]:

$$\delta = 23.45\sin\left[\frac{360(284+n)}{365}\right] \text{ [°]} \tag{42}$$

where n is the day number of the year with January 1st having a value of 1 and December 31st a value of 365.

The total measured irradiation is broken down into beam and diffuse components. The amount of diffuse radiation is calculated by considering the hourly clearness index (k_T). This value is determined by considering the ratio of the total amount of solar radiation on a horizontal surface on the earth's surface to the total amount of radiation on a horizontal surface outside the atmosphere ($G_{o,h}$). The expressions for $G_{o,h}$ and k_T are [49]:

$$G_{o,h} = G_{sc}\left[1+.033\cos\frac{360n}{365}\right]\cos\theta, \beta = 0 \text{ [W/m}^2\text{]} \tag{43}$$

$$k_T = \frac{G_h}{G_{o,h}} \tag{44}$$

where G_{sc} is the solar constant and represents the amount of energy per unit are on a surface outside the earth's atmosphere perpendicular to the beam propagation. It has an accepted value of 1367 W/m^2.

The ratio of the diffuse radiation to the total radiation measured at the earth's surface is a function of the hourly clearness index. After calculating this ratio, the total beam radiation can also be calculated in that the beam radiation is the difference between the total measured radiation and the diffuse radiation [49]:

$$\frac{G_d}{G_h} = \begin{bmatrix} 1.0 - .09k_T \qquad \{k_T \le .22\} \\ .9511 - .1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 \qquad \{.22 \le k_T \le .80\} \\ .165 \qquad \{k_T \ge .80\} \end{bmatrix} \tag{45}$$

$$G_b = G_h - G_d \tag{46}$$

From this information, the variable G_{solar} can now be solved.

The temperature of the sky is dependent on the air temperature, cloud cover, and dew point. For a fully cloudy sky, the radiative temperature is roughly equal to the ambient air temperature[49]. For a 50% cloudy sky, the following relationship has been proposed [49]:

$$T_{sky} = T_{air}\left[.8 + \frac{\left(T_{\text{dewpoint}} - 273\right)}{250}\right]^{0.25} \text{ [C]} \tag{47}$$

For a simpler analysis, the following expression has also been proposed [49]:

$$T_{sky} = 1.2T_{air} - 14 \text{ [C]} \quad (48)$$

As a result, recalling Figure 14, the total heat flux to an exterior surface on a residence can now be more precisely defined by the following expression:

$$\dot{Q}_{surface} = A\begin{bmatrix} \alpha_{solar}G_{solar} - \left(\dfrac{T_{surface} - T_{inside-air}}{R_{Total}}\right) - h_c\left(T_{surface} - T_{outside-air}\right) \\ -\sigma\varepsilon F_{surface-sky}\left(T_{surface}^4 - T_{sky}^4\right) \end{bmatrix} \text{ [W]} \quad (49)$$

Equation (49) considers heat transfer to the surface as positive and away from the surface as negative. Assuming a steady state energy balance with a net heat flux of zero and a defined inside air temperature, the surface temperature can be calculated given that the other parameters have known (or calculated) values. Once the surface temperature is calculated, the heat transfer through the wall membrane can also be calculated.

Glazing Radiation

Now, that the analysis for $\dot{Q}_{Membrane}$ has been determined, the next step is to determine the other components of heat transfer that place a thermal load on the interior conditioned space. $\dot{Q}_{Transmitted}$ is the heat transfer due to radiation being transmitted through the wall membrane via primarily glazing in doors and windows. In practice, the amount of solar heat transmitted through glazing is referred to as the Solar Heat Gain Factor ($SHGF$). It is a function of the Solar Heat Gain Coefficient ($SHGC$) and the solar irradiance (G_{solar}) incident on the glazing. The $SHGC$ is usually provided on the window data specifications sheet and the equation for $SHGF$ is given by:

$$SHGF = SHGC \times G_{solar} \text{ [W/m}^2\text{]} \quad (50)$$

The total heat gain associated with the solar load on the glazing system is therefore:

$$\dot{Q}_{Radiation} = A_{glazing} \times SHGC \times G_{solar} \text{ [W]} \quad (51)$$

where $A_{glazing}$ is the area of the glazed surface.

Air Exchange

Referring to the governing heat transfer Equation (16), a significant amount of thermal loading is placed on the building by air infiltration into the building enclosure. It is estimated that air leakage into and out of a building can account for 50% of the total thermal load on a well-insulated house [49]. Because air contains water vapor, air transport also affects the moisture content in the house and corresponding energy needed to humidify and dehumidify the space. Air enters the enclosure both intentionally through vents (including open windows) and unintentionally through the wall membrane, cracks around windows and doors, and the occasional opening of doors. As the intentional control of air into and out of the building is usually a part of the heating and cooling system, it is the unintentional leakage of air into or out of the enclosed space that places an additional thermal load on the residence.

Air leakage most commonly occurs through cracks in the wall, primarily around doors, windows, receptacle outlets, and other exterior penetrations. Although the wall membrane is composed of porous materials that themselves slowly leak air, current construction technologies generally employ a significant amount of air barriers inside the wall membrane such that the contribution to the thermal load of air leaking through the wall itself is minimal [49]. The driving force for air leakage across the wall membrane is a pressure difference between the inside and outside air. This pressure difference is primarily due to stack effect, building pressurization, and to wind. In equation form, the total pressure difference is

$$\Delta P = \Delta P_s + \Delta P_w + \Delta P_b \text{ [Pa]} \tag{52}$$

where ΔP_s, ΔP_w, and ΔP_b are the pressure differences due to the stack effect, wind, and building pressurization, respectively. Either positive or negative pressure differences could exist across a building surface. A positive pressure difference will result in outside air infiltrating the building, and a negative pressure difference will result in inside air exfiltrating the building. In terms of the associated heat transfer, air exfiltrating and infiltrating the building have the same energy implications, and thus in the calculations the absolute value of the pressure difference is considered.

It is not normal for residential buildings to be pressurized, and in this analysis building pressurization is not considered ($\Delta P_b = 0$). The stack effect is a result of a temperature difference between the inside and outside air resulting in dissimilarity in the air density, and a change in the density of the air as a function of height. This stack effect is quite significant for high-rise buildings; for most residential buildings that are one or two stories, this effect is minimal and assumed negligible ($\Delta P_s = 0$).

The pressure differential arising from a prevailing wind depends on the location and geometry of the building, as well as the direction and speed of the wind. It is common to calculate a stagnation pressure from a given wind speed and air density according to Bernouli principles, and then adjust that calculation according to certain building design parameters [49]. The equation for the stagnation pressure is given as:

$$P_{stag} = \frac{1}{2}\rho_{air}V_{wind}^2 \text{ [Pa]} \tag{53}$$

The external pressure acting on the surface of the building is then the stagnation pressure multiplied by the external pressure coefficient (C_{pe}). This coefficient has been experimentally measured by AHSRAE, and the values depend primarily on the direction of the wind and height of the surface. For low rise buildings, the C_{pe} for the windward side of a house is roughly 0.7 and -0.14 for the leeward side [49]. Maximum positive pressures occurs on a surface oriented perpendicular to the direction of the wind (C_{pe} = 0.7), and the maximum negative pressure occurs on a leeward surface oriented 135 degrees to the direction of the wind (C_{pe} = -0.6) [49]. The total pressure differential is the difference between the exterior surface pressure and the interior surface pressure. For low rise buildings, the interior surface pressure coefficient can be considered to be a constant of -0.2 [49]. The expression for the pressure difference between the inside and outside of a wall is thus given by:

$$\Delta P_w = P_{stag}\left(C_{pe} - C_{pi}\right) = P_{stag}\left(C_{pe} + 0.2\right) \text{ [Pa]} \tag{54}$$

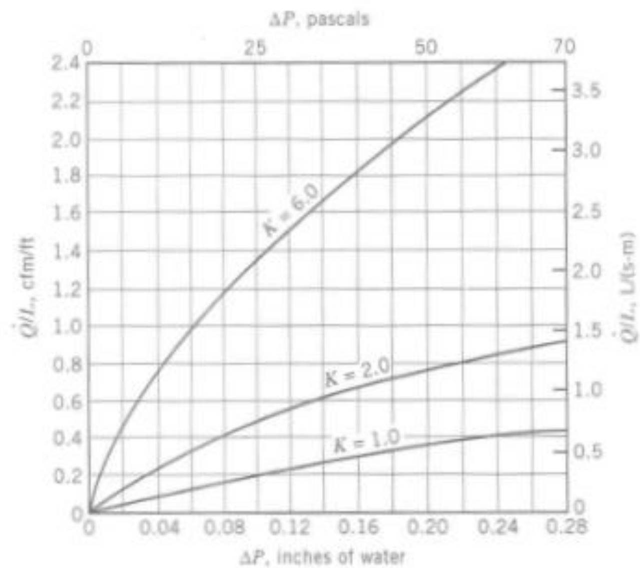


Figure 19: Infiltration rate per unit crack length for windows and doors [55]

One common method of determining the amount of air infiltration or exfiltration to the enclosure is to use the crack method. This method assumes that the majority of air leakage occurs around windows and doors. Then, based on a pressure difference one can calculate the volumetric flow rate per length of crack for the window or door:

$$\dot{V}_{air} = A_{crack} C \Delta P^m \text{ [m}^3\text{/s]} \tag{55}$$

where A_{crack} is the effective leakage area of the crack, C is the flow coefficient dependent on the type of flow through the crack, and m is an exponent depending on the severity of the crack (both C and m are determined according to the application and installation). Using the analysis in Equation (55), ASHRAE has compiled a means of determining the volumetric flow rate of air based on the quality of door or window installation and the pressure difference as seen in Figure 19. The relation between the volumetric flow rate and A_{crack}, C, and m is assumed into a new value K that represents how tight-fitting is the window or door unit penetration. Figure 19 depicts how the volumetric flow rate of air per unit length of exterior penetration is assessed for a given door or window. In this case, a K value of 1, 2, or 6 corresponds to very tight, average, or loose fitting window or door, respectively. New doors and windows properly installed will have a K value of 2 or higher.

Heat loss due to air leakage is directly correlated to the amount of air entering or exiting the enclosure. The sensible heat loss is calculated by determining the heat storage capacity of the air. The expression for the sensible heat transfer to the infiltrated air is given by:

$$\dot{Q}_{S-Airexchange} = \dot{V}_{air}\rho_{air}c_{p-air}\Delta T_{air} \text{ [W]} \tag{56}$$

where c_{p-air} is the specific heat of the air at constant pressure, and ΔT_{air} is the temperature difference between the inside ($T_{inside-air}$) and outside ($T_{outside-air}$) air. Depending on how well the humidity level is controlled in the residence, a latent heat transfer to the exterior air also occurs. The expression for determining the latent heat transfer is given by:

$$\dot{Q}_{L-Airexchange} = \dot{V}_{air}\rho_{air}h_{fg}\Delta W \text{ [W]} \tag{57}$$

where h_{fg} is the latent heat of vaporization at constant temperature, and ΔW is the difference in the humidity ratios between the inside and outside air.

Internal Heat Sources

The final element of heat transfer in a residence is the sensible thermal load occurring from the activity of people, lighting, and appliances inside the house. While a latent load occurring from human activity and the operation of certain appliances does exist, it is considered relatively small compared to the thermal load and will not be considered in the analysis. As people move and work inside the residence, they generate heat and moisture. The amount of heat generated by people in the residence is determined by two main factors: the number of people (N) and their level of activity (taking into account their age). For the sensible heat gain, the internal heat gain is first absorbed by the surrounding environment and then slowly released into the inside air. In order to measure the effect of this time delayed heating, a cooling load factor (F_{cl}) applied [56]. The magnitude of this factor is determined primarily by how long the activity has already been in progress. The sensible heat generated by people is given as [56]:

$$\dot{Q}_{S-people} = NF_{cl}\dot{q}_{S-people} \text{ [W]} \tag{58}$$

where $\dot{q}_{S-people}$ is the rate of heat transfer per person.

Lighting and appliances also generate a significant amount of sensible heat. In this analysis, appliances include all of the loads that are operated out of a wall socket including electronics but excluding lighting loads. The amount of lighting and appliances being used at a given time is determined by a usage factor (F_u, also referred to as a diversity factor). This factor is a measure of the percentage of maximum load that is currently in use and as such has values between 0 and 1. The lighting load takes into account a ballast factor (F_b) which is a measure of the additional power consumption of the light bulb when operated on different ballast than that on which it was rated. A cooling load factor is also applied in determining the sensible heat generated by the both the lighting and appliance loads. The expressions for the lighting and equipment loads are given as, respectively [56]:

$$\dot{Q}_{S-lighting} = F_{u,l}F_bF_{cl,l}W_l \text{ [W]} \tag{59}$$

$$\dot{Q}_{S-appliance} = F_{u,a}F_{cl,a}W_a \text{ [W]} \tag{60}$$

where W_l and W_a represent the total lighting and appliance load in the residence, respectively. The total internal loads are determined by summing the different internal load components as follows:

$$\dot{Q}_{S-Internal} = \dot{Q}_{S-people} + \dot{Q}_{S-lighting} + \dot{Q}_{S-appliances} \text{ [W]} \tag{61}$$

Analyzing the Impact of Wind on Heat Transfer Analysis

This analysis begins with a statement of the governing assumptions:

- Conductive heat transfer occurs in one dimension only, namely that which is perpendicular to the plane of the surface
- Over short increments of time, the heat transfer process is steady state, during which time the increment members of the wall do not store heat or increase/decrease in temperature
- During increments in which a net heat transfer to or from the interior space occurs, the net heat gain or loss is imparted to the interior air only, this includes internal loads and as such the cooling load factor will assume a value of one
- Thermo-physical properties of the building materials are constant within the temperature range observed by the structure
- Temperature distribution of the air inside the residence is uniformly distributed
- Solar radiation is the only component of radiation transmitted through the glazing into the interior conditioned space

Table 19: Building specifications and design criteria

Building Location	**Topeka, KS**
Latitude	**39.07 deg**
Longitude	**95.63 deg**
Summer Indoor Design Temp	**23.9 C**
Summer Design Humidity	**60%**
Winter Indoor Design Temp	**18.3 C**
Winter Design Humidity	**50%**
Building Footprint	**12.2 m x 12.2 m**
Geometry	**Rectangle**
Wall Height	**2.4 m**
Number of Stories	**1**
Ground Floor	**On ground-adiabatic**
Roof Slope	**Flat**
South Wall Orientation	**True South**

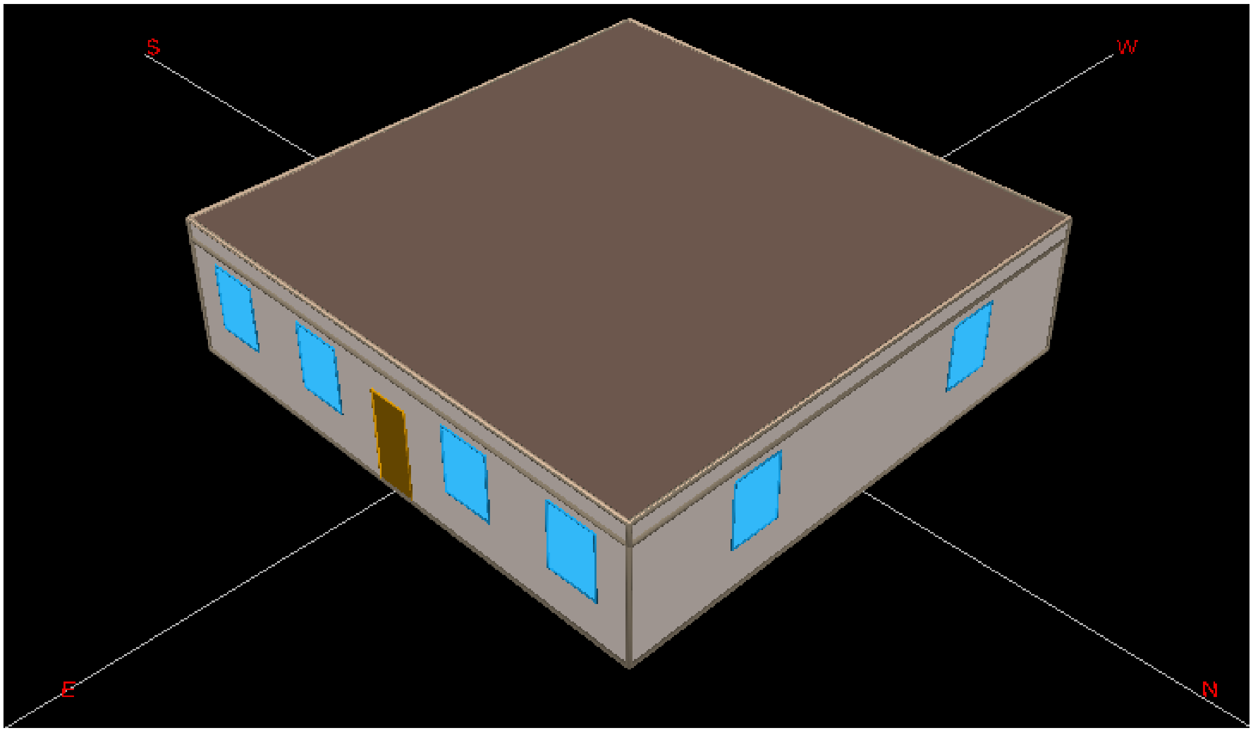


Figure 20: The simple structure considered in the analysis

In order to analyze the suitability of using a heat pump to store excess electricity generated by the wind turbine, a basic residential structure is considered. Table 19 lists the location, design criteria, and geometry of the structure while Figure 20 depicts the simple design utilized. It will be assumed that the floor is well insulated and sealed and that the heat transfer between the floor and the ground is negligible. A flat roof is modeled to aid in the simplicity of the analysis. The south wall is oriented due south and has a surface azimuth angle of 0 degrees. Two exterior entries doors exist; one on the south and one on the north wall. The south, east, and west facing walls all have 25% of their surface area covered by windows, and the north wall has 10%; the ratio of the crack length to the area of window is 3 m/m^2. Each door has a crack length of 5.2 meters.

Table 20: Thermal Properties of Walls and Roof

Wall Thermal Resistance				Roof Thermal Resistance			
Material	**Conductivity**	**Thickness**	**R**	**Material**	**Conductivity**	**Thickness**	**R**
~	**W/(m-K)**	**m**	**K-m^2/W**	**~**	**W/(m-K)**	**m**	**K-m^2/W**
Inside airfilm	~	~	0.660	Inside airfilm	~	~	0.610
Sheetrock ½ "	0.16	0.013	0.081	Sheetrock5/8"	0.16	0.016	0.100
2x6 Pine	0.12	0.14	2.947	2x12 Pine	0.12	0.286	6.933
Fiberglass-batts	0.04	0.14		Fiberglass-blown in	0.036	0.286	
Polystyrene foam 1/2"	0.024	0.013	0.542	1/2" OSB	0.1	0.013	0.130
Pine T&G 3/4"	0.12	0.019	0.158	Tar Paper	60	0.001	0.000
Total			**4.389**	Metal	60	0.001	0.000
				Total			**7.773**
Window			**1.25**				
Door			**1.51**				

Table 21: Radiative properties of building surface

Radiative Properties	$\varepsilon_{sky}/\alpha_{sky}$	α_{solar}	τ_{solar}
Wall	0.82	0.92	0
Roof	0.85	0.92	0
Door	0.9	0.26	0
Glass	0.9	0.12	0.25*
*effective transmittance, SHGC rating			

Table 22: Internal load component parameters for design case 1

$\dot{q}_{S-people}$	65 Watts
w_l	6.45 Watts/m^2
w_a	10.76 Watts/m^2
N	4 people
F_{cl}	1
$F_{u,l}$	0.25
$F_{u,a}$	0.25
F_b	1

Table 20 and Table 21 list the thermo-physical properties of the structure. Table 22 lists the parameters used to calculate the internal loads. The heat gain from people was determined using ASHRAE data assuming a relatively low level activity for this period of day [55]. The lighting and appliance load densities are eQUEST recommended values for residential units [57]. The lighting usage factor assumes that some percentage of lights are always left on, as well as that at this time some of the household members have risen and are performing basic morning functions. The appliance usage factor recognizes that certain appliances are always left on (refrigerator) and estimated what an average appliance load for that time of the day might be.

Table 23: Design criterion for design case 1

Design Case #	**1**		n	1
Date	1-Jan		$\delta°$	-23.01
Solar Time	6:00 AM		$\varphi°$	39.07
Indoor Temp	18.3° C		$\omega°$	-90
Indoor Rel. Humidity	60%		G_h	0 W/m^2
Outdoor Temp	-17.8° C		ρ_g	0.25
Outdoor Rel. Humidity	40%		ρ_{air}	1.29 kg/m^3
Prevailing Wind Direction	Out of North		$c_{p\text{-}air}$	1.006 kJ/(kg-K)
Sky Temperature	-35.3° C		h_{fg}	2458 kJ/kg

Table 23 lists the design criteria for a heat transfer analysis performed on the building during winter. The temperature of the sky was calculated using Equation (48). Equation (34) was used to determine the convection coefficient for each exterior surface at the given wind speeds. In order to determine the influence of the wind on the heating load, the analysis on a given surfaces is performed at multiple wind speeds. The surface temperature is solved for through Equation (49) by setting the net heat flux to the surface to zero. After this value is calculated, the net heat transfer across the membrane is calculated. The pressure difference across each surface is determined assuming a C_{pe} of 0.7 for the windward side, -0.14 for the leeward side, and -0.5 for sides oriented 90 degrees to the direction of the wind. The flow rate of air per unit crack length was determined using Figure 19. In order to better describe the relationship between the K value, pressure difference, and flow rate, data points were taken from Figure 19 at intervals of 5 Pa and a second order polynomial was fitted to the data. The derived expressions for the three different K values were determined to be:

$$\dot{V}_{air} / L_{K=1} = -.000000127\Delta P^2 + .000017685\Delta P \;\; [(\mathrm{m^3/s})/\mathrm{m}] \tag{62}$$

$$\dot{V}_{air} / L_{K=2} = -.000000208\Delta P^2 + .000034149\Delta P \;\; [(\mathrm{m^3/s})/\mathrm{m}] \tag{63}$$

$$\dot{V}_{air} / L_{K=6} = -.000000520\Delta P^2 + .000091679\Delta P \;\; [(\mathrm{m^3/s})/\mathrm{m}] \tag{64}$$

The unit for ΔP is the pascal. Using the above equations for the air flow rate per unit crack length, the sensible and latent heat transfer to the infiltrated air are calculated using Equations (56) and (57).

Table 24: Resulting surface temperatures and pressure differences across building for design case 1

		$T_{surface}$ (°C)			ΔP (Pa)		
		V=1 m/s	V=5m/s	V=10 m/s	V=1 m/s	V=5m/s	V=10 m/s
South Side	Wall	-18.97	-18.42	-18.19	0.04	0.97	3.87
	Door	-17.99	-17.89	-17.85	0.04	0.97	3.87
	Window	-17.64	-17.70	-17.73	0.04	0.97	3.87
East Side	Wall	-18.97	-18.42	-18.19	-0.19	-4.84	-19.35
	Window	-17.64	-17.70	-17.73	-0.19	-4.84	-19.35
West Side	Wall	-18.97	-18.42	-18.19	-0.19	-4.84	-19.35
	Window	-17.64	-17.70	-17.73	-0.19	-4.84	-19.35
North Side	Wall	-18.97	-18.42	-18.19	0.58	14.51	58.05
	Door	-17.99	-17.89	-17.85	0.58	14.51	58.05
	Window	-17.64	-17.70	-17.73	0.58	14.51	58.05
Roof	Roof	-20.82	-19.50	-18.90	0.45	11.29	45.15

Under the conditions listed in Table 23, the net heat transfer across each wall and roof surface was calculated. The internal loads were calculated according to Table 22. Table 24 shows the resulting surface temperatures and pressure difference for each building surface when evaluated at wind speeds of 1, 5, and 10 m/s. It can be seen from Table 24 that for each wind speed the surface temperature of the roof and walls is significantly colder than the outdoor temperature, while the surface temperature of the windows and doors is just about the same as the outdoor temperature. The roof and walls have a much higher thermal resistivity than the windows and doors, and thus there exists a higher temperature gradient between the inside and outside temperatures for the roof and walls. This, as well as the cold sky temperature, accounts for the roof and walls having a colder temperature than the windows and doors, as well as the outdoor air.

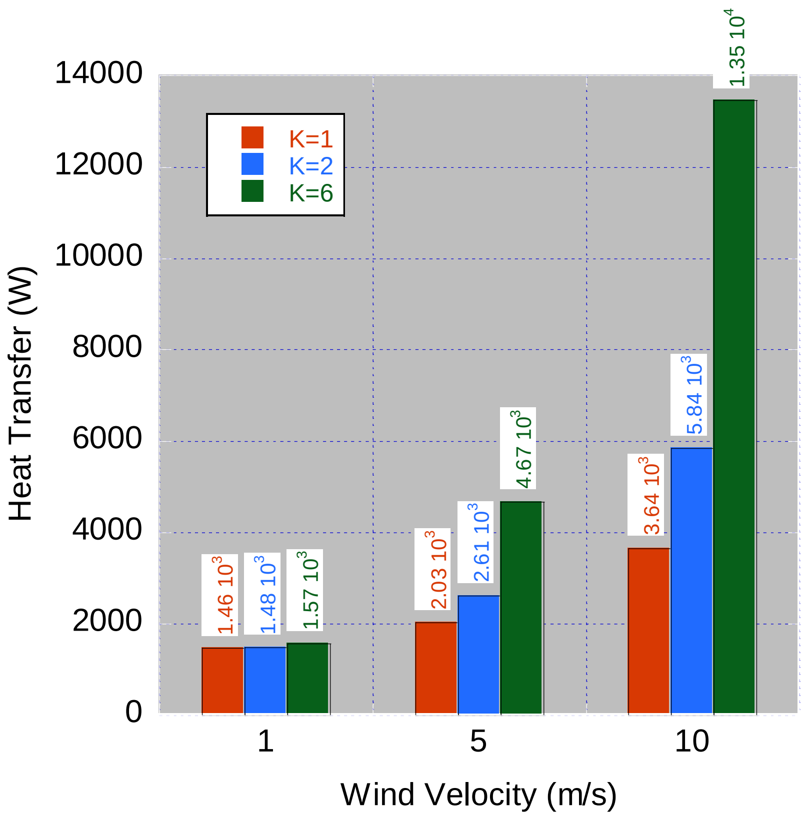


Figure 21: Net Heat transfer across building for given K value and wind velocity for design case 1

Figure 21 depicts the net heat transfer across the building (including the interior loads) assuming three different K values for the windows and doors at the three wind speeds mentioned prior. As illustrated, the net heat transfer dramatically increases as the velocity of the wind increases; this is due primarily to the increased pressure gradient between the inside and outside environments caused by increased wind speeds. At a velocity of 1 m/s, the net heat transfer for the different K values are relatively similar; however, the heat transfer associated with the higher wind speeds significantly increases as the K value increase. This indicates that at low wind speeds, the pressure gradient across the building is relatively insignificant, and the majority of the heat transfer occurs via conduction through the building membrane.

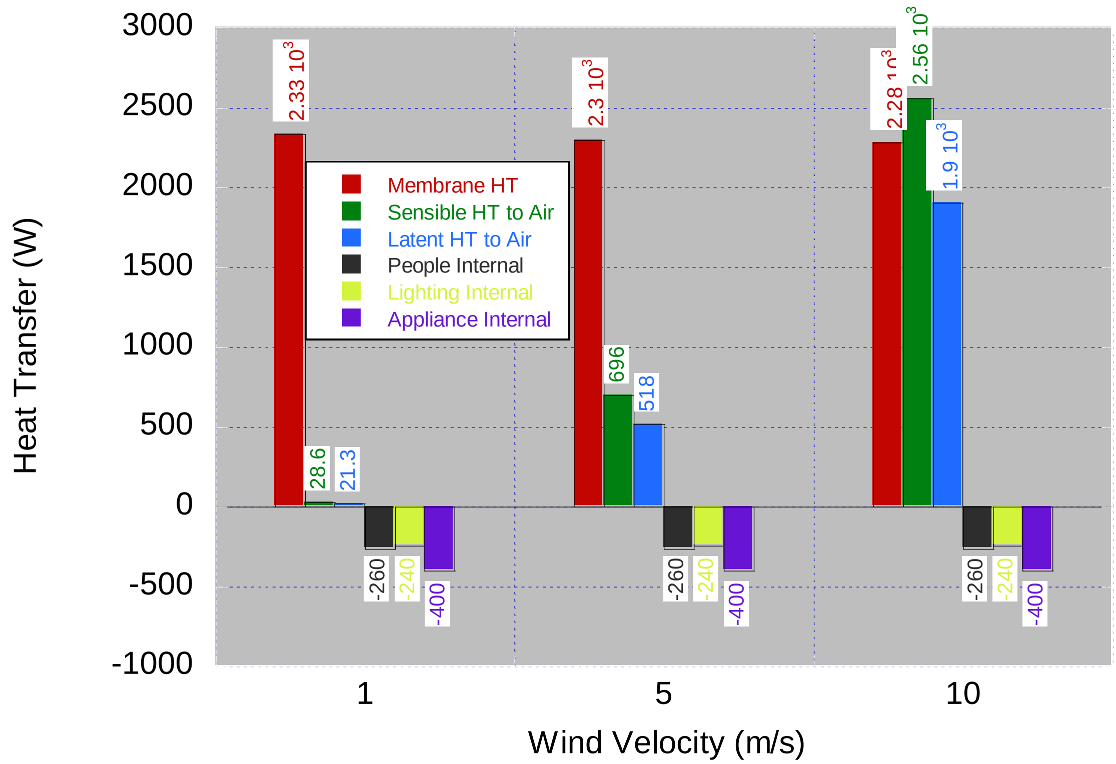


Figure 22: Net heat transfer across building for K=2 for design case 1

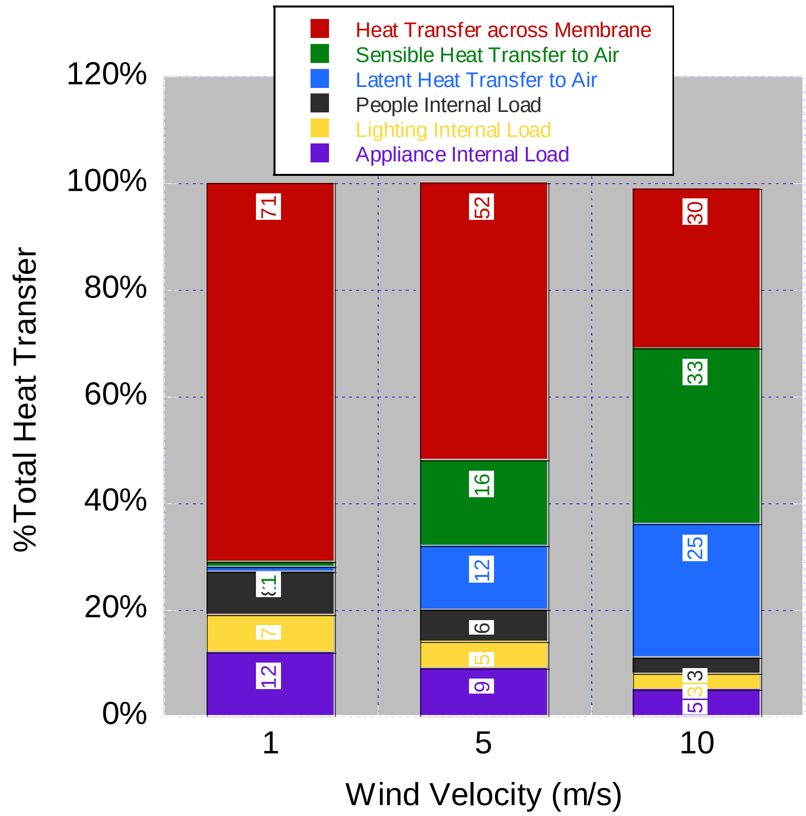
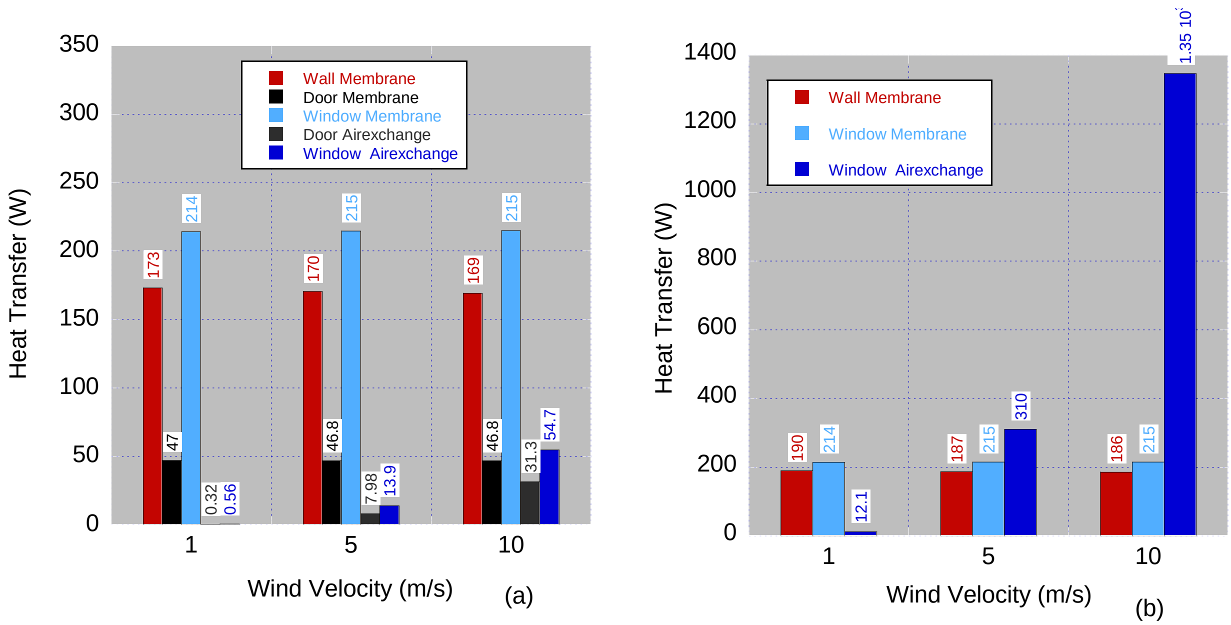
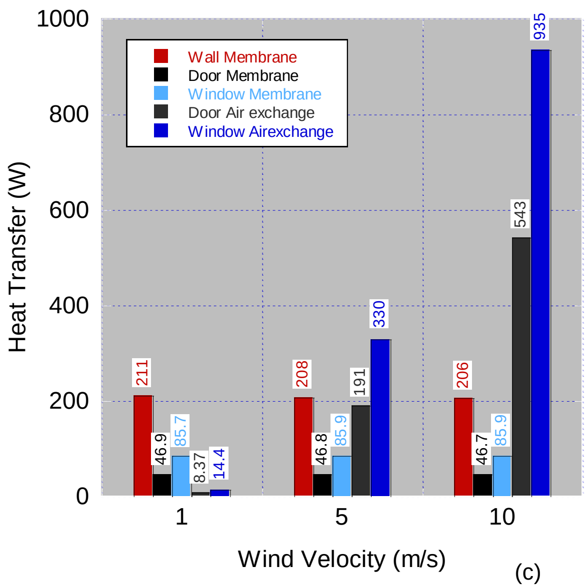


Figure 23: % component heat transfer across building for K=2 for design case 1

Figure 22 displays the net heat transfer broken into its different components that takes place when the K value is equal to two. Figure 23 shows the percent contribution of each load component compared to the total heat transfer at each wind velocity. The internal loads were included in this analysis by considering their absolute value. Though there is quite evidently a significant increase in the heat transfer to the air associated with an increased wind velocity, the conductive heat transfer across the membrane itself slightly decreases. Because the surface temperature of the roof, walls, and doors is colder than that of the air, heat is convected from the air onto the exterior surface; the reverse of this is true for the windows. As the wind speed increases, the convection coefficient increases, and more heat is being convected onto the roof, walls, and doors. This causes an increase in the surface temperature of these components resulting in less heat escaping the building across the membrane. In total, the internal loads account for 900 watts of heat transfer. As these loads are inputting heat into the interior space, they are reducing the thermal load on the heat pump and, thus, the overall heat transfer across the building. While the internal and thermal loads across the membrane remain relatively constant, the thermal load due to the air exchange significantly increases as the wind velocity increases. At a wind speed of 10 m/s, the dominant mode of heat transfer is via sensible and latent heat exchange with infiltrating air; 58% of the total heat transfer is due to the air exchanges.





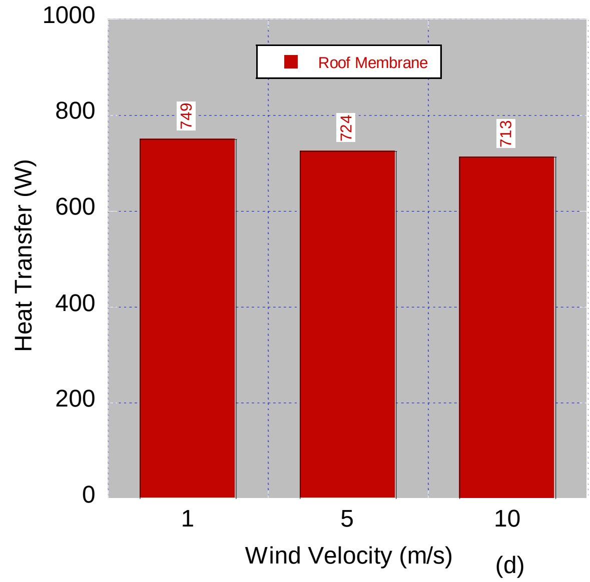


Figure 24: Heat transfer across the south, east/west, north, and roof sides of the building (a,b,c,d) for design case 1

Figure 24 shows the heat transfer across each side and surface of the building assuming a K value of 2. The latent and sensible heat exchanges around the doors and windows are combined into one air exchange term. For this design scenario, the heat transfer across the east and west sides are identical; also keep in mind that no doors exist on these sides. In terms of heat transfer through the membrane, the greatest value occurs over the roof. This is due to it having the largest surface area of the sides (five times that of the walls). The south side has the next highest amount of heat transfer through the membrane; this is due to it having the highest concentration of windows and doors. The east/west side has the highest amount of heat transfer via air exchanges followed by the north side. Even though the highest pressure difference occurs across the north side (being the windward side), the east/west sides have more windows and, thus, a higher amount of crack length. Given that as these sides have the highest heat transfer via air exchange; these sides see the greatest increase in net heat transfer corresponding to an increased wind velocity.

Table 25: Design criterion for design case 2

Design Case #	2		n	182
Date	1-Jul		δ	23.12°
Solar Time	3:00 PM		φ	39.07°
Indoor Temp	23.9° C		ω	45°
Indoor Rel. Humidity	60%		G_h	900 W/m^2
Outdoor Temp	37.8°C		ρ_g	0.25
Outdoor Rel. Humidity	70%		ρ_{air}	1.225 kg/m^3
Prevailing Wind Direction	Out of South		$c_{p\text{-}air}$	1.006 kJ/(kg-K)
Sky Temperature	31.3°C		h_{fg}	2411 kJ/kg

Table 26: Internal load components for design case 2

$q_{S\text{-}people}$	70 Watts/person
w_l	6.46 Watts/m^2
w_a	10.76 Watts/m^2
N	4 people
F_{cl}	1
$F_{u,l}$	0.50
$F_{u,a}$	0.50
F_b	1

The second heat transfer simulation of the building model analyzes heat transfer during the middle of the summer. The primary difference in this analysis is that solar radiation will be included, and its effect will be considered in the evaluation of the energy balance performed on each exterior surface. The amount of solar irradiation incident on a surface is determined using Equation (39). The solar properties of the different surfaces are listed in Table 21**.** Table 25 lists the design criteria for this analysis. The sky temperature was calculated using Equation (47) and adjusted according to [49] for a slightly less than a 50% clear sky. The prevailing wind in this case is from the south. Table 26 describes the components of the internal loads. The heat transfer due to human activity represents that for light activity seated or standing. The lighting and appliance load density remains the same as in design case 1 (same house), but now the usage factors are 0.50. These values assume that at this time of the day there is more activity in the house resulting in more lights and appliances in use.

Table 27: Resulting surface temperatures and pressure differences across building for design case 2

		G_{solar}	$T_{surface}$ (°C)			ΔP (Pa)		
		W/m^2	V=1m/s	V=5m/s	V=10m/s	V=1m/s	V=5m/s	V=10m/s
South Side	Wall	291.65	54.13	47.07	43.80	0.55	13.78	55.13
	Door	291.65	40.81	39.52	38.91	0.55	13.78	55.13
	Window	291.65	38.08	37.95	37.89	0.55	13.78	55.13
East Side	Wall	186.75	47.82	43.46	41.46	-0.18	-4.59	-18.38
	Window	186.75	37.28	37.49	37.59	-0.18	-4.59	-18.38
West Side	Wall	836.31	85.66	65.59	55.92	-0.18	-4.59	-18.38
	Window	836.31	42.20	40.33	39.45	-0.18	-4.59	-18.38
North Side	Wall	186.75	47.82	43.46	41.46	0.04	0.92	3.68
	Door	186.75	39.07	38.52	38.26	0.04	0.92	3.68
	Window	186.75	37.28	37.49	37.59	0.04	0.92	3.68
Roof	Roof	900.00	79.17	63.94	55.55	0.43	10.72	42.88

Due to the warm summer air and solar radiation, there is net heat transfer into the building that places a cooling load on the heat pump. Table 27 shows the surface temperature and pressure differences for each of the surfaces on the different sides of the building. Due primarily to the absorbed solar radiation, the surface temperatures of the roof, walls, and doors are warmer than the outside air temperature. This is also true of the south and west side windows that are predominantly in the sun; however, the surface temperatures of the north and east windows are slightly cooler than the outside air. Being in the shade, having lower solar absorptive properties, and a relatively low thermal resistivity all contribute to this phenomenon. Of note, at a wind velocity of 1 m/s the temperatures of the west wall and roof are extremely hot (85.6°C and 79.17°C, respectively). While this seems unreasonable, it is estimated that the maximum temperature over the course of a year for a vertical wall and roof are 87.8°C and 110°C respectively [58]. For a west wall, the maximum solar irradiation will occur in the middle of summer about four hours after noon [58]. This fact combined with a α_{solar} value of 0.92 and a relatively low convection coefficient accounts for the high surface temperature of the west wall. Similar to design case 1, the highest pressure difference occurs on the windward side (south side) of the house and the lowest on the leeward side. Table 27 also shows the solar irradiation on the different surfaces.

As can be seen, the west side has the highest irradiation followed by the south side; the north and east sides are equal and indicating a minimal amount of surrounding solar reflectivity.

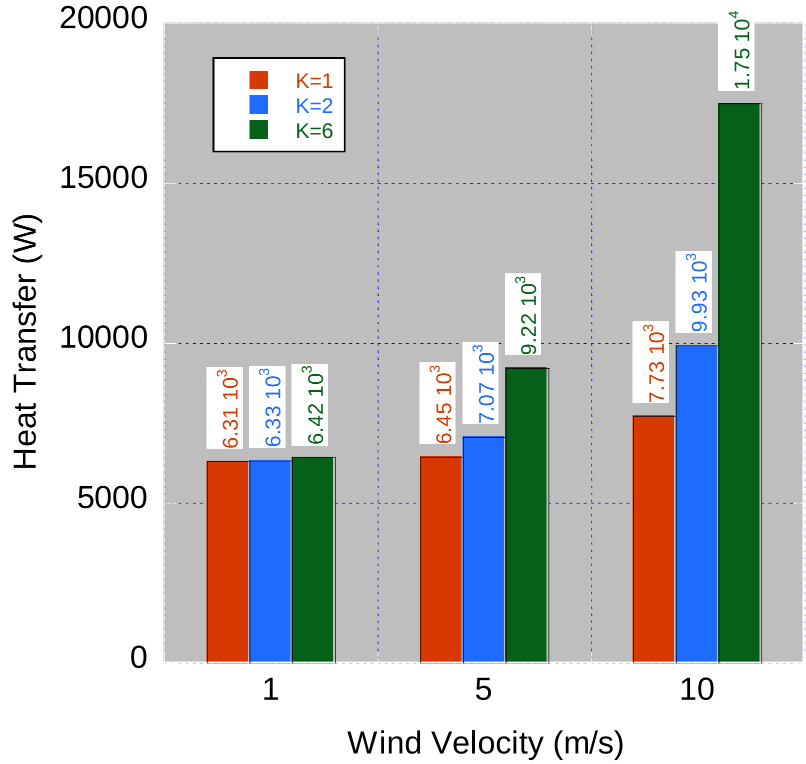


Figure 25: Net heat transfer during summer for given velocity and K value for design case 2

Figure 25 depicts the net heat transfer across the building including the internal loads for the given K values and velocities. Similar to design case 1, higher K values, as well as increased wind velocities both result in a higher thermal load. However, unlike the previous design case, the percent increase in total heat transfer is not as significant. There are two main reasons why this is the case. First, the solar load on the building results in significant amount of heat transmitted through the windows, especially on the south and west sides that exists independent of the wind velocity. Second, the temperature difference between the outside and inside air is significantly lower, which coupled with a lower outside air density results in significantly smaller amount of sensible heat being transferred to the infiltrated air.

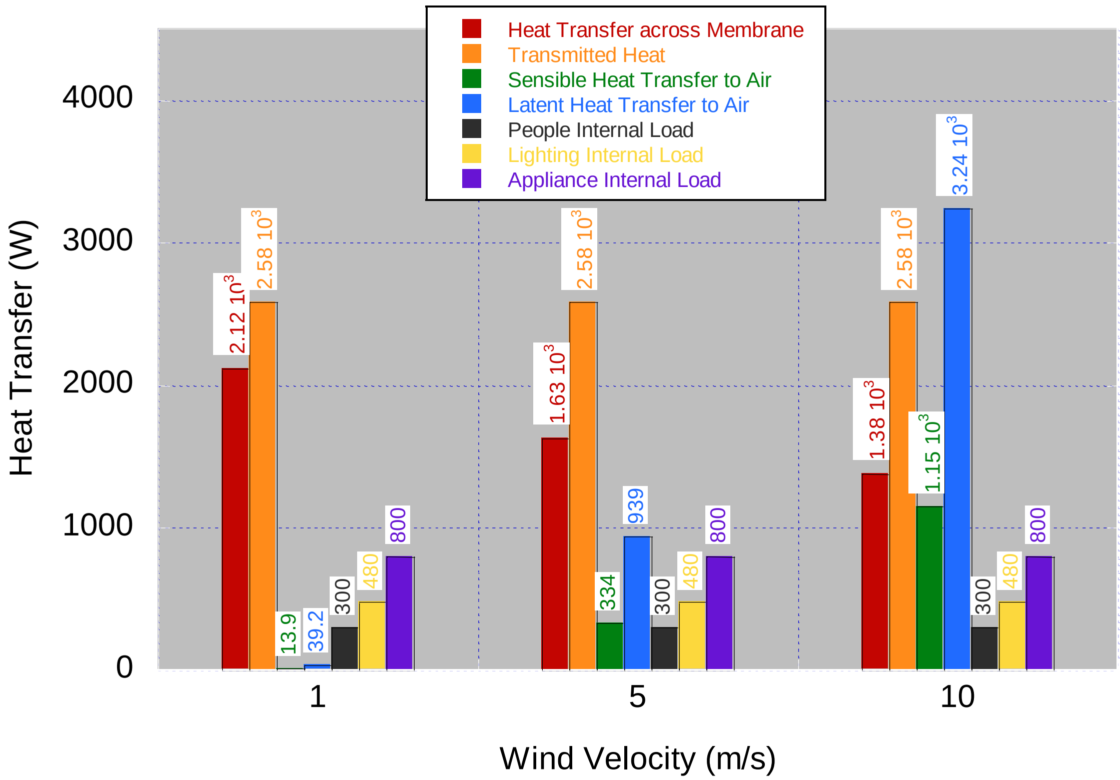


Figure 26: Component heat transfer across building for K=2 for design case 2

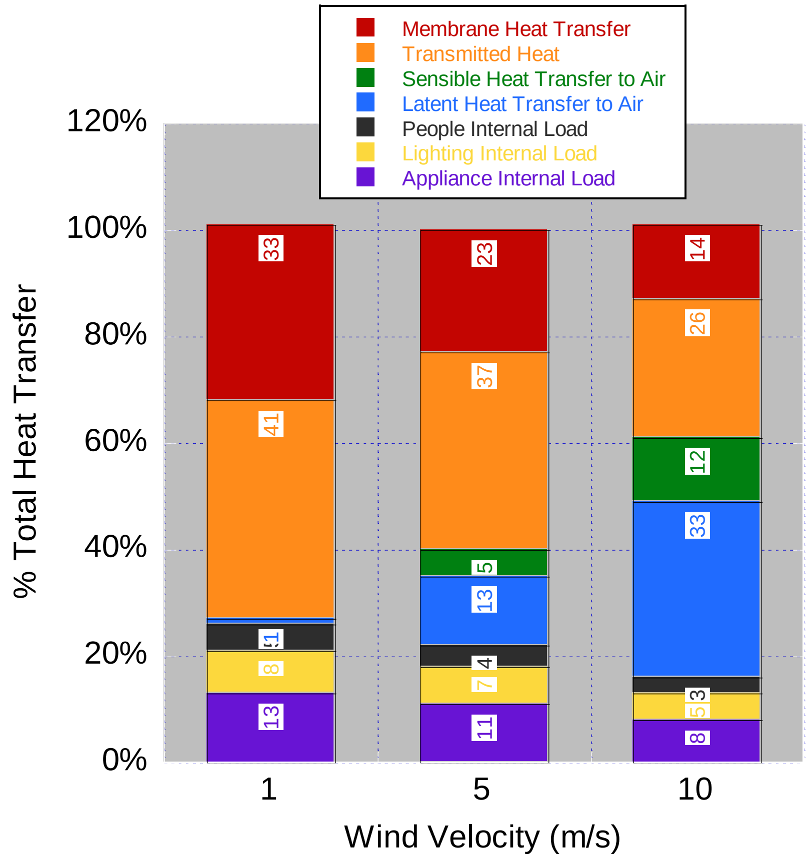
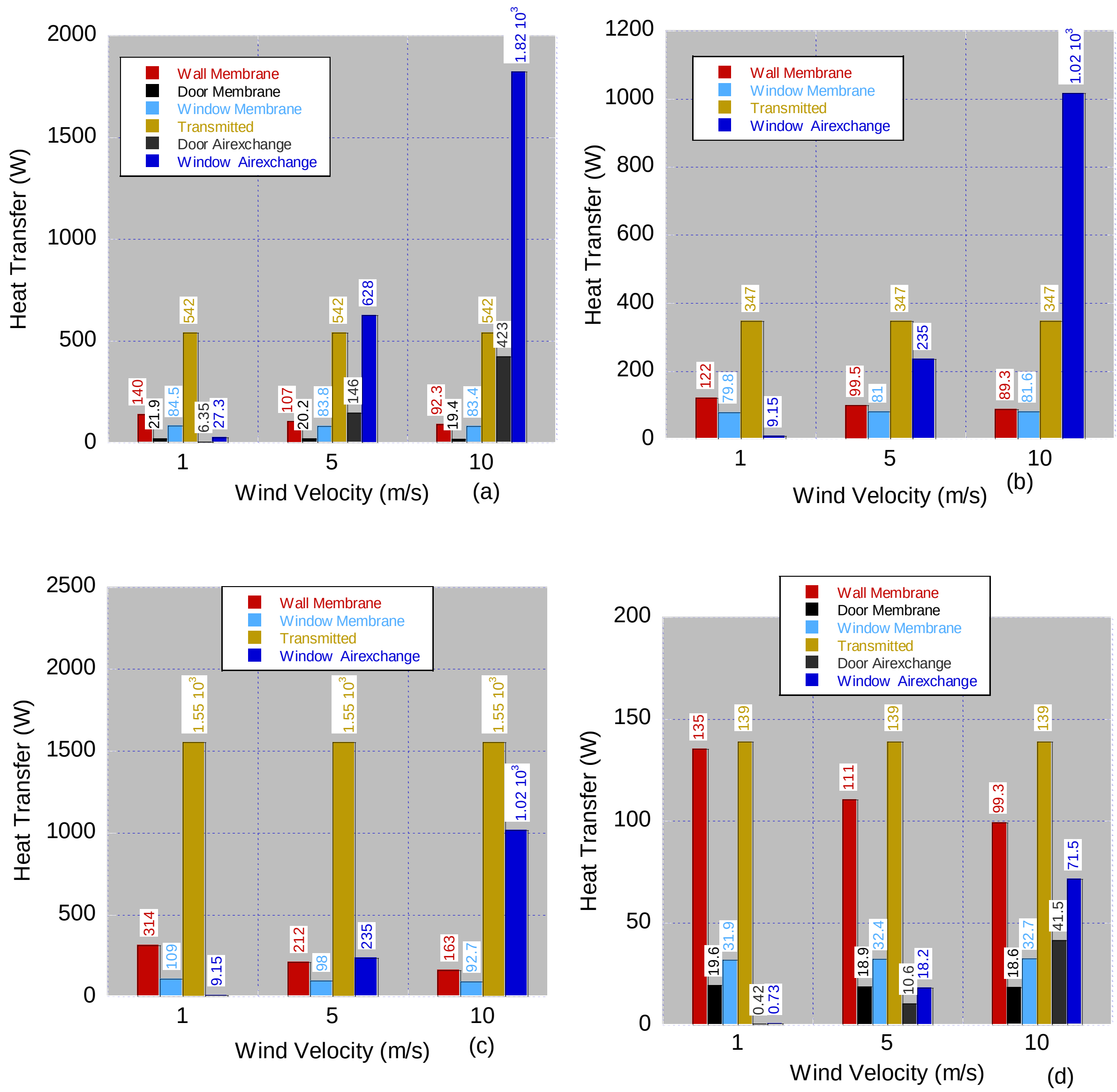


Figure 27: % component heat transfer across building for K=2 for design case 2

Figure 26 shows the heat transfer across the building associated with the different components of thermal loading assuming a K value of 2, and Figure 27 shows the percent contribution of the total thermal load at each wind velocity for each load component. The transmitted heat and the internal thermal loads are constant. The heat transfer across the membrane substantially reduces as the wind velocity increases. As mentioned prior, the surface temperatures for the roof, walls, and doors are hotter than the outside air. Thus, the convective heat transfer is cooling the building, and as the wind speed increases so does the convective heat transfer coefficient. Similar to design case 1, as the wind speed increases so does the amount of infiltrated air and corresponding thermal load. Of note, because of an increased moisture content in the outside air, the latent heat transfer to the air in this design case results in a significant thermal load on the building. The percent contribution of the latent heat exchange increases from 1% at a velocity of 1 m/s to 33% at a velocity of 10 m/s.



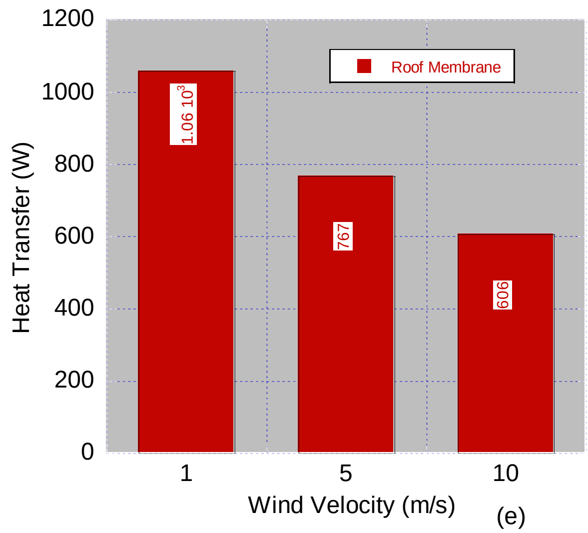


Figure 28: Heat transfer across the south, east, west, north, and roof sides of the building (a,b,c,d,e) for design case 2

Figure 28 shows the heat transfer across each side of the building; again, there are no doors on the east and west sides of the house resulting in zero heat transfer via membrane and air exchanges on those sides. It can be noted that the heat transfer through the membrane slightly decreases for each side as the wind speed increases; this is especially true for the roof that sees over a 40% reduction in heat transfer across the membrane. The surface temperature of this side is the highest, and thus an increasing convection coefficient associated with the increasing wind has a significant effect. The west side has, by far, the highest amount of transmitted heat, totaling more than all three other sides combined. Given the orientation of the sun, this is to be expected. The highest amount of heat transfer to air exchange occurs across the south side. Because this is the windward side and has the highest concentration of windows and doors, this also is to be expected. At higher wind velocities, the majority of heat transfer across this side is due to the air exchanges.

In design case 2 an increasing wind speed resulted in an increased thermal load. This is because the temperature of the outside air is warmer than that of the inside air, and increased amounts of infiltrated air result in increased sensible heat transfer. However, it should be noted that at times during the summer when the outside air is cooler than the desire indoor temperature, the effect of an increased wind speed is a reduction in the thermal load on the residence. In summer, this phenomenon often happens at night when the temperature drops to colder values. In winter, the outdoor temperature is almost always colder than the indoor air temperature.

The analysis in design case 1 and 2 suggest that the wind velocity has a significant influence on the net heat transfer across a residence. This is due to the increased amounts of air leakage across the membrane. Thus, for many old or poorly constructed houses that leak a fair amount of air, there will be a significant increase in the electric load on the heat pump as the wind speed increases. While this analysis assumed a relatively high percentage of windows, it ignored the influence of air penetration through the wall membrane itself, as well as through the opening and closing of doors and cracks around other exterior penetrations. The contribution of these influences to the total air leakage could be significant, and a thermal load placed on the residence due to air leakage could be higher than analyzed here.

Table 28: Comparison of sensible heat transfers

~	**Design Case 1 (Winter)**			**Design Case 2 (Summer)**		
Velocity	$\dot{Q}_{Membrane}$	$\dot{Q}_{S-Airexchange}$	% $\dot{Q}_{S-Airexchange}$	$\dot{Q}_{Membrane}+\dot{Q}_{Transmitted}$	$\dot{Q}_{S-Airexchange}$	% $\dot{Q}_{S-Airexchange}$
1 m/s	2334.9 W	28.6 W	1.2%	4698.8 W	13.9 W	0.3%
5 m/s	2299.5 W	696.5 W	23.2%	4213.4 W	333.5 W	7.3%
10 m/s	2283.6 W	2557.6 W	52.8%	3961.2W	1150.8 W	22.5%

However, it should be noted that a significant portion of the heat transfer to the air is due to latent heat transfer. Many residences do not thermally control the humidity level, and in these instances the thermal load associated with air leakage will be significantly reduced. Table 28 shows the contribution of the heat transfer through the membrane, the transmitted heat, and the sensible heat transfer to the air across the building for design case 1 and 2. It also illustrates the percentage of the sensible heat transfer relative to those three components. It can be seen that even ignoring the latent heat transfer, the contributions of the heat transfer to the air are still significant, especially at high wind speeds and during winter months.

Table 29: Total heat transfer and corresponding heat pump power input and normalized wind turbine power at given velocities

~	Wind Speed	Heat Transfer	Heat Pump Input Power	Turbine Power
	m/s	W	W	W/A_{rotor}
Design Case 1	1	1484.8	674.9	~0
	5	2614.4	1188.4	32.3
	10	5844.7	2656.7	258.6
Design Case 2	1	6331.9	1997.5	~0
	5	7066.3	2229.1	30.6
	10	9933.2	3133.5	245.0

Wind velocity significantly affects the thermal loading on a residence, and thus in some sense using a wind turbine to power a heat pump represents a synergistic use of energy. Table 29 shows the total heat transfer (including both the sensible and latent heat transfer to the air) for design case 1 and 2, the associated heat pump input power and heat pump COP of 2.2 for heating and 3.17 for cooling (from the results of the studies presented prior), and the power generated by the turbine normalized to the rotor area assuming a turbine power coefficient of 0.40 (an estimate based on small wind industry goals; recall from earlier that the overall industry goal is to achieve 45%). As can be seen, increasing the wind velocity from 5 to 10 m/s results in a thermal load that more than doubles while turbine power output increases eight fold. In this sense, implementing a wind turbine into the home energy system represents a synergistic use of energy: as the ability of the natural phenomenon to impart a thermal load increases, so does its ability to supply that thermal load.

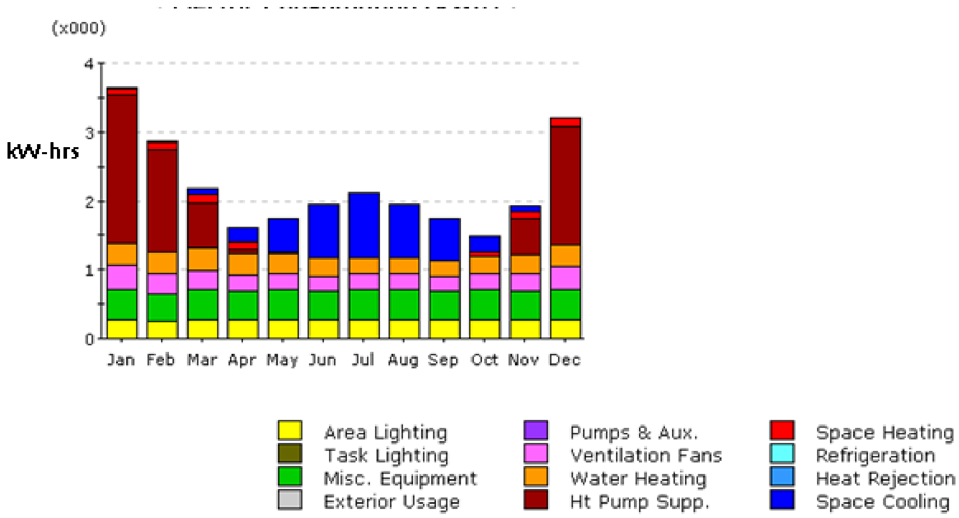
Assessing Heat Transfer as Effective means of Energy Storage

As analyzed in design case 1 and 2, wind velocity significantly affects the thermal loads on a residence. In the winter scenario, doubling the wind velocity from 5 to 10 m/s resulted in a thermal load that more than doubles, as well as an eight fold increase in the wind turbine power output. It thus appears that the available wind power scales well with an associated thermal load, and using heat pump technology to store excess electricity in the form of energy inside the residence has merit. The intent of this analysis is primarily to understand the trends between an increasing wind velocity and an associated thermal load. In order to illustrate this, a simplified approach to building heat transfer was considered. However, given that wind turbines operate year-round, how well heat pumps could serve as a means of "storing" excess electricity so that full value of the generated electricity is maintained will depend on the year-round thermal loads on the residence. Design case 1 and 2 analyze the thermal load for a cold winter day and a warm summer day, respectively. In both these cases, a relatively high temperature difference between the inside and outside of the enclosure exists, and this difference drives the magnitude of the thermal load. For many locations, there are a number of seasons and or days in which the outdoor temperature is comfortable and the associated thermal load is relatively small or non-existent. In these weather conditions, it is not so obvious that storing excess electricity as energy in the home has value. Thus, in order to determine the suitability of heat pumps for utilizing excess electricity, year round weather conditions and heat transfer pathways need to be considered. Also, a more thorough and complex analysis is desirable to more accurately determine the actual thermal load on a house under certain conditions.

Table 30: eQUEST simulation input parameters

Building location	Topeka, KS
EQUEST building type	Single family residential
Area of building	148.6 m^2
People load	70 Watt/person
Lighting load	6.46 Watt/m^2*
Plug load	10.76 Watts/m^2*
Number of people	4 people
% Occupied	75%
% Lighting Load while occupied	50%
% Lighting load while unoccupied	10%
% Plug load while occupied	50%
% Plug load while unoccupied	12.5%
Cooling setpoint while occupied	23.9 C
Cooling setpoint while unoccupied	26.7 C
Heating setpoint while occupied	18.3 C
Heating setpoint while occupied	15.6 C
Air changes per hour	5 [59]
Infiltration rate	.000185 $m^3/(s\text{-}m^2)$*
HeatPump size	Auto calculated by EQUEST
HeatPump SEER	14
HeatPump *COP (B)*	2.2
Hot water heater type	Electric, 154.4 liter tank
Hot water consumption	56.8 L/person/day
*EQUEST Defaults for given building type	

Because the analysis in design cases 1 and 2 suggest that heat pumps could be a viable means of storing excess electricity, eQUEST [57] was used to better model the thermal load on a building. eQUEST is a program developed by the DOE that is free for the public and can simulate building performance. eQuest V3.65 was used to design the structure shown prior in Figure 20 and to perform a year-round energy simulation on the structure. The design of the structure in terms of the thermo-physical properties is the same as that assumed in the analysis of design case 1 and 2. The internal loads were assigned using built-in eQUEST algorithms that specify certain lighting and appliance usage parameters; these parameters are defined in Table 30. eQuest uses an air exchange method to account for the heat transfer due to air infiltration. This method assumes a number of air exchanges per hour and an infiltration flow rate per area of wall including humidity control. For purposes of simplification, it is assumed that the load profiles remain constant throughout the week and year. The structure is heated and cooled using air source heat pump technology.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.01	0.02	0.08	0.22	0.47	0.78	0.93	0.79	0.59	0.23	0.07	0.01	4.19
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.09	0.10	0.13	0.09	0.02	-	-	0.00	0.01	0.06	0.10	0.12	0.72
HP Supp.	2.15	1.49	0.64	0.07	-	-	-	-	-	0.01	0.53	1.73	6.63
Hot Water	0.33	0.31	0.34	0.32	0.30	0.26	0.24	0.22	0.22	0.24	0.26	0.30	3.35
Vent. Fans	0.34	0.29	0.27	0.22	0.22	0.21	0.22	0.22	0.21	0.22	0.25	0.33	3.01
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	0.45	0.40	0.45	0.43	0.45	0.43	0.45	0.45	0.43	0.45	0.43	0.45	5.26
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.27	0.25	0.27	0.26	0.27	0.26	0.27	0.27	0.26	0.27	0.26	0.27	3.22
Total	3.64	2.86	2.17	1.62	1.73	1.95	2.11	1.96	1.73	1.48	1.92	3.21	26.38

Figure 29: eQUEST monthly electric consumption

	Electricity kWh
Space Cool	4,192
Heat Reject.	-
Refrigeration	-
Space Heat	717
HP Supp.	6,630
Hot Water	3,350
Vent. Fans	3,007
Pumps & Aux.	-
Ext. Usage	-
Misc. Equip.	5,256
Task Lights	-
Area Lights	3,224
Total	26,377

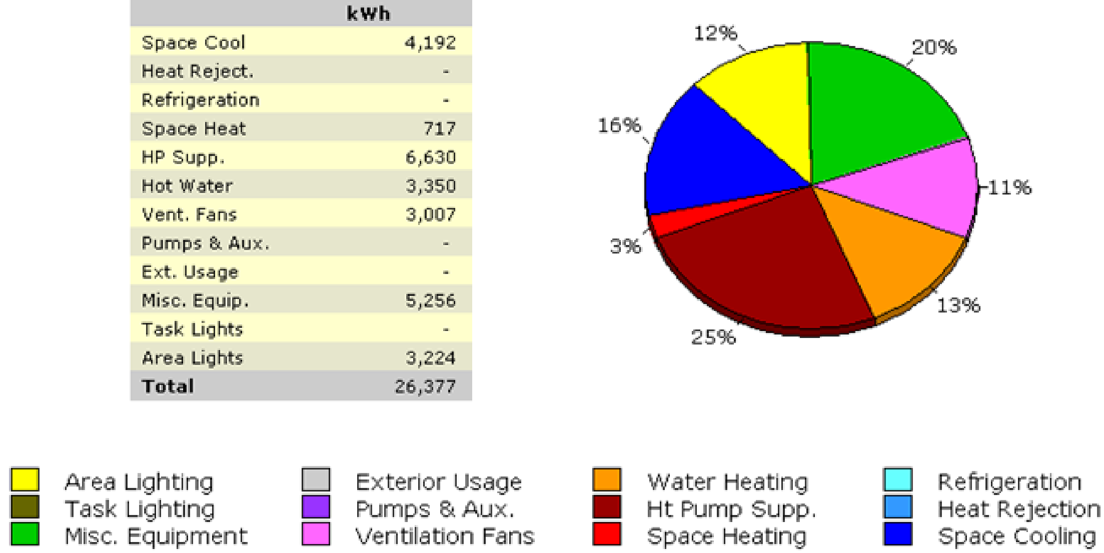


Figure 30: eQUEST annual energy consumption by end use

Table 31: Description of components analyzed in eQUEST simulation

Space Cool	Electricity used by the heat pump for cooling purposes
Space Heat	Space heaters used to supplement the heating load on the heatpump
HP Supp.	Electricity used by the heat pump for heating purposes
Hot Water	Electricity used by the hot water heater
Vent. Fans	Fans used to transport the cooled and heated air to different parts of the residence
Misc. Eqiup.	The appliances operated according to the plug load allocation
Area Lights	The lighting loads in the house

Figure 29 and Figure 30 show the eQUEST simulations results for the given building design and electric load profile using a 2001 weather file from Topeka, KS. Table 31 describes the different load components analyzed in the simulation. As can be seen from Figure 29, the Area Lights and Misc. Equip. (representing the lighting and plug electric loads) remain constant over the year at 270 and 450 kW-hours per month, respectively (variation between months is due to the length of month). While it states that the refrigeration load is zero, the consumption resulting from using a freezer and refrigerator are included in the Misc. Equipment category. The electric consumption of the hot water heater varies slightly over the course of the year as the ground and inlet water temperature change. The consumption of the ventilation fans is associated with operating the heating and cooling equipment. The space cooling is the amount electricity used by the heat pump to provide the cooling load, and the Ht Pump Supply is the amount of electricity used by the heat pump to provide the heating load. At times, given the load on the heat pump, eQUEST chooses to supplement the heating system with space heaters. Figure 30 displays the total annual consumption by end usage. In total, the 1600 square foot house consumes 26,377 kW-hours of which 55% is used to supply the thermal load (space cooling, heat pump supply, space heating, and ventilation fans). The end usage breakdown is similar to the breakdown determined by the U.S. Energy Information Administration shown in Figure 2, with the exception that in this analysis the cooling loads are substantially higher and the heating loads slightly lower.

Analyzing the Cost Economics of the Utilization of a Heat Pump for Storing Excess Electricity

Because of the thermal load that exists on the building, one could maintain the value of the excess electricity by storing it in the form of energy inside the building (i.e., adding or extracting heat as needed). Rather than utilizing batteries, excess electricity produced by the turbine (electricity not immediately needed in the residence) is sent to the heat pump which then converts that electricity into heat (or the removal of); thus, essentially storing the electricity for later use. At times, utilizing excess electricity in this manner will result in more energy entering or leaving the building than is needed to maintain the desired indoor environment (e.g., air conditioning on a hot day will reduce the temperature below the set point of the consumer). However, given a thermal load that exists over a certain period, the excess energy stored earlier will reduce the required energy input later. In the coming analysis, it is assumed that that the excess electricity stored as energy inside the building equals the amount of electricity that would have had to be purchased from the grid, and thus maintains the full value of the generated electricity. Granting this, this energy storage system acts just like a battery bank, except the cost of this energy storage system is zero as it is assumed that the heat pump system already exists in the *HES*. If the heat pump does not already exist in the HES, adding a heat pump merely to utilize excess electricity in this manner would likely not be cost effective given the additional costs. However, most houses will require some method of heating anyway, and if the cost of the heat pump system is assumed to be external to the turbine system then the economic viability is maintained.

As mentioned prior, a main drawback to this system is that at times more energy will be put into or taken out of the residence than is desired. For instance, in the winter, if the turbine is producing power at a time when there are no electric loads on the residence, all of the electricity generated by the turbine will be stored as energy inside the house, possibly increasing the indoor air temperature by a few degrees (or more depending on the scenario). There are a couple reasons why this should not be a major concern. First, as illustrated in design case 1 and 2, the thermal load increases with wind velocity, and thus as more power is generated by the turbine more electricity is also likely needed to maintain the desired indoor environment. Second, while residents set their thermostats at a certain temperature, there is a range of temperatures that are more or less comfortable. Hence, it seems unlikely that if this system utilizes a wind turbine that is well matched to the size of the house, there will be an issue with storing too much excess electricity inside the residence in this manner.

One aspect that needs to be clarified is that of the thermal load acting as both a regular electric load and as a means of storing excess electricity. From here on, the electric load on the house will be divided into auxiliary and normal loads. The auxiliary load represents the thermal loads that are allocated for storing energy. The normal load represents the remainder of the electric load (possibly including some percentage of the thermal load); the amount is the difference between the total load and the auxiliary load. A new term called the EER (similar to the ELR) represents the ratio of the monthly-generated electricity to the monthly normal load, and the BER (similar to the BLR') represents the ratio of the monthly auxiliary load to the monthly generated electricity. The difference between the ELR and the EER, as well as the BLR' and the BER, is that given a monthly load profile (as generated by eQUEST), the EER and BER are intended to be assessed on a monthly basis. In addition, they represent a system that uses thermal loads to store energy rather than a traditional battery bank.

Just like in the optimization of the $CESS$, the size of the wind turbine can be optimized according to the thermal and non-thermal loads of a residence. Given a total electric consumption for a given month, a wind turbine could be sized to generate any percentage of that total load. However, if it is sized to generate 100% of the total load, the system would have zero energy storage, and the associated system performance (X_{sys}) would be quite poor. If the turbine is sized to generate electricity for only the non-thermal loads, then the system would have the thermal loads as a means of energy storage, and the associated X_{sys} will be higher. Assuming a constant amount of electricity generated by the turbine each month according to a specified capacity factor, the question becomes what size of turbine (in kW) should be utilized so as to optimize the performance of the energy system in regards to cost economics. As mentioned prior, year-round data needs to be taken into account. For instance, looking at Figure 29, the month of January has the highest thermal load and total consumption. By sizing a turbine according to this month's load profile, this will likely result in a system that has poor performance and reduced cost economics for the majority of the year. Using the same method for determining the system performance as performed prior in this chapter, the system performance and corresponding NPV for a given sized turbine can be determined using the monthly load data from the eQuest simulation.

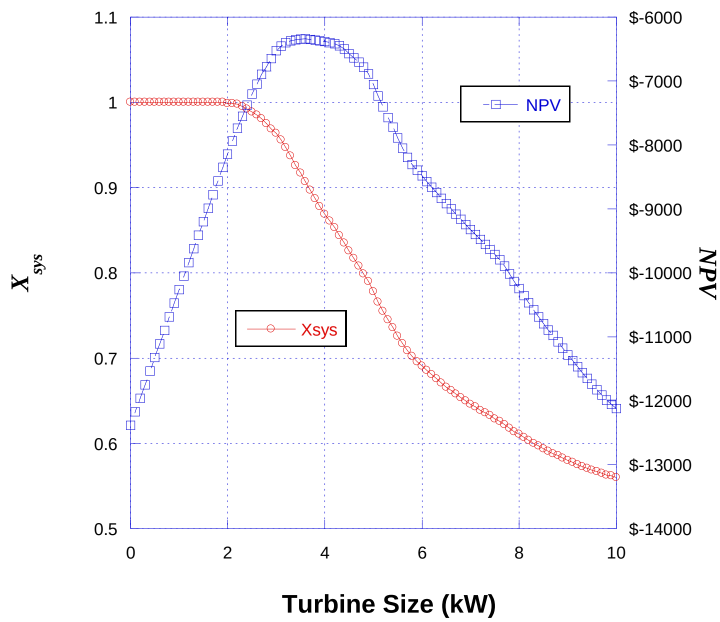


Figure 31: System performance and economic viability vs size of turbine

Figure 31 shows the resulting system performance and economic viability for different sized turbines utilized to generate electricity for the residence detailed prior. Thermal loads are used to store energy, and for a given turbine size each month has a determined EER, BER, and X_{sys} according to the monthly generated electricity assuming a 25% capacity factor. The X_{sys} displayed in Figure 31 is the yearly average determined by weighting the system performance values of each month. The cost economics are evaluated at a discount rate of 5%. As can be seen, small turbines result in a system performance of 1.00 (due to low EER and high BER, but due to a low ratio of $NAEP$ to the installed cost render poor economic viability. Large turbines have a higher $NAEP$ to installed cost ratio, but they generate more electricity than can be stored in the house (in a manner that maintains full value) which results in poor system performance (due to high EER and low BER). The maximum NPV occurs when a 3.6 kW turbine is utilized.

Table 32: Optimal turbine system performance using thermal load storage for the residence simulated in eQUEST

Month	Total Load	Turbine Generated	Normal Load	Auxiliary Load	EER	BER	X_{sys}
~	kW-hrs	kW-hrs	kW-hrs	kW-hrs	~	~	~
January	3640.0	669.6	1050.0	2590.0	0.64	3.87	1.00
February	2860.0	604.8	960.0	1900.0	0.63	3.14	1.00
March	2170.0	669.6	1050.0	1120.0	0.64	1.67	0.96
April	1620.0	648.0	1020.0	600.0	0.64	0.93	0.78
May	1730.0	669.6	1020.0	710.0	0.66	1.06	0.82
June	1950.0	648.0	960.0	990.0	0.68	1.53	0.93
July	2110.0	669.6	960.0	1150.0	0.70	1.72	0.95
August	1960.0	669.6	950.0	1010.0	0.71	1.51	0.91
September	1730.0	648.0	920.0	810.0	0.70	1.25	0.88
October	1480.0	669.6	960.0	520.0	0.70	0.78	0.74
November	1920.0	648.0	970.0	950.0	0.67	1.47	0.92
December	3210.0	669.6	1050.0	2160.0	0.64	3.23	1.00
Turbine Size	3.6 kW						
Yearly Avg X_{sys}	0.91						
NPV	($6336.00)						

Table 32 lists the optimized turbine system for the simulated residence using heat pump technology to store energy assuming a capacity factor of 25% and a discount rate of 5%. The monthly-generated electricity varies according to the length of the month. By looking at Table 32 and at Figure 29 together, it can be seen that the auxiliary loads of each month are equal to the thermal loads. This means that over the course of the year, there is a premium on energy storage and it is better to reserve the thermal loads as means of storing energy rather than to use them as a normal electric load. For each month, the EER values are less than 1.00, and it can be seen that the turbine is generating less electricity than the normal load which increases the system performance. During the colder months

(December, January, and February), the thermal load is substantial enough to render BER's of up to 3.87 and system performance values of unity for each of these months. October is the month with the lowest thermal load, and has the corresponding lowest system performance. For a year-round evaluation, the average system performance using this method of energy storage is 0.91 and the optimal turbine size for this house is 3.6 kW. Though the investment NPV of the turbine is still substantially negative, utilizing this means of energy storage results in a much more attractive investment than employing a $CESS$. In Table 16 and Table 18 ($CESS$ economic viability, current battery costs and reduced battery costs), the NPVs for a similarly sized turbine are ($10,428.60) and ($9474.74), respectively (linearly interpolated). Thus, this methodology appears to be more economically viable than storing energy in batteries (even assuming a major decrease in battery cost and increase in battery performance), and it represents a better way to integrate the wind turbine into the HES. However, given the relative expensive cost of the turbine and the relative cheap cost of grid-electricity, the economic viability of small wind turbines is far from being viable.

Conclusion

Residential wind turbines have the capacity to provide electricity for a number of residences across the U.S. There are numerous benefits to successfully employing wind turbines to provide electricity for residences. However, the COE associated with residential wind turbines is constraining the market. The annual energy production (and profit) as compared to the installed cost of the turbine is low enough to make these turbines not a sound investment. In order for wind turbines to gain prominence, this ratio needs to be increased. In the discussed analysis, the optimal size of turbine for the residence was 3.6 kW. At a capacity factor of 25% and prescribed discount rate of 5%, this turbine had an installed cost of $25,820, a $NAEP$ of 7,884 kW-hrs, and a resulting NPV of ($6,336.62). The analysis assumes relatively high turbine performance, and for the turbine to become more economically viable, it is the initial cost that needs to decrease. If the installed cost of the turbine was reduced to $19,250.00, the investment would have a NPV of $0.00; if the installed cost was halved, it would have a positive NPV of $5175.00. These values would make investing in wind turbine much more attractive to customers, and would thereby better the market for small-scale wind turbines in the U.S.

For many applications, an energy management method that utilizes all or nearly all of the generated electricity needs to be integrated into the wind turbine system in order to make investing in a turbine economically sound. The conventional method of storing excess electricity in a battery bank has two main drawbacks of cost and space, both of which decrease the economic viability of the system. Heat pumps can offer a better means of storing excess electricity than the $CESS$ and have the potential to increase the economic viability of integrating a small wind turbine into the HES. Given the relation between the thermal load on a residence and the available power in the wind, they also would manage a better system integration of the wind turbine into the HES. However, until the ratio of the cost of small-scale wind turbines to their energy production is reduced, addressing the issue of energy management alone will not make the small-scale wind turbine economically viable.

Chapter V: Wind Turbine Application in a Developing Country

Small-scale wind turbines could be an effective means of generating electricity in developing countries. One particular application for wind turbines in this manner is for refrigeration purposes and food preservation. Many people in developing countries rely on food production and/or gathering for their livelihood, but they often have a very limited means of preserving their food. In addition, refrigeration could be important for storing certain medication like insulin. In this manner, the prior discussed conventional economic downfall of small-scale wind turbines is outweighed by humanitarian needs.

Many villages in the country of Haiti are a good example of the need for refrigeration. Haiti, along with the Dominican Republic, makes up the island of Hispaniola. According to the U.N., it qualifies as a fourth-world country and is considered the least developed country in the western hemisphere. Illevache is an island off the south coast of the mainland. Many of the men on this island are subsistence fisherman, and they currently do not have a means of preserving their fish. In 70°F temperatures, fish will begin to spoil in 24 hours; hence, if they are not able to sell or consume their fish within that time, the fish will go to waste. Small amounts of refrigerated capacity would substantially increase the viability of the local fishing community. At just above freezing temperatures, fish can be preserved for multiple days, and properly frozen fish can be preserved for months [60]. Some of the people on the island also are diabetic, but not having a means to keep insulin at proper temperatures limits their ability to use the medicine.

Figure 32: JUST MERCY base of operation in Kaikok

JUST MERCY is a charitable organization located in Illevache that is focused on bettering the quality of life for the local people. They are accomplishing this in two primary ways. First, by aiding the local economy; they have a sawmill on the island and they work with the locals to saw lumber for multiple purposes including buildings, boats, and chairs. They are also invested in teaching the locals how to be better carpenters. Second, they help by supplying people with necessary but hard to get medicine, especially during times of widespread disease. An example of this is the Chickengunya outbreak that swept across Haiti in late spring of 2014. JUST MERCY distributed much-needed Tylenol to many people who otherwise would have gone without. Because there is no official doctor on the island, JUST MERCY also serves as an organization that provides sick or injured people with basic health care. JUST MERCY rents a small piece of property in KaiKock (a small village on the northside of Illevache) containing a house, cookshack, and bathroom facilities that serves as their base of operations as depicted in Figure 32.

JUST MERCY is considering employing a small-scale wind turbine for two main energy needs. The first application is providing the basic household electrical requirements of their residence. This primarily includes food refrigeration, lighting, charging electronics, charging power tool batteries, fan operation, and operating an audio system. Currently, they supply these electrical needs with a Honda gasoline generator. The second application for a small wind turbine would be providing electricity to operate two large freezers that can be used by the local fisherman to aid in food preservation. Two or three freezers would be intended to service the needs of one small village. The freezers would also be used for ice production so that fisherman can take a chest and a small amount of ice with them as they fish. Because the fishing areas near the villages are being depleted and fisherman are traveling further to find fish, having a means to preserve the fish while still on the boat is becoming more important.

Wind Turbine Utilization and Analysis

There are many people in third world countries that do not have access to a centralized power grid, but instead must rely on small, distributed sources of energy for electricity. Though economically impractical for many applications in developed countries like the U.S., small-scale wind technology still has the ability to provide many people with electricity that otherwise they would be without. Therefore, a small-scale wind turbine project was undertaken on the island of Illevache in order to understand wind energy beyond a purely economic outcome. The purpose of the project was to determine how well a small wind turbine could be used to provide the electrical needs of JUST MERCY, with a particular emphasis on comparing small wind turbine technology with a conventional gasoline generator and solar photovoltaic technology. As mentioned prior, there are two separate energy needs: 1) providing electricity for the JUST MERCY base of operations and 2) generating electricity to power freezers to be used by the local fisherman. Given that 1) is a current need whereas 2) is a potential plan for the future, more effort was spent in assessing the suitability of a wind turbine for 1).

Figure 33: Blue Sky 2 kW Wind Turbine

A small wind turbine company named Blue Sky Wind Power operating out of Joplin, MO donated a 2 kW rated wind turbine to JUST MERCY as shown in Figure 33. The turbine is 2 meters in diameter, uses three blades, and operates downwind. It has a planetary gear train located directly behind the rotor with a gear ratio of 6 to 1. The generator outputs three-phase AC current that is rectified to DC on the turbine mount. It does not employ any means of speed regulation, and in high winds, the manufacturer stated that it could output up to 6 kW of electricity. In order to maintain simplicity in the manufacturing, the company chose to make the blades using schedule 40 PVC pipe. They did not offer many performance specs, but stated that the turbine can produce (during some months) over 1000 kW-hrs of electricity; this value was confirmed when talking with a customer who had purchased the wind turbine. One of the main advantages of this turbine for this project is the generator size and weight. The generator weighs about 25 pounds and is close to a large vehicle alternator in size; this allowed the generator to be transported via checked luggage on an airplane. This company sells and installs the turbine and tower for $3200. They also donated a Coleman C60 charge controller and a Cobra 5000 inverter. Along with this turbine, charge controller, and inverter, the following instrumentation was used for assessing the viability of the wind turbine:

- Vortex wind anemometer and MadgeTech data logger capable of recording wind speeds up to 50 mph and logging data at 1 m/s intervals
- WattsUp.Net power meter with data logging capability used to measure appliance power and net electrical consumption
- KilaWatt meter used to measure appliance power and net electrical consumption
- Watts view power monitor used to measure DC power output up to 10 kW
- Measurement Computing USB voltage data logger used to log battery voltage

JUST MERCY Base of Operations Energy System

Figure 34: JUST MERCY base of operations location

The JUST MERCY base of operations is located right on the coast of a small harbor. Figure 34 depicts the location of the building in regards to the ocean. Most of the time there is a breeze blowing, and in the initial planning of this project, it was thought that wind resources would be sufficient to utilize a wind turbine. Of note, it was not practical to perform a wind energy study ahead of time given the remote logistics involved.

Figure 35: JUST MERCY base of operation energy system

The current energy system of the JUST MERCY base consists of a Honda EU 2000i generator (rated at 2000 W), four Trojan T105 batteries, and a Magnum RD2212 charger controller and inverter. Figure 35 depicts the different components of the energy system (minus the generator). These components are contained in a small tool shed built on the back of the primary structure. The Trojan T105 battery is a 6 VDC lead acid battery designed for renewable energy applications. It has a capacity of 250 amp-hours when discharged at a C20 rate, giving it a total energy capacity of 1.5 kW-hrs. It has max discharge rate of 75 amps. In the energy system, the four batteries are wired two in series and two in parallel, giving a system voltage of 12 VDC, 500 amp-hours of capacity, and 6 kW-hrs of energy. The Magnum RD 2212 is designed for operation with 12 VDC systems. It has a charge efficiency of 85% and an inverter power factor of 0.95. It is rated to continuously invert 2200 W. The system is setup so that when the generator is running, the electricity produced directly supplies the electric loads in the house, and the excess electricity is used to charge the battery bank. When the generator is not running, the

Magnum RD2212 inverts electricity from the battery bank to supply the electric load. The system is set with a low voltage cutout of 11 VDC to protect the batteries from being damaged by over discharge.

Table 33: Base of operation average daily electric loads

Daily Loads	Power	Operating Time	Energy
~	W	hrs	kW-hrs
Freezer	120	9.5	1.10
Fridge	100	0.0	0.00
Lights	50	2.0	0.10
Charge Dewalt Batts	70	4.0	0.14
Charge Electronics	10	4.0	0.04
BOSE Sound	25	4.0	0.10
Fan	30	10.0	0.30
Total			**1.78**

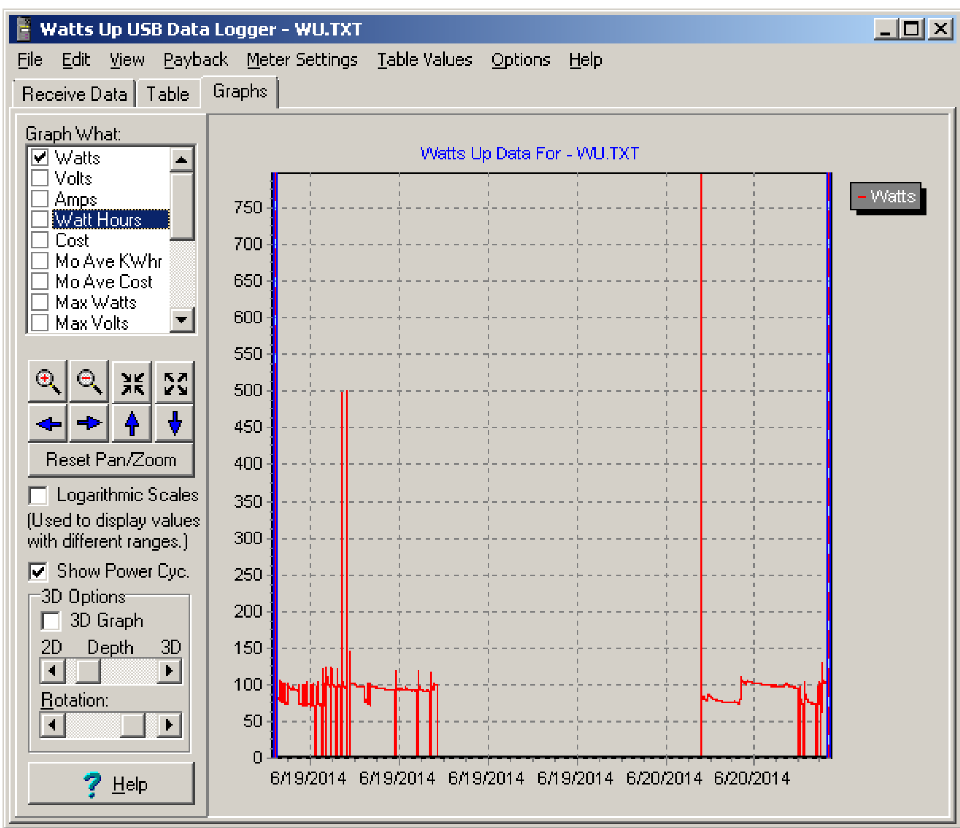


Figure 36: Haier Freezer electricity consumption profile

Table 33 depicts the average daily electric consumption for the base of operations; the average daily electric load found to be 1.78 kW-hrs. As can be seen, most of the electricity is used for refrigeration purposes. Currently, the base of operations has both a freezer and a refrigerator, but the demand is low enough that only the freezer is used on a regular basis. The freezer is 9.6 cubic feet in size and made by Haier. The power consumption of the freezer was measured using the WattsUp.Net power monitor; Figure 36 depicts the power consumption of the freezer from June 18, at 9:30 p.m. to June 20, at 10:30 a.m. During the thirty-seven hour period, the freezer consumed 1.65 kW-hrs of electricity. The other significant loads on the system are operating a fan and charging the DeWalt batteries. The fan is used primarily for comfort while sleeping; whereas, the DeWalt batteries are used to operate a number of power tools including drills, flashlights, and vacuum cleaners. With a battery bank energy storage of 6 kW-hrs and a daily electric load of 1.78 kW-hours, the system has a BLR' ratio of 3.37 if the turbine is designed to produce the same amount of electricity as is consumed (ELR = 1). This ratio is quite high; referring to Chapter 4the system performance of this energy system would be 100%.

Wind Turbine Performance for Base of Operation Application

Given this power consumption, it was deemed desirable to integrate the Blue Sky wind turbine into the JUST MERCY base of operations energy system. The first step was to determine where to install the turbine;two locations were considered. Location 1A would be on a small tower set approximately 30 feet to the north of the building. Location 1B would be on the roof of the building. The two main points of consideration for each location were the wind resources and the difficulty of the installation.

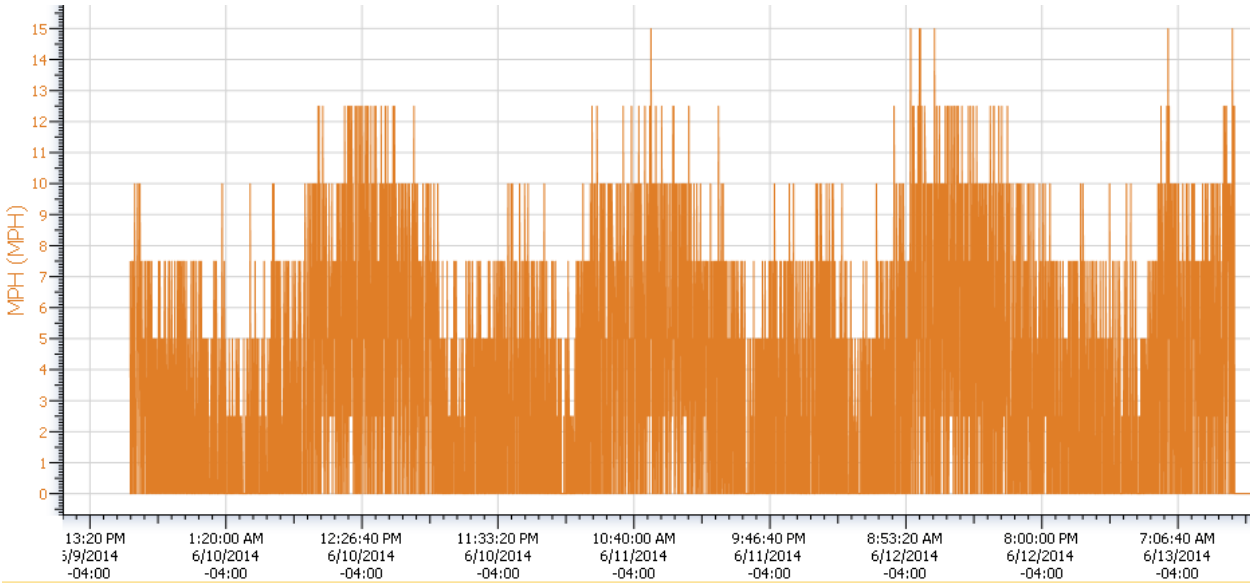


Figure 37: Wind resources of location 1A

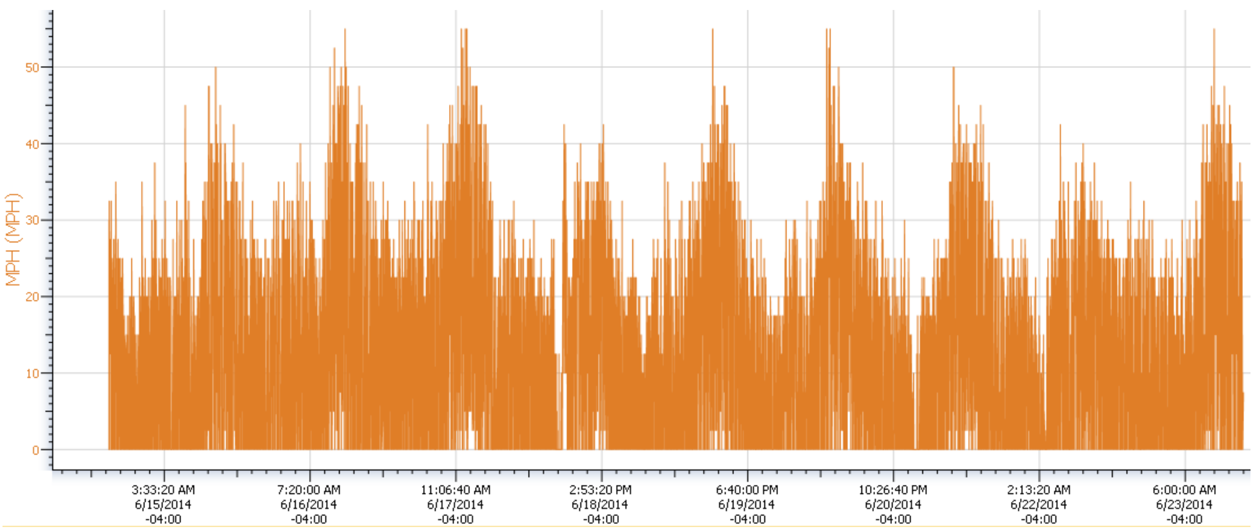


Figure 38: Wind resources of location 1B

The potential wind resources of both locations were measured using the vortex anemometer. Figure 37 depicts the wind speed of location 1A in miles per hour as measured from June 9, 2014 at 5:30 p.m. to June 13, 2014 at 11:20 a.m. The anemometer was placed 9 feet off the ground (not possible to place higher due to safety concerns), and the data was recorded in one-second intervals. The average speed was calculated to be 2.90 mph using all data points. Figure 38 depicts the wind speed of location 1B in miles per hour as measured from June 14, 2014 at 5:00 p.m. to June 23, 2014 at 5:00 p.m. The anemometer was placed 5 feet off the roof of the building (approximately 20 feet above the ground), and the data was recorded in 4 second intervals. The recorded data suggested that wind speeds at this location were significantly higher than the location lower to the ground. As can be seen from Figure 38, wind speeds in excess of 25 mph seem to be fairly common. However, it is suspected that these high wind speeds were a result of some error in the data acquisition. Referring back to Figure 34, there are a number of palm trees interfering with the wind flow at this height, and it was thought that this interference was the cause of a significant amount of turbulence across the anemometer. Likely, this turbulence resulted in some inaccurate sensor readings. Upon review of the wind speed measurements, it was recorded that 4.2% of the time the wind blew with a wind speed of 25 miles per hour or greater. However, it never seemed that the wind blew with a speed greater than 25 miles per hour. If 25 miles per hour is considered the maximum wind speed observed and all wind speeds greater than that are considered to be 25 miles per hour, the average wind speed of that period of time was 10.15 miles per hour. Thus, in terms of wind speed location, 1B seemed to be substantially better than location 1A.

In terms of ease of installation, location 1B also proved to be a better place to install the wind turbine. Attaching the wind turbine to the existing structure was thought to be much simpler than building a small tower on the ground. The builder of the structure deemed that it was strong enough to withstand the forces exerted by the wind turbine. Furthermore, installing the turbine on the roof facilitated the easier connection of the electric wires from the turbine to the shed where the battery bank and electronic equipment was located.

Figure 39: Blue Sky wind turbine attached to the structure of the base of operations

Because of the reasons mentioned prior, the wind turbine was installed on the roof and attached to the structure of the house for support. Figure 39 illustrates the turbine installed on the roof of the house and the support for the turbine was 2 ½-inch schedule 40 steel pipe. Ten feet of pipe was used to support the turbine: three feet sticks down below the roof and is attached to a vertical stud in the wall supported by two ½" carriage bolts, and seven feet sticks above the roof. Ideally, the turbine would be placed well above the surrounding trees to obtain minimal interference. However, the tops of the trees are around 30 feet above the roof of the building, and mounting the turbine at this height was not possible primarily relating to issues of structural integrity. The height of seven feet above the roof was chosen because it set the turbine below the branches of the surrounding palm trees which helped to reduce their interference.

The performance of the wind turbine was measured using the Wattsview_434 sensor and software. While this software had the capability to record the data acquisition, it required an external battery supply and a computer for operation. This made logging data for long periods of time difficult, and the power production and energy capture were measured only over short periods of time, particularly when it seemed that the wind was blowing with a relatively higher speed.

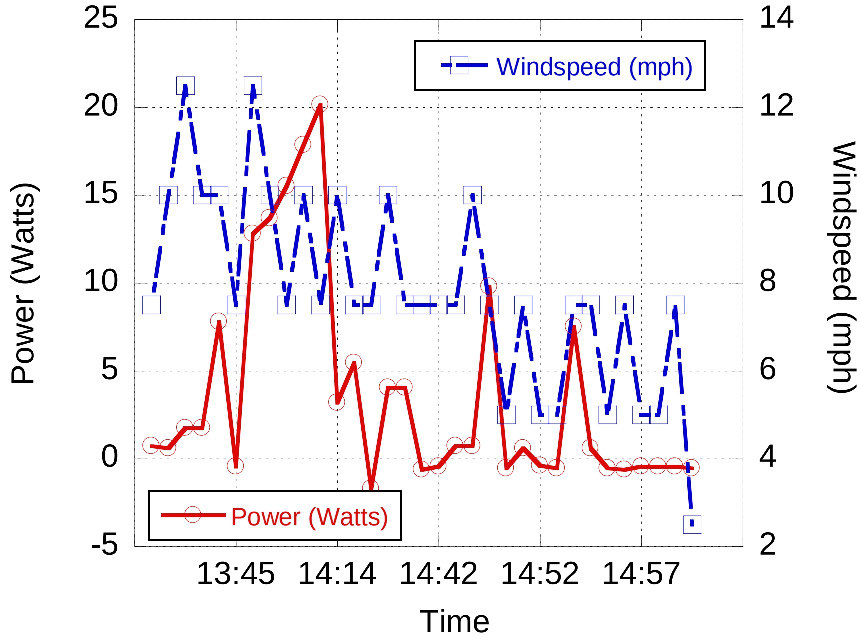


Figure 40: Wind turbine power production

Unfortunately, the wind turbine proved to have poor efficiency in low winds, and it seemed that the turbulent nature of the wind flow substantially affected the turbines ability to produce power. Figure 40 depicts the power generation in of the turbine and corresponding wind speed for roughly one and a half hours on June 26, 2014. Of note, the data logging capability of the Wattsview_434 sensor resulted in irregular data recording. In Figure 40**,** the points of recorded power production and wind speed were taken at the same time. As can be seen, wind speeds over 8 miles per hour resulted in some power generation while wind speeds below that did not. While not a data logged point, during a brief sustained wind gust of 15 miles per hour, it was manually recorded that the turbine produced 50 watts of power. Given a turbine diameter of two meters and assuming standard air density, this calculates out to be an aerodynamic power coefficient of 0.085. At this low wind speed, the tip speed ratio is far from optimal and it would be expected that the power coefficient would be low; however, this poor performance rendered the turbine almost completely ineffectual at this location. Rarely was there a sustained wind speed of 15 miles per hour or more, and during operation the turbine produced a minimal amount of electricity. Over the course of the hour and a half period of recording, it was measured that the turbine had produced 12 W-hrs of electricity. This is an average of 8 W-hrs per hour, which is essentially an insignificant amount of power.

Hence, using the wind turbine for generating electricity for the basic household needs illustrates that the available wind resources at that location were not sufficient to make utilization of a wind turbine feasible. The prevailing wind comes from the east, and the structure is in a small cove with a neighboring hill blocking much of the wind off the ocean. Given the local topography, it is estimated that it would take a tall tower, approximately 75 feet, to make a significant difference in the available wind resources. The difficulty in building and erecting the tower, as well as maintaining the turbine at that height yielded other methods of electricity production as more desirable.

Wind Turbine Suitability for Freezer Application

In order to help the local fishing economy of Illevache, JUST MERCY is considering using a wind turbine to power a number of freezers for fish preservation. The same Blue Sky wind turbine would be used for this application with the number and size of freezers determined by the power output of one of these wind turbines. The intent of JUST MERCY is to build a small structure roughly 600 square feet in size to house the freezers.

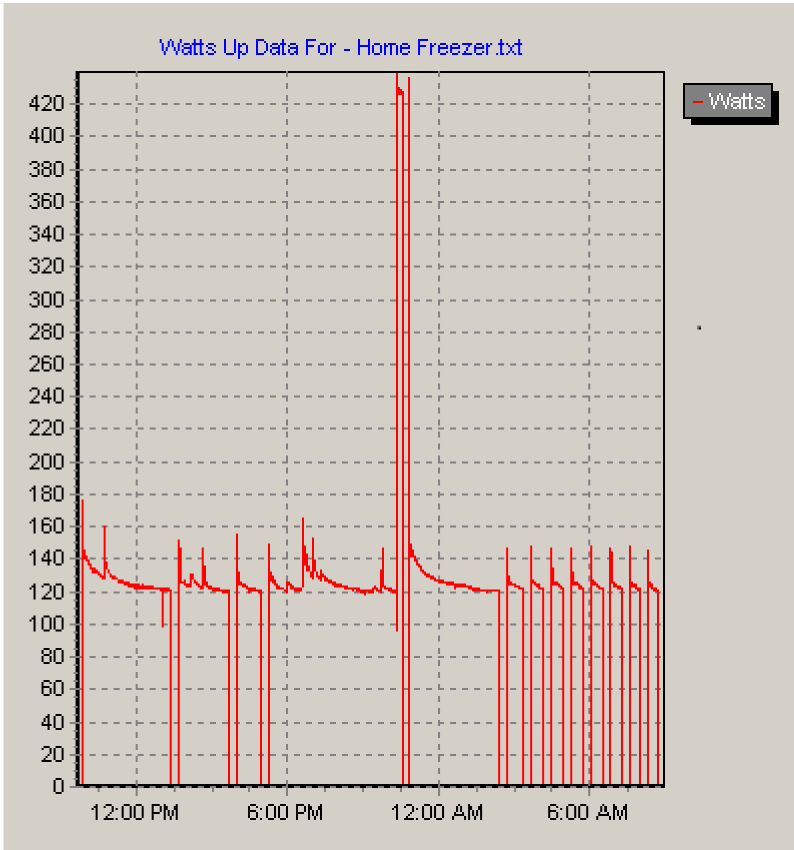


Figure 41: Daily energy consumption of 25 cubic foot freezer

Freezing food results in a relatively large amount of power consumption. The power consumption of a 25 cubic foot Kenmore freezer operating in an air-conditioned residence was measured using the WattsUp?.net power meter from 8:40 a.m. July 14th to 8:00 a.m. July 15th. Figure 41 shows this power consumption. As can be seen from Figure 41, the freezer is drawing about 120 watts the majority of the day. As measured by the WattsUp?.net meter, during the short day, the compressor of the freezer was in operation 85% of the time, and the total electric consumption was 2.5 kW-hrs.

JUST MERCY had intended to implement these freezers on piece of ground next to their base of operations. However, as mentioned prior, the wind resources at this location are not near enough to provide power for any significant amount of freezer operation. Because of this, it became desirable to find another location on the island that would have the wind resources required. One place that was considered was a small village called Grand Saab located about 4 miles east of Kaikok and the JUST MERCY base of operation. This village is on the coast, and it is reported by the locals that a strong wind blows the majority of the time. In order to validate this, the wind resources of Grand Saab were measured using the vortex anemometer and madgetech data logger for one day from 2:10 p.m. on June 24th to 2:10 p.m. on June 25th. While this is not necessarily an accurate test of the wind resources, it was the best the author could do given the logistics and time spent on the island.

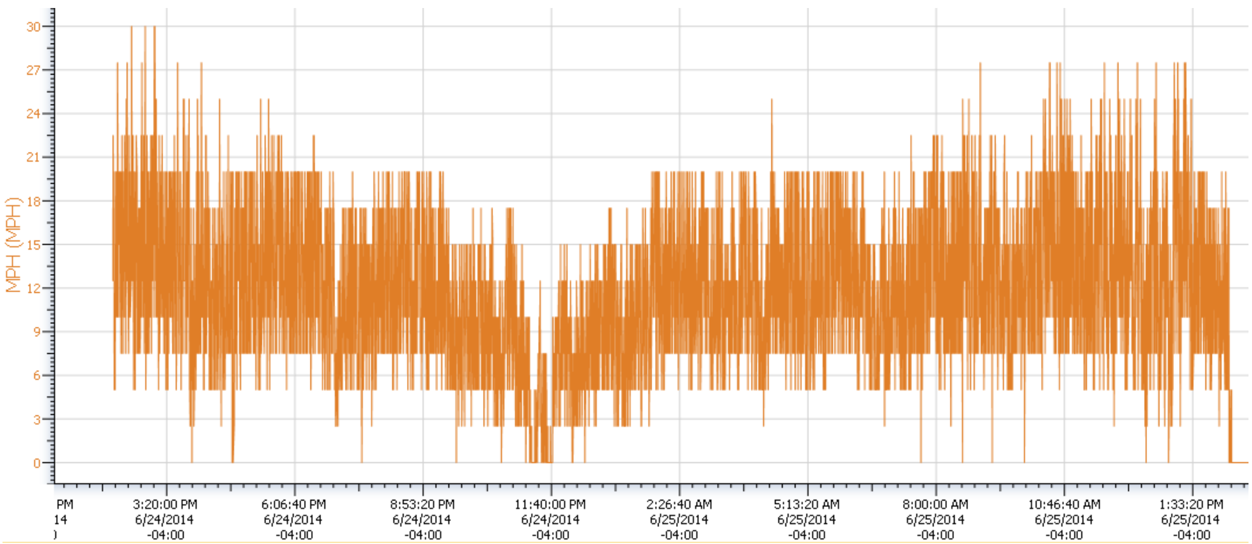


Figure 42: Grand Saab wind resources

Figure 42 shows the data collected from Grand Saab at one-second intervals. The anemometer was placed only six feet off the ground, and thus the data represents the wind speed at ground level. The average value of the wind speed was 11.78 miles per hour. As can be seen from Figure 42, the wind across the anemometer appears to be less turbulent and more steady; this would likely result in better turbine performance.

Table 34: Turbine power output in watts for various power coefficients at different wind speeds

Wind Speed	Power Coefficient					
mph	0.085	0.15	0.2	0.25	0.3	0.4
5.0	0.0	0.0	0.0	0.0	0.0	0.0
7.5	0.0	0.0	0.0	0.0	0.0	0.0
10.0	15.4	27.1	36.1	45.2	54.2	72.3
12.5	30.0	52.9	70.6	88.2	105.9	141.2
15.0	51.8	91.5	122.0	152.5	183.0	244.0
17.5	82.3	145.3	193.7	242.1	290.6	387.4
20.0	122.9	216.9	289.1	361.4	433.7	578.3
22.5	175.0	308.8	411.7	514.6	617.5	823.4
25.0	240.0	423.5	564.7	705.9	847.1	1129.5
27.5	319.5	563.7	751.7	939.6	1127.5	1503.3
30.0	414.7	731.9	975.8	1219.8	1463.8	1951.7

From previous testing, it was determined that this wind generator had a power coefficient of 0.085 in sustained low winds (15 mph and lower), and that in wind speeds less than 10 miles per hour the turbine had roughly zero power output. Due to the absence of higher wind speeds, the performance of the generator in higher wind speeds was not able to be determined. Table 34 lists the power output of this turbine for different windspeeds assuming different power coefficients; it was derived using Equations (1) through (9) from Chapter 2. If it is assumed that this wind generator has a power coefficient at all wind speeds of 0.085, then the daily energy capture over June 24th and 25th could have been approximately 800 W-hrs of electricity. Given that this estimate does not take into account the effect of turbulence on the performance, it likely over-estimates the power production. This amount of electricity would supply only about 1/3 of the 25 cubic foot Kenmore freezer, and thus this turbine would be nowhere near sufficient to provide the required energy. If it is assumed that at higher wind speeds (greater than 15 mph) the power coefficient is 0.25, then this turbine could have produced 1450 W-hrs. This value is still insufficient for the 25 cubic foot freezer. If it is assumed that at higher wind speeds the turbine has higher performance with a power coefficient of 0.4, then this turbine could have produced 2050 W-hrs of electricity. This value is nearing the required amount for one 25 cubic foot freezer, but remembering that calculations likely over-estimate the power production, the performance of this turbine is likely not sufficient to make utilization at this location successful. Given that 86% of the time the recorded wind speed was 15 miles per hour or less, the efficiency of this turbine in low winds needs to be improved for it to be useable. If this turbine had a power coefficient of 0.25 at low wind speeds and a higher efficiency of 0.4 at higher wind speeds, this turbine could have produced 2950 W-hours of electricity, and could have successfully powered one freezer.

As a result, the current performance of the wind turbine is not sufficient to yield a viable means of generating electricity at the Grand Saab location assuming that the measured wind resources are representative of the average daily wind resources at this location. The first solution would be to design different blades for this turbine that yield higher performance in low wind speeds. It would also be recommended that depending on the size and number of freezers desired, the diameter of the turbine be increased so that available energy capture is increased. It is believed that the current generator is built sturdy enough to withstand a substantial increase in turbine diameter, and thus the increase in blade size would accompany the blade re-design.

Comparison of Wind, Solar, and Gasoline Generator Technology

Three common technologies for off-grid power generation in developing countries are wind turbine technology, solar photovoltaic technology, and gasoline or diesel generator technology. Part of the purpose of the project in Haiti was to determine how wind turbine technology for developing country application compared to these other two means of generating energy. Solar photovoltaic technology represents another viable renewable energy technology, and the gasoline generator represents the conventional means of generating energy. The following performances of each technology will be considered: cost, performance, and ease of installation and operation.

Conventional Gasoline Generator Technology

A conventional means of generating electricity in an off-grid location is to use a gasoline or diesel generator. These generators can be purchased with various power output ratings. At their base of operations, JUST MERCY utilizes a Honda 2000 EUi gasoline generator to provide their power needs. It is rated to continuously output 2000 watts of power, and it is able to provide up to 2500 watts of power for short periods. The fuel capacity of the generator is one gallon. Using the KillaWatt sensor, it was measured that the generator could run for just under six hours while outputting roughly 1600 watts. On Illevache, the price of fuel is $6.00 per gallon. Depending on how closely the generator and battery bank state of charge were monitored, approximately ½ gallons of fuel is used each day to provide the base electric loads as listed in Table 33. This results in an operating cost of roughly $100 per month. The primary advantage of the generator is that it allows for on demand power generation. During the time spent on the island, the supply of gasoline was reliable, and the ability to generate electricity was directly controllable based on current needs. Another main advantage is the ability to deliver a higher power output for power tools like circular saws and sanders. Using the battery bank to supply that type of consumption is undesirable as it results in a relatively high current discharge rate that can be detrimental to the battery. The primary disadvantage is the cost associated with operation. Part of the reason for the high cost is the relatively inefficient way in which the generator is operated. The system is setup so that the generator delivers a constant power output regardless of the electric load. This results in a substantial amount of gasoline being wasted, and the battery bank's status of charge needing to be closely monitored in order to efficiently operate the system. It is relatively undesirable to continuously monitor the energy situation, and this is one of the main drawbacks to using the generator. Based on these findings, the following is a list of the pros and cons associated with using the gasoline generator.

Pros

- The generator produces on demand electricity generation
- The generator is portable and can be moved to desired location
- The assembly, installation, and maintenance are relatively simple and easy
- It can be stored in safe location while not in use
- Appropriate means of generating electricity for power tools

Cons

- The fuel source is expensive and at times not available
- Requires close human control in order to efficiently control the fuel consumption
- The generator is noisy

Solar Photovoltaic Technology

For many off-grid applications, solar photovoltaic technology can offer an effective and affordable means of generating electricity. In a 2012 consumer report on residential solar photovoltaic systems in the U.S., NREL reported that the average cost for residential systems was $2.15 for per watt for the solar panels and $0.40 per watt for the mounting hard ware and wiring [61]. Currently, a Suniva Optimus Monocrystaline solar module rated at 260 watts can be bought for roughly $300 [62]. The panel is rated to have 16% efficiency and is just over 1.6 square meters in size resulting in a cost of $1.15 per watt. Assuming a smaller reduction of 25% in the mounting hardware and wiring costs, a solar system for the JUST MERCY base of operations would cost roughly $1.50 per watt. However, as mentioned prior, for energy applications the power rating of the generating unit is often not as important as the capacity factor. Solar photovoltaic technology has a relatively low capacity factor averaging between 10 and 25% depending on the time of year [63]. This is substantially lower than wind, which in the same report was estimated to produce capacity factors between 20 and 40%. Similar to wind there is some difficulty in predicting the capacity factor for a given location. As a country, Haiti is reported to have excellent solar resources.

Table 35: Required solar panels for JUST MERCY base of operations

Panel Rating		260 Watts	
System Efficiency*		81%	
Required Daily Energy		2.20 kW-hrs	
Capacity Factor	Number of Panels	System Wattage	System Cost
10%	4	1040	$ 1,560.00
15%	3	780	$ 1,170.00
20%	2	520	$ 780.00
25%	2	520	$ 780.00
*Considers charge controller and inverter inefficiencies			

Table 35 lists the cost of the solar system for delivering the electrical needs of the JUST MERCY base of operations electric loads assuming different capacity factors. From Table 33, the average daily electric load of the JUST MERCY base of operations was 1.78 kW-hours. Given the inefficiency associated with charging batteries and inverting the electricity from DC to AC, the amount of electricity that needs to be produced by the solar system needs to be slightly larger than the electric consumption. The JUST MERCY base of operations has a roof sloped at a 33 degree angle facing south. There is a small amount of tree cover that will affect the solar irradiation in the late afternoon, but the solar panels still would have relatively good exposure to the sun. Assuming a solar system capacity factor of 15%, three 260 watt solar panels would be required to meet the daily electric load. At a per watt cost of $1.50, this would result in a system cost of $1170. As stated prior, the average fuel cost of running the generator is approximately $100 per month. Assuming zero maintenance costs on the solar system, it would not take long for the solar system to amortize itself. In addition, while the solar energy from the sun remains free, it is likely that the cost of the gasoline will increase over time, and in this sense, also having a source of energy that is stable regarding human activity is desirable. Hence, the benefits and drawbacks of a solar system are estimated as:

Pros

- The solar energy is free, and it is more reliable relative to wind
- Relatively simple and easy installation and maintenance
- No moving parts resulting in a low likelihood of malfunction

Cons

- Difficult to secure or protect from theft when absent from location
- Low power output and not suitable for sourcing high power appliances for longer periods of time

Wind Turbine Technology

Table 36: Energy density of the wind across a turbine at different wind speeds

Windspeed	Energy Density
mph	W/m^2
5	2.9
10	23.0
20	184.1
30	621.2
40	1472.6

While the attempt to use a wind turbine to generate the electric needs for the JUST MERCY base of operations was unsuccessful, wind turbines can still be a desirable means of generating electricity for developing countries. In a location that has strong wind resources, wind turbines can be a more effective means of generating electricity than solar photovoltaic technology [11]. The main reason for this is that depending on the wind speed, the energy density of the wind turbine can be substantially higher than the energy density of a solar panel. Another way of saying this is that per square meter, depending on the wind speed there can be a lot more available energy in the wind than the available energy from solar radiation. The maximum amount of solar radiation on an object at the surface of the earth is roughly 1000 W/m^2**.** Current solar photovoltaic technology is approximately 15% efficient which yields a per meter energy capture of 150 watts. Table 36 lists the energy density of a wind turbine at different speeds assuming a power coefficient of 0.40. As can be seen, at low wind speeds the energy density is low and utilizing solar photovoltaic technology will likely be more attractive than using wind turbine technology. However, at higher wind speeds, wind turbines have the ability to produce higher amounts of electricity than solar panels. One of the other primary benefits of wind turbines over solar panels is that wind turbines potentially produce electricity during all periods of the day, unlike solar. Depending on the wind resources, this can result in a substantially higher amount of energy capture during the day. Similar to the other two technologies considered, the following are the primary positives and negatives associated with using wind turbines assuming operation at a location with sufficient wind resources to warrant utilization.

Pros

- High energy density and corresponding higher energy output than solar panels
- Potentially less expensive means of generating electricity than solar
- Wind as the fuel source is free and, thus, so is the operation (as compared to a conventional generator)

Cons

- Likely require to be installed on a tall tower which makes the installation and maintenance difficult
- Wind is stochastic, more so than solar radiation, and the power output of the turbine is difficult to forecast

- Operation results in a whirling noise which can be annoying

Conclusion

Small-scale wind turbine technology can be an effective means of generating power for off-grid locations in developing countries. However, suitable applications are limited by two main factors. First, there needs to be significant wind resources that warrant utilizing a wind turbine over solar photovoltaics. Second, the operation for which the turbine is being utilized needs to be large enough to warrant the installation of a sizeable tower. The purpose of this tower is to place the turbine above surrounding obstacles such that the airflow across the turbine is laminar as opposed to turbulent. Turbulence has a significant impact on the performance of small wind turbines; this was concluded in the wind turbine project undertaken in Illevache. Thus, for small power applications, such as powering electronics or minimal amounts of refrigeration, lighting, and charging batteries, solar photovoltaics and conventional generators will offer a better means of generating electricity in most cases. For larger operations, like powering multiple freezers or providing electricity for multiple houses in a village, undertaking the investment in a wind system including an appropriate tower still has merits.

Given the available wind and solar resources at the JUST MERCY base of operations, solar photovoltaic technology is a better option than wind. In addition, for generating the basic household electric needs, it is advisable to replace the gasoline generator with solar photovoltaic system. Not only would this save a significant amount of money, but also it would allow JUST MERCY to be less dependent on other organizations and people for their energy production. It is still advisable to keep the generator for use as a backup power source and also to generate the electricity needed for high power applications such as power tools.

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