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OPTIMIZATION OF A HYBRID, SMALL, DECENTRALIZED POWER PLANT

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ABSTRACT

The worldwide dependence on fossil fuels and the harmful environmental consequences of this dependence have several scientists, engineers, and concerned citizens around the world interested in alternative sustainable energy systems. Additionally, in rural and developing areas, many people do not have access to electricity. One solution is the hybrid decentralized small power plant, which uses renewable resources such as wind, solar radiation, and biomass inherently available in a specific geographic area to produce electricity not dependent on the presence of a power grid. The focus of this research is to create a tool that will take into account geographic information (such as wind speed magnitude and probability, solar radiation, biomass types and availability, and weather patterns) for a specified area and determine what portion of an initial investment should be delegated to each type of energy (biomass, wind or solar). The overall power output for the average day as a function of time will be made available, as well as the contributions of each biomass, wind, and solar portion. This tool will help investors by recommending systems that will provide a reliable, optimized power output for a specified location.

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AWKNOWLEDGEMENTS:

I would like to thank my thesis advisor, Dr. Kulkarni, for guiding me through this project. I would also like to thank my family for their support. A special thanks to my mom and dad for making my Penn State experience possible by generously paying for my tuition and supplies. Thanks to Sylvia for her positive attitude, and for providing an inspiring model of someone who believes that anything is possible and goes after their dreams. Finally thank you to my wonderful fiancé Ross for the endless love and for being my emotional support system through the ups and downs of this process.

DEVELOPMENT OF HYBRID SYSTEMS

Introduction:

Across the globe, millions of people are living with limited or no access to electricity and power systems. It is well documented that access to electricity can have significant positive impacts on people's quality of life. Currently a large portion of power used in the world is generated through fossil fuels, which are expensive and depleting. Alternatives that are more suitable for rural and remote areas are becoming more and more feasible. Decentralized renewable energy systems promise to increase access to electricity by taking advantage of resources that are plentiful and renewable in specific areas. Various locations have different resources (such as sunlight, wind, and biomass material) available, and therefore to optimize the energy conversion, or power, output for different locations we need to find a way to best take advantage of what's available in a specific area. The focus of this research project is to create a computer tool that will optimize the energy conversion based on user inputs. This ultimately will allow investors to allocate their money to the energy systems that would benefit the people who need the energy the most.

Objective:

The objective of this research is to create a model to help investors determine how to spend their money for a hybrid, small, decentralized power plant, optimized to meet user criteria, for example minimum hourly or daily energy conversion.

Literature Review:

It is no secret that the carbon fossil fuels currently depended on to meet the world's growing energy needs are becoming more expensive and will eventually become extinct. With this in mind, it is imperative that people search for alternative sources of energy. According to the Energy Information Administration the energy consumption by supply source for 2008 in the United States is as follows: 37.1% petroleum, 23.8% natural gas, 22.5% coal, 7.3% renewable energy, and 8.5% nuclear electric power [1]. In Europe Denmark generated 21% of its electricity from wind power, Germany generated 7% from wind power, and Spain generated 12% from wind power [2]. It is evident from these statistics that renewable energy is a feasible source of electric power, but improvements need to be made so that sources of renewable energy can account for a greater percentage of the world's energy consumption.

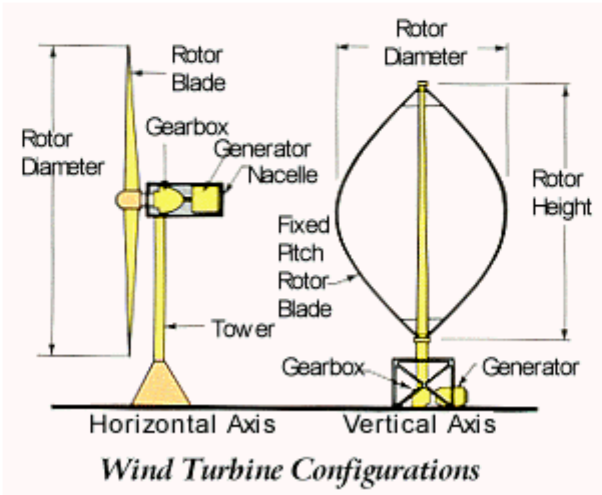
Various renewable energy sources exist. Biomass, geothermal pumps, ocean power, hydro power, solar power, wind power, and alternative fuel sources for transportation (such as ethanol) are in this category [1]. Considering the objective of this research, the following sections will focus largely on current uses and implications of wind, solar and biomass power, individually and as part of a hybrid system.

Wind Energy

Wind Energy is one of the fastest growing sources of electricity in the world [3]. Currently, the United States can generate enough electricity through wind to power 7 million average American homes [3]. It is predicted that wind energy could eventually supply 20% of the United States' energy needs [3]. Wind as a source of energy has been used for centuries for activities such as grinding grain using windmills, irrigation systems, and powering sailboats [4]. These days, wind turbines are used to convert wind energy to electricity. Wind itself is a great fuel source because it is both free and abundant, preventing complications and costs associated with transporting and storing fuel.

Wind turbines take the wind's kinetic energy and convert it to electrical or mechanical energy. Essentially, the rotors of the turbine turn due to the movement of the wind, and this is turned into rotational shaft energy which is then transferred to a drive train and a generator. Turbines can either be horizontal or vertical turbines, however horizontal-axis turbines are the most common and utility-scale turbines (those that can produce 100 KW or more) are always horizontal [5].

Fig. 1 Horizontal and vertical turbines – from American Wind Energy Association Wind Web Tutorial [5].



Wind turbines have been increasing in size, and since the amount of energy depends on both the speed of the wind and the area the rotors sweep, they have also been increasing in power. For utility-scale windmills, the rotor blade length ranges in length from 50 to 90 meters, and towers are in a similar range [5].

Wind power is already considered a feasible method for generating electricity in many areas. It is, however, prohibitively expensive for some locations. However, since wind is an essentially free resource and is renewable (in the sense that it is not destroyed by the wind turbine and is plentiful) it has a low operating cost, and it could be used to provide energy to remote locations and areas that cannot be connected to a larger energy grid.

A recent article published in Energy Policy, entitled "Renewable energy sources (RES) projects and their barriers on a regional scale: The case study of wind parks in the Dodecanese islands, Greece", looked into the feasibility of wind farms on some of Greece's many small islands, which have no connection to the electrical systems on the mainland. The Dodecanese islands examined in this article are traditionally small and remote islands that have seen an increased demand for electricity due to tourism. In fact, between 1975 and 2005 energy consumption has increased ten fold [2]. OptiRes software was used to determine possible wind farm projects on the islands. This software took into account a number of factors, including digital terrain modeling, infrastructure, energy consumption data and forecasts, land use, wind measurements, availability of solar energy, available biomass, financial information such as the cost of energy and taxes, along with additional data. Filtering was then done to exclude areas meeting specific criteria, such as areas where the average wind speed was less than 7.5 m/s, areas that were not accessible, and areas that are environmentally protected [2]. It was determined that creating additional wind farms to generate electricity for the islands was a good idea.

However, another part of the study examined barriers to increased renewable energy sources. Five major types of barriers were discussed. These were as follows: technological, environmental, social/public opinion, economic, and regulatory, legislative, administrative. Technological barriers are network limitations, the inability of the network to absorb all the power produced by the wind parks due to small size or weak connections [2]. The next type, environmental, deals with effects on the ecosystem, landscape, and land usage. The normal environment of animals living in the area where a wind farm or wind park is to be created will be destroyed. Additionally birds and bats can be killed in the windmill blades, which is of particular concern to these Grecian islands since many migratory birds pass through the area. Landscape-wise, the destruction of the landscape is of great concern to an area that relies heavily on tourism as a source of income.

Additionally, during turbine installation a large amount of dust and noise is a concern. Issues relating to land usage are also of concern, since property values may be affected by the presence of wind turbines. It will also be necessary to consider the original use of the land, and find other locations that can be used for the same tasks [2]. The social and public opinion barrier is the result of a number of issues. First on small islands, the wind farms could have potentially harmful optical effects, therefore the number of wind turbines needs to be considered carefully so as not to upset the public. Another contributor to this barrier was found to be insufficient sources of information for the public. The economic barriers were due to marketing obstacles, the inability to make accurate predictions that include environmental and social costs, and in the case of Greece no incentive for domestic and commercial use of renewable energy [2]. Finally the last barriers are legislative, regulatory, and administrative barriers. These are identified as lack of investment and development structures, lack of rules, limited measures for insuring that laws that protect the environment are followed, and issues with the permissible load factor of the turbines, which for the Dodecanese islands must be small because of stability problems in the regional network [2].

Clearly, the above case discusses a very specific location, but it does provide some insight into the types of issues and problems associated with building renewable energy systems, and in particular wind systems. Every location will have its own set of legislative, environmental, social, technological, and economic barriers. These will all need to be considered in varying degrees when constructing or planning a wind farm.

Another article from Energy Policy, "Distributed generation: remote power systems with advanced storage technologies", first discusses the general issues surrounding distributed generation (i.e. power systems that provide electricity for an area close to this source, as opposed to directly connected to a bulk power system) and then discusses the application of a combination wind-diesel hybrid system for a fictional Alaskan coastal village (where information for the fictional village is taken from other coastal villages as well as the University of Alaska) [6]. The paper argues that currently remote communities, such as those on the Alaskan coastline, pay both an economic and environmental cost for their dependence on fossil fuels, since besides the cost of the fuel itself they must pay hefty fees for transportation and deal with oil spills and other harmful environmental costs. As a result, these remote communities are ideal places for distributed generation, since due to the high costs associated with traditional energy generation, renewable sources are economically comparable. In general, the paper states, in order for renewable energies to gain ground the cost must be reduced. However, as previously mentioned, in some areas they are economically competitive, and in the long run may prove to be the better choice. This article was published in 2004, and points out that distributed generation would also allow the energy infrastructure to be functional in the face of a terrorist attack (a concern in the post 9-11 world). These distributed generation systems are largely also renewable or environmentally friendly systems, and this is another reason besides the economics to consider their implementation [6].

Regarding the Alaskan town discussed in the article, the proposed distributed generation system was a hybrid wind-diesel system, which includes wind turbines and a diesel generator. It is mentioned in the article that the use of photovoltaic cells was considered, however ultimately they were not included due the high cost of solar panels [6]. It is to be noted, however, that the use of solar panels is mentioned as a possible option, and that there has been a decrease in the price of solar panels since this article was published. In the hybrid system, the wind turbines provide the electricity and the generator provides power only when the wind produces insufficient power. The article states that with the use of wind turbines, "the saving of diesel fuel can be more than 50% at a cost saving of over 30%" [6]. This is just another example of how wind power can improve lives in remote communities and reduce damage to the environment. While this was a hybrid wind-diesel system, it is clear that using wind power had an overall positive effect, and that the possibility of coupling wind power with other sources of power, such as solar, exists.

Solar Energy

Solar energy is another form of renewable energy. Solar power systems use the sun as a heat source and come in a number of different forms. Three main types are used to produce electricity for power plants, and these are linear concentrator, dish and engine, and power tower systems. In the linear concentrator, light hits curved rectangular mirrors that are tilted towards the sun. Tubes in the mirrors are filled with fluid which heats up due to radiation from the sun. This fluid then moves and is used to boil water in a traditional steam turbine [7]. The dish/engine system uses a mirror as well, but this mirror is dish shaped in order to focus sunlight on a thermal receiver, which transfers heat to an engine generator. The Stirling engine is a heat engine frequently used in the dish/engine system, and fluids heated by the receiver cause pistons to move, thus creating mechanical power [7]. The mechanical power is used in an alternator or generator to create electricity. The third type of solar system, the power tower, uses heliostats (sun-tracking mirrors) to direct sunlight at a receiver which is positioned at the top of a tower. A fluid in the receiver is heated and used to generate steam for use in a traditional turbine generator to produce electricity [7].

Solar PV systems are used in a variety of applications, both large scale and small scale. In Laos, the government hopes to increase rural access to electricity to 90% of the country by 2020 [8]. However, the government does not want to rely on a centralized system to deliver electricity to remote areas. With the help of a company called Sunlabob, they have found a way to overcome the often prohibitive costs of solar-PV systems. Essentially, the PV systems are rented by a Village Energy Committee (VEC) selected by the community, and trained franchisees monitor the quality of the systems. Each household can lease access to the electricity from the VEC, allowing price and payment structures to be determined within the community. Larger systems are also rented to healthcare facilities, which has made a significant difference in the quality of life. A doctor at the Ban Kuai village where the health center is powered through solar power, explains that before the solar systems were put into place there was no way to keep medicines and vaccines cool therefore every time something was needed it had to be imported from another location. In the time it took for the vaccines to arrive the patient’s condition may have deteriorated even further. Additionally the access to electricity allows the people in the community to have light for chores, school work, and craft work that could generate income. The Sunlabob company is considering expanding the concept into other areas such as Cambodia, Indonesia, East Timor, Eastern Africa, and Latin America [8].

One of the major roadblocks to the use of solar power and alternative energies in general is the issue of cost. Solar power utilizes radiation from the sun, which is plentiful in many areas and free to the people living there. However, the installation and maintenance costs can be high, so areas that might benefit greatly from such a system are unable to afford it. It appears that compromises can be made, and with innovative thinking and/or government involvement, it is possible to find a way to make electricity affordable for people all over the world.

Biomass Systems

Biomass is another source of fuel that can be used to create electricity. It can be burned directly or can also be converted into liquid fuel for use in heating applications, transportation, and energy generation. While biomass is responsible for only a small portion of US energy consumption, it does account for a large part of the renewable energy production, in fact it accounts for 48% of the energy coming from the renewable energy sector [9]. Biomass is renewable if monitored correctly, and while using biomass does release CO_2, the CO_2 released is balanced by the CO_2 used to grow the fuel [9]. Biomass is very versatile, it can be converted into all types of fuel that people need: both liquid and gas, and can be used for heating as well as electricity. One major benefit of biomass systems is that they provide a constant amount of energy at all times. Notably many developing countries that would benefit from increased access to electricity have a great deal of agricultural residue including rice husks, wheat straw, cotton stalks, and coconut shells, which can be used as fuel in a biomass system [10]. In addition to agricultural residue, crops can be specifically grown and harvested for use as biomass fuel.

Small biomass systems have been successfully installed in many places, providing electricity to people who have no access to the grid. Particularly in remote areas that are far from urban areas or are separated by difficult terrain, renewable energy systems such as biomass offer the only answer to the lack of electricity. Biomass is well suited to these situations, because it can take advantage of a variety of fuel types. For example, in India a small biomass system was put in place in Hosahalli and Hanumanthenagara, small villages comprised of between 200 and 300 people [11]. These systems are able to meet the needs of the inhabitants, who use electricity primarily for domestic lighting, irrigation, and small scale commercial activities. The system installed uses woody biomass and forest residue as fuel, and has been able to provide electricity for 90% of the year. Other small biomass gasifiers have also been put in place, taking advantage of the different resources, for example waste from a sawmill, as fuel [11].

Hybrid Systems

Hybrid systems are those that utilize two or more methods for creating power. In particular, this paper will look at hybrid wind-solar-biomass systems. Hybrid systems are useful because wind turbines alone only operate when the wind speed is above the cut-in speed and below the cut-out speed, solar panels cannot work at night, and biomass systems are dependent on the availability of fuel. Therefore a combination will allow power to be generated with greater reliability than any system on its own.

Several studies on hybrid systems have been done. Recently, Sanjoy Nandi and Himangshu Ghosh published an article in Energy Policy, "A wind P-V battery hybrid power system at Sitakunda in Bangladesh" [12]. They focused on the possibility of implementing a hybrid wind-photovoltaic (solar) system to address the electrical needs of the country. According to the article, only 38% of the population has access to electricity, and 96% of grid electricity comes from fossil fuels. The authors examine the possibility of using a local micro-grid wind-PV system to make electricity accessible to a greater percentage of the population and reduce the dependence on fossil fuels. The town that is considered is Sitakunda, a small coastal town. The proposed system should create enough energy to support the community's domestic activities, including lighting, cooling, and entertainment. No sources of measured solar radiation data were available at this location, so cloud cover and sunshine duration data were collected and used to determine the solar components of the system according to standard equations. The hybrid system proposed for Sitakunda is composed of 58% solar power and 42% wind power. It was determined that a combination of solar and wind power would be more beneficial than either system on its own. The article states that a hybrid system is one which provides “synergistic benefits in which the whole is greater than the sum of its parts” [12]. This proposed system would allow electricity to reach a larger portion of the population, and reduce the consumption of fossil fuels. The article notes that in order for alternative energy systems to be implemented on a larger scale, incentives must be provided for developers or network operators. However, it also asserts that as the price of fossil fuels increases due to scarcity, hybrid systems and micro-grid technologies will become competitive [12].

This article provides an example of a hybrid system that could be implemented in a remote community. In this case Sitakunda is located in an area that receives a great deal of sunshine, therefore a majority of power generation is from solar sources. However, in areas where there is less sunshine or more cloud cover, the percentage of wind contribution will be higher. While there are some costs that need to be considered when building hybrid systems, it is clear that they provide a highly feasible alternative to traditional fuels and could solve many problems associated with access to electricity.

Sources that can provide renewable energy hold the key to the future. As fossil fuels become scarcer and therefore more expensive, alternative energies will become more and more competitive. Additionally, they will not release harmful emissions into the atmosphere, which contribute to pollution and global warming. Hybrid systems allow energy to be generated more consistently, since they are less subject to the constraints associated with a single method system (i.e. solar power cannot be generated at night, wind power can only be generated when the wind speed is in a certain range). A wind solar biomass system can be devised for any geographic location with a varying percent of the output from each component based on the availability of sunshine and wind and biomass fuel. In addition to the possible economic advantages and more environmentally-friendly outputs, these systems could potentially be implemented in rural and remote areas, allowing greater access to electricity and improving the quality of life for people around the world.

METHODS

Objective

The objective of this research is to create a tool to optimize the energy conversion for a small, decentralized power plant. A small, decentralized power plant could be built in any location, including remote and developing areas. By taking into account the renewable resources such as wind, radiation from the sun, and biomass these power plants could be optimized to provide the greatest amount of power possible without being connected to a power grid. The term optimization means that the system will be able to meet specific user defined criteria or constraints, such as providing a set minimum amount of energy daily or even hourly. This could improve the quality of life for many people around the world who have limited or no access to electricity. Using a hybrid system will allow the greatest energy conversion at all times of the day. For example, a solar system will only generate power during the day when sunlight is available, while a wind turbine only works within a specific range of wind speeds (between the cut in and cut out speeds).

Data Analysis

The goal was to create a tool that would determine how to delegate resources for a small, decentralized hybrid wind-solar-biomass power plant. The first step in the process was to locate a database with the necessary information for wind and solar energy conversion. For the wind portion, it was found that the National Renewable Energy Laboratory (NREL) has wind speeds at 100 meters mapped across the country, covering over 30,000 locations [13]. This wind data is provided in 10-minute intervals for each year 2004, 2005, and 2006. The National Solar Radiation Database offered solar data in a similar format, providing the incident solar radiation (in addition to a plethora of other information) in hourly intervals for a span of 30 years [14].

With this data available, the variation in both wind speed and solar radiation was investigated at three different locations to understand how the fluctuations might affect the power output. Three locations were chosen for comparison, San Diego CA, Chicago IL, and State College PA. San Diego was selected because it is very sunny, Chicago because it is very windy, and State College because it is a familiar location. Comparing the wind speed distributions, Chicago did tend to have more wind at higher speeds, however the profiles are not extremely different (see figure 2,3,4).

Fig. 2 - Distribution of wind speeds for San Diego

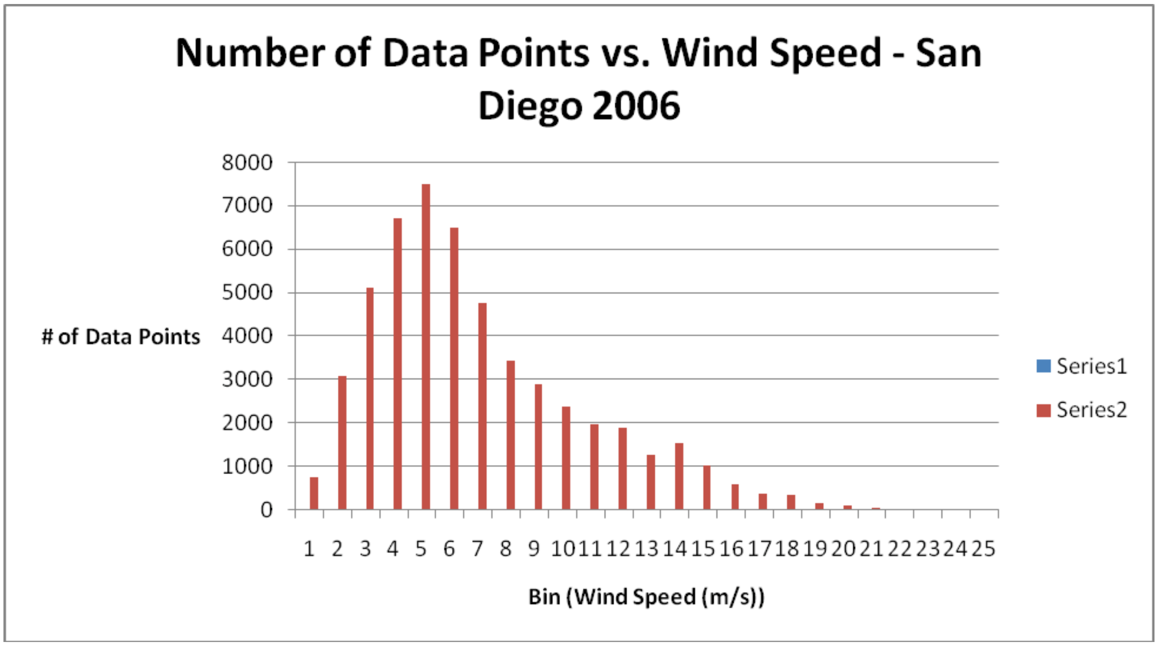


Fig. 3 - Distribution of wind speeds for State College.

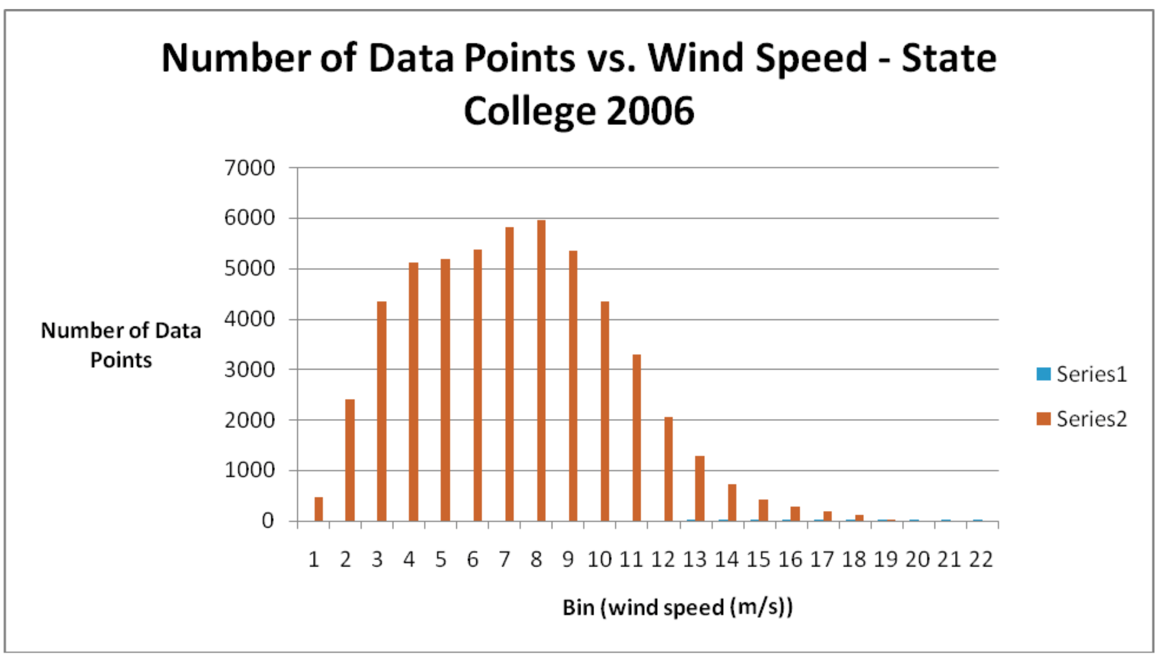
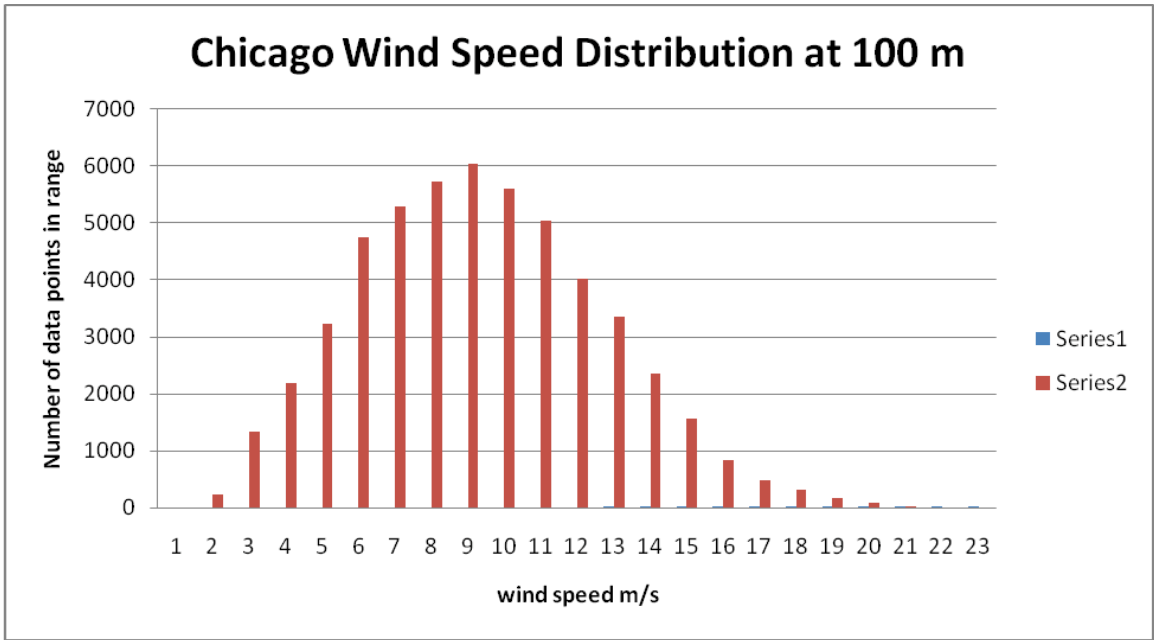
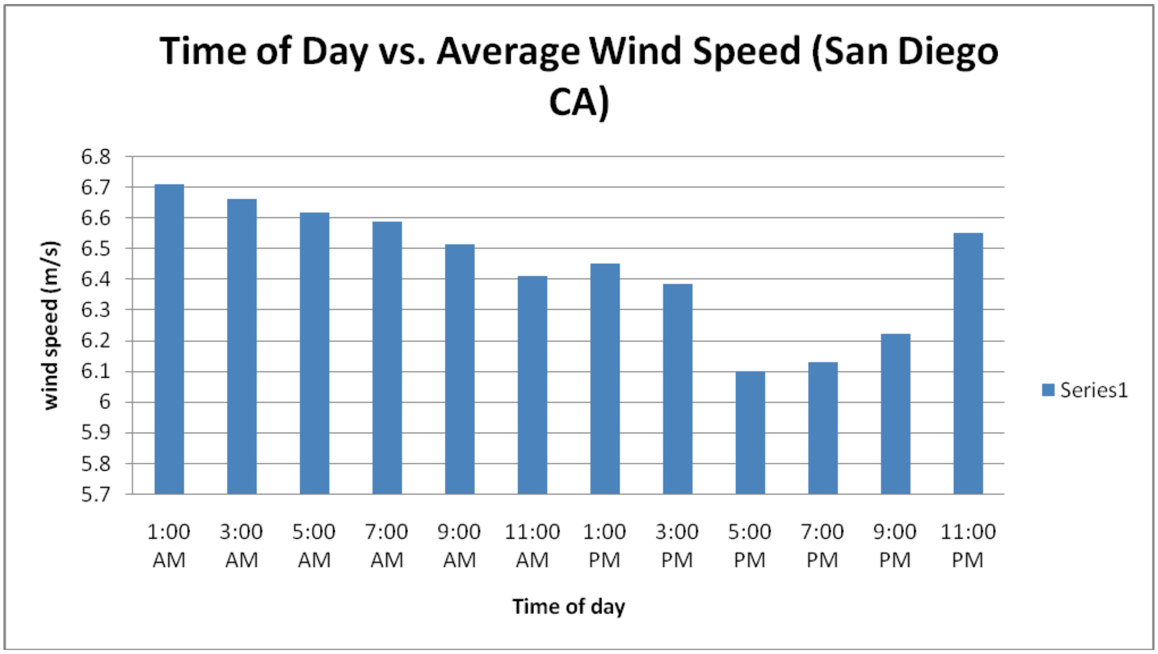


Fig 4. – Distribution of wind speeds for Chicago.



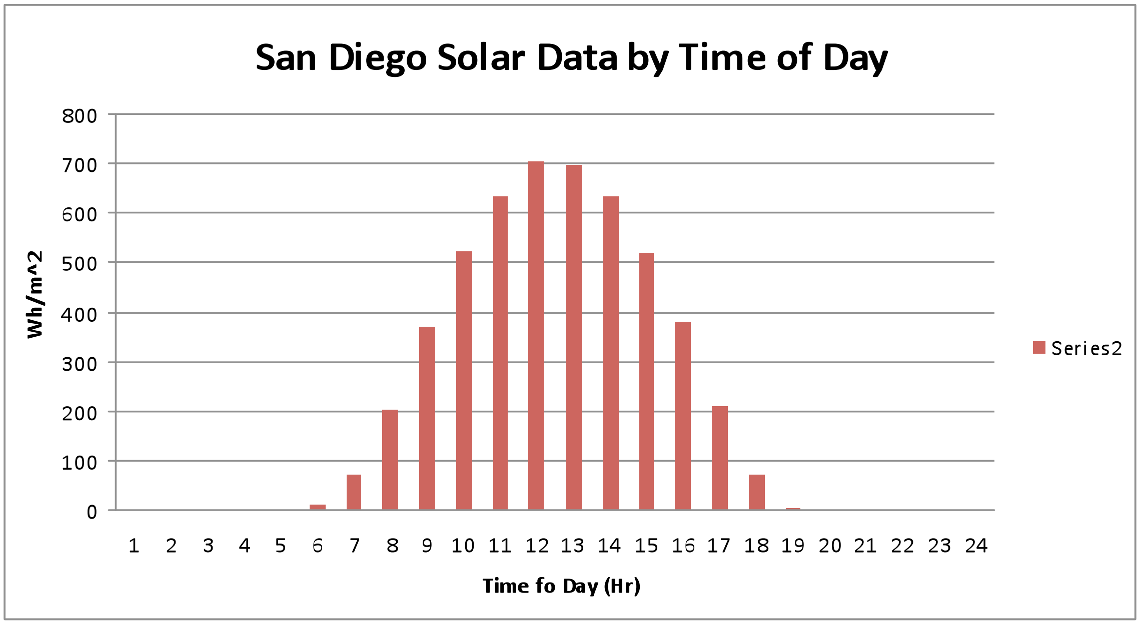
These trends give a general idea of the wind speed distribution in each location. More pertinent for both the investor and consumer are the daily wind speed distributions (i.e. how the wind speeds are distributed over the course of the day). Therefore the yearly data was sorted by time of day and the wind speeds were averaged to see how the wind speed varied over the course of an average day.

Fig. 5 - Average daily wind speed over the course of a day.



A similar approach was taken with the solar data for an initial analysis to improve the overall understanding of how the solar radiation varies with time. From the graph (below) it is obvious that solar radiation can contribute nothing to the power during the night, but at its peak can provide a comparably significant amount of energy.

Fig. 6 - Average solar radiation over the course of a day.



Creating the Tool

Armed with a general understanding of the trends in the wind and solar data as discussed above, focus was shifted to the next stage and bulk of the project: developing the tool. The tool is created in excel for two reasons, the first being that the data from NREL and NSRDB are both provided in large excel files. The second is that excel is an easy and familiar format for the user to interact with, and allows the user to follow the steps taken in many of the calculations. The purpose of the tool is to allow the user to input a budget and for the tool to output "weighting factors". These weighting factors represent the fraction of the budget that should be devoted to each type of energy: wind, solar, and biomass. Accordingly, three variables a, b, and c will be the weighting factors for wind, solar, and biomass respectively so that a + b + c = 1. These are the values that are outputted to the user at the end of the program's analysis.

In the first step of the program, all the possible combinations of a, b, and c adding up to 1 are placed in a matrix. The values of a, b, and c are in 10% intervals, ranging from 0 to 1. A portion of this matrix is shown in Table 1:

Table 1 - Example of how the weighting factors are combined.

a (wind fraction)	b (solar fraction)	c (biomass fraction)
1	0	0
0.9	0.1	0
0.9	0	0.1
0.8	0.1	0.1
0.8	0.2	0
0.8	0	0.2
0.7	0.3	0
0.7	0	0.3
0.7	0.2	0.1
0.7	0.1	0.2
0.6	0.4	0
0.6	0	0.4
0.6	0.3	0.1
0.6	0.1	0.3
0.6	0.2	0.2
0.5	0.5	0
0.5	0	0.5
0.5	0.4	0.1
0.5	0.1	0.4
0.5	0.3	0.2
0.5	0.2	0.3
0.4	0.6	0

The next step is to determine the available budget for each type of technology (wind, solar, and biomass) by multiplying a, b, and c by the initial budget the user wants to invest (indicated on the user input sheet) as shown in Table 2.

Table 2 - example of step two with a user input budget of $30,000.

wind budget	solar budget	biomass budget
30000	0	0
27000	3000	0
27000	0	3000
24000	3000	3000
24000	6000	0
24000	0	6000
21000	9000	0
21000	0	9000
21000	6000	3000
21000	3000	6000
18000	12000	0
18000	0	12000
18000	9000	3000
18000	3000	9000
18000	6000	6000
15000	15000	0
15000	0	15000
15000	12000	3000
15000	3000	12000
15000	9000	6000
15000	6000	9000
12000	18000	0
12000	0	18000

This information can be used to determine the height of the wind tower, area of the solar panels, and size of the biomass system. These factors will determine the energy conversion for the hybrid system.

Wind Portion

Knowing the amount of money available for wind power, the amount of power that can be produced can be determined using a few key equations. First, the data is sorted by time of day, since later it will be useful to look at the data for an average day. Then it is known that the height of the tower will be a function of price. Using an equation from the NREL Wind-Turbine Design Cost and Scaling Model one can determine the relationship between the height of the tower based on the price [15].

$$\text{Height (m)} = [(4/1.5 * 0.3973 * pi)*(cost(\$) + 1414)]^{1/3}$$

It is important to note that this is the cost of the turbine tower itself and does not account for other components, such as the generator and rotor. Therefore this is a significant simplification. Additionally, for the purposes of this project it is assumed that the blades account for 20% of the total cost of the turbine [16]. So in place of cost($) above the following will be substituted:

$$\text{Cost}(\$) = .8 * (\text{User input budget}(\$)) * a$$

This will provide a value for the amount of money for each value of a that will be dedicated to the cost of the tower. From this relationship we can determine the height for each possible budget:

$$Height (m) = [(4/1.5 * 0.3973 * pi)*(a * .8 *(User Input Budget(\$)) + 1414)]^{1/3}$$

This will result in 11 unique heights for the wind turbine, since a can range from 0 to 1 in steps of .1. Some of these heights may include decimal portions of a meter, therefore in the program these numbers are rounded down.

Once the 11 heights have been determined (with h_1 corresponding to a = 1, h_2 corresponding to a = .9, h_3 corresponding to a = .8, etc.) these can be used along with the wind data provided by NREL to determine the yearly wind speeds at each of these heights. The NREL wind data provides the wind speed in m/s for a year at 10 minute intervals, with the wind speed measured at 100 meters. The following equation is used to determine the wind speeds at each 10 minute interval for the heights h_1 through h_{11} [17]:

$$V = V_{ref} * (H/H_{ref})^{1/7}$$

Where H_{ref} is 100 meters and V_{ref} is the wind speed provided from the NREL data. Completing this analysis, the yearly wind speeds in 10 minute intervals for the reference height and each of the heights h_1 through h_{11} will be available. At this point, it is important to consider how the power produced is related to the wind speed. Before getting into the specifics, the cut-in and cut-out speeds of the turbine need to be considered. Essentially below the cut-in speed and above the cut-out speed the turbine will not generate any power. Accordingly it is essential to check the data and account for any wind speeds that are not in the usable range. Therefore excel must do a “check”, first for the cut-in speed and then for the cut-out speed. In the first step if the wind speed at the specified height is less than the cut-in speed, that value is set to zero, thus preventing the wind speed from contributing anything to the power production. Then these edited wind speed values are used in the check for the cut-out speed. Any value above the cut-out speed is set to zero. Following this process the values left are strictly with values for wind speeds within the usable range.

The next step is to use these checked wind speeds to determine the power output. The power is related to the wind speed as follows [18]:

$$P = \text{efficiency} * .592 * \text{pi} * \text{density of air} * (.5 \text{ Blade diameter})^2 * (\text{Wind speed})^3$$

Here another important simplification is made: it is assumed that the blade diameter is equal to the tower height [19]. Using the calculated turbine heights and wind speeds at each height the energy conversion (or power output) can be determined based on the following substitutions:

$$P = \text{efficiency} * .592 * \text{pi} * \text{density of air} * (.5\ H_n)^2 * (V_n)^3$$

With this relationship, the appropriate values can be substituted for each height and corresponding wind speeds to get the power produced at each ten minute interval for each height of the wind turbine. Once this is completed, the data is grouped by time of day and the average power produced for each hour of the day is determined. The total energy conversion for an average day is also calculated by summing the hourly contributions.

Solar Portion

For the solar portion this research used the data from NSRDB. This gives the incident solar radiation for the specified year for each hourly interval. Knowing the budget to be used for solar panels (b * User Input Budget) the program can calculate the area of the solar panels, which will ultimately determine the power output. This is a relatively straightforward calculation. Knowing the cost of solar panels per meter squared (which is a variable that the user can input and change as they wish), the area of solar panels that can be purchased is:

$$\text{Area of Solar Panels (m)} = (b * \text{User Input}) / (\text{Cost of solar panels/m}^2)$$

Repeating this calculation for each possible budget (i.e. each distinct value of b) will result in 10 possible areas for the solar panels (b = 1 is excluded since this will not provide power at night). From this information the power can easily be determined. Since the solar data is provided to us in Wh/m^2 from NSRDB, it is clear that multiplying the hourly incident radiation by the area of the solar panels will give the maximum power production. However the efficiency of the solar panels still needs to be taken into account. Thus the hourly power is:

P = efficiency * (Incident solar radiation) * (area of solar panels)

As with the wind power, the energy conversion for each value of b is calculated. Then the average energy conversion for each hour of the day for each area can be calculated. The next step is to sum the hourly powers to get the average daily power output.

Biomass Portion

A simplified approach for the biomass analysis was chosen. The biomass portion of the program is based in the BioMax 15. The BioMax 15 was developed by the NREL and Forest Products Lab. It costs approximately $1,800 per kW and requires a constant input of 544 kg/hr (1,200 lbs/hr) of woodchip fuel to provide 15 kW per day [20]. For the biomass component, a nominal cost for the user to input was created that would account for the cost of fuel in addition to other factors such as processing and availability. This nominal cost reflects how the price of gathering and preparing fuel for use in a biomass system can very greatly based on the specific location.

In addition to the capital cost of $1800/kW there is also an additional cost for the fuel that is dependent on the nominal cost:

Cost of biomass ($/kW) = [(nominal cost ($/ton))* (1 ton/2000 lb) * (1200 lb/kW)] + 1800 ($/kW)

With this relationship the tool can determine the energy conversion contribution in kW from the biomass system:

P = (c * User Input) / ([(nominal cost ($/ton))* (1 ton/2000 lb) * (1200 lb/kW)] + 1800 ($/kW))

Combining Wind, Solar, and Biomass

Once the energy conversions for the wind, solar, and biomass portions have been individually calculated for each value of a, b and c respectively, the total power output for each combination of a, b and c is calculated by summing the three components:

Total Power = Wind Power + Solar Power + Biomass Power

Once the total power is calculated for each combination of a, b and c the maximum power is identified and the values for a, b and c corresponding to this maximum value are outputted for the user's reference.

Example of Tool Analysis

In this portion an example of the steps the user and program would go through in a typical analysis are presented, accompanied with images of what the user would see.

Table 3 shows an example of what the user will see when he or she opens the program. The shaded boxes are variables that the user can enter or adjust to suite their needs.

Table 3 – Example of user input data sheet.

	A	B
1	Budget to Invest	30,000
2		
3	Nominal Cost of Biomass Fuel ($/ton)	0
4		
5	Turbine Height (m)	
6		
7	Cut-in Speed (m/s)	4
8	Cut-out Speed (m/s)	25
9	Turbine Efficiency	0.33
10	air density	1.2
11		
12	Cost of Solar Panels ($/m^2)	620
13	Solar Efficiency	0.12
14		
15	Cost of Biomass Facility ($/kW)	1800
16	Fuel Conversion (kW/lb)	0.0125
17		
18	Total Energy Conversion in One Day (kW)	31.9
19	Solar Energy Conversion in One Day (kW)	0
20	Wind Energy COnversion in One Day (kW)	30.3
21	Biomass Energy Conversion in One Day (kW)	1.67
22		
23	a	0.9
24	b	0
25	c	0.1

In this particular example, the budget of $30,000 was selected, reflecting the scale of investment that it is anticipated would be necessary to create a small, decentralized power plant for a small community. The wind information is taken from WinWinD [21]. The solar panel variables are based off the Sharp off-grid 80 Watt model [22]. The biomass components are based on the BioMax 15 [20]. The example location is Palm Springs, CA.

Once the user inputs the budget and adjusts the variables to suite their specifications (i.e. change the costs, efficiencies, etc.) the rest of the analysis is done by the program. The wind data analysis is performed in the series of steps previously discussed (determining the heights, sorting, testing for cut-in and cut-out speed, power production).

First the possible heights are determined (Table 4). Then the wind speeds at each height are calculated (Table 5). These wind speeds are then checked to make sure they are within the usable region (above the cut-in speed and below the cut-out speed) (Table 6). Once this check has been done, the power produced in each 10 minute interval is determined (Table 7). Finally the average hourly power and average daily power output are calculated for each height (Table 8).

Table 4 – Example of wind analysis to determine height

D	E	F	G	H	I
wind budget	solar budget	biomass budget		**turbine hieght (m)**	rounded height (m)
30000	0	0		37.87	37
27000	3000	0		36.64	36
27000	0	3000		36.64	36
24000	3000	3000		35.32	35
24000	6000	0		35.32	35
24000	0	6000		35.32	35
21000	9000	0		33.89	33
21000	0	9000		33.89	33
21000	6000	3000		33.89	33
21000	3000	6000		33.89	33
18000	12000	0		32.33	32
18000	0	12000		32.33	32
18000	9000	3000		32.33	32
18000	3000	9000		32.33	32
18000	6000	6000		32.33	32
15000	15000	0		30.61	30
15000	0	15000		30.61	30
15000	12000	3000		30.61	30
15000	3000	12000		30.61	30
15000	9000	6000		30.61	30
15000	6000	9000		30.61	30
12000	18000	0		28.66	28

Table 5 – Determining wind speeds from reference data.

	A	B	C	D
1	Date(YYYY-MM-DD hh:mm:ss)	100m wind speed (m/s)	wind speed at h1 (m/s)	wind speed at h2 (m/s)
2	1/1/2006 0:00	2.08	1.81	1.80
3	1/2/2006 0:00	5.61	4.87	4.85
4	1/3/2006 0:00	1.94	1.68	1.68
5	1/4/2006 0:00	0.83	0.72	0.72
6	1/5/2006 0:00	2.01	1.75	1.74
7	1/6/2006 0:00	2.22	1.93	1.92
8	1/7/2006 0:00	2.76	2.40	2.39
9	1/8/2006 0:00	1.47	1.28	1.27
10	1/9/2006 0:00	4.85	4.21	4.20
11	1/10/2006 0:00	1.4	1.22	1.21
12	1/11/2006 0:00	0.66	0.57	0.57
13	1/12/2006 0:00	2.52	2.19	2.18
14	1/13/2006 0:00	2.2	1.91	1.90
15	1/14/2006 0:00	3.67	3.19	3.17
16	1/15/2006 0:00	0.42	0.36	0.36
17	1/16/2006 0:00	10.39	9.02	8.99
18	1/17/2006 0:00	8.44	7.33	7.30
19	1/18/2006 0:00	2.29	1.99	1.98
20	1/19/2006 0:00	2.4	2.08	2.08
21	1/20/2006 0:00	2.94	2.55	2.54
22	1/21/2006 0:00	3.58	3.11	3.10
23	1/22/2006 0:00	6.47	5.62	5.60
24	1/23/2006 0:00	4.51	3.92	3.90
25	1/24/2006 0:00	5.56	4.83	4.81
26	1/25/2006 0:00	2.3	2.00	1.99
27	1/26/2006 0:00	1.98	1.72	1.71
28	1/27/2006 0:00	0.97	0.84	0.84
29	1/28/2006 0:00	7.71	6.69	6.67
30	1/29/2006 0:00	1.86	1.62	1.61

Table 6 – Test for cut-in and cut out speed.

C	D	E
wind speed at h1 (m/s)	cut-in test	cut-out test
1.81	0	0
4.87	4.87	4.87
1.68	0	0
0.72	0	0
1.75	0	0
1.93	0	0
2.40	0	0
1.28	0	0
4.21	4.21	4.21
1.22	0	0
0.57	0	0
2.19	0	0
1.91	0	0
3.19	0	0
0.36	0	0
9.02	9.02	9.02
7.33	7.33	7.33
1.99	0	0
2.08	0	0
2.55	0	0
3.11	0	0
5.62	5.62	5.62
3.92	0	0
4.83	4.83	4.83
2.00	0	0
1.72	0	0
0.84	0	0
6.69	6.69	6.69
1.62	0	0

Table 7 – Example of wind speed power calculations.

C	D	E	F
wind speed at h1 (m/s)	cut-in test	cut-out test	**Power at h1 (Whr)**
1.81	0	0	0
4.87	4.87	4.87	14576
1.68	0	0	0
0.72	0	0	0
1.75	0	0	0
1.93	0	0	0
2.40	0	0	0
1.28	0	0	0
4.21	4.21	4.21	9418
1.22	0	0	0
0.57	0	0	0
2.19	0	0	0
1.91	0	0	0
3.19	0	0	0
0.36	0	0	0
9.02	9.02	9.02	92597
7.33	7.33	7.33	49634
1.99	0	0	0
2.08	0	0	0
2.55	0	0	0
3.11	0	0	0
5.62	5.62	5.62	22359
3.92	0	0	0
4.83	4.83	4.83	14190
2.00	0	0	0
1.72	0	0	0
0.84	0	0	0
6.69	6.69	6.69	37837
1.62	0	0	0

Table 8 – Example of average hourly and total daily wind power.

AV	AW	AX	
Hour	Average Power at h1 (W)	Average Power at h2	A
0	0	0	
1	0	0	
2	0	0	
3	0	0	
4	0	0	
5	0	0	
6	0	0	
7	0	0	
8	0	0	
9	0	0	
10	0	0	
11	0	0	
12	0	0	
13	0	0	
14	4177	3908	
15	0	7078	
16	5671	5306	
17	9743	9116	
18	0	0	
19	5191	4857	
20	0	0	
21	0	0	
22	0	0	
23	0	0	
Total Daily Energy Conversion (kWhr)	24.8	30.3	

For the solar portion, the budgets are used to determine the available area for solar panels, and the areas are truncated (Table 9). The solar data is sorted by time of day and the hourly and average daily solar radiation are calculated (Table 10). This average daily radiation is then multiplied by the area of the solar panels and the efficiency to get the power production for each possible value of b (Table 11).

Table 9 – Determining the area of the solar panels.

Available area for solar panels (m^2)	rounded area (m^2)	
0	0	a1
4.84	4	a2
0	0	
4.84	4	
9.68	9	a3
0	0	
14.52	14	a4
0	0	
9.68	9	
4.84	4	
19.35	19	a5
0	0	
14.52	14	
4.84	4	
9.68	9	
24.19	24	a6
0	0	
19.35	19	
4.84	4	
14.52	14	
9.68	9	
29.03	29	a7
0	0	

Table 10 – Average hourly and daily solar radiation.

K	L	M	N
Hour	Average Incident Radiation (Wh/m^2)	Total Average Daily Radiation (Whr/m^2)	2770
0	0		
1	0		
2	0		
3	0		
4	0		
5	0		
6	0		
7	0		
8	53		
9	226.5		
10	307		
11	467.5		
12	478		
13	531.5		
14	369.5		
15	213		
16	114.5		
17	9.5		
18	0		
19	0		
20	0		
21	0		
22	0		
23	0		

Table 11 – Determining the daily solar power production.

L	M	N	O
Available area for solar panels (m^2)	rounded area (m^2)		Daily Solar Power Production (kWhr [
0	0	a1	0
4.84	4	a2	1.33
0	0		0
4.84	4		1.33
9.68	9	a3	2.99
0	0		0
14.5	14	a4	4.65
0	0		0
9.68	9		2.99
4.84	4		1.33
19.4	19	a5	6.32
0	0		0
14.5	14		4.65
4.84	4		1.33
9.68	9		2.99
24.2	24	a6	7.98
0	0		0
19.4	19		6.32
4.84	4		1.33
14.5	14		4.65
9.68	9		2.99
29.0	29	a7	9.64
0	0		0
24.2	24		7.98
4.84	4		1.33
19.4	19		6.32
9.68	9		2.99

The energy conversion from biomass is determined using an equation relating cost and power output, as discussed earlier. The total daily energy conversion for each combination is determined by adding the wind, solar and biomass contributions.

The maximum total energy conversion is determined, and the values of a, b, and c corresponding to this max value are outputted to the user input sheet, and can be seen at the bottom of Table 3.

Discussion

This model was developed to help an individual investor or organization decide how best to spend their money when choosing to invest in a small, hybrid, decentralized system to meet the needs of people living in rural or developing areas. In the example from the previous section, the model recommended investing 90% of the budget in wind power and 10% in biomass power. The model has a trend towards recommending that a high percentage of the initial budget be invested in wind power when values from Sharp, WinWind, and the BioMax 15 are used. However prices are not static, they fluctuate due to a number of factors, and therefore this program is very useful in considering these changes.

Clearly as technology improves the cost of solar panels and their efficiency will improve, resulting in a greater percentage of the budget being dedicated towards solar power. Similarly, the capital cost per kW for biomass systems will also decrease, making them more competitive. Additionally, government subsidies could help bring down the cost for investors. These improvements can be reflected by changing the costs and efficiencies in the user interface, resulting in a more equal distribution of the initial budget.

An interesting aspect of renewable energy is that governments are often interested in encouraging the growth of the technology. For example in Germany (and many other countries in the European Union) the government has implemented "feed-in tariffs". The feed-in tariffs reward investors for investing in renewable energy by paying owners for the energy sold to the public grid. The owner is paid a certain amount of money per kilowatt, and this amount will change over time. This is to encourage investment in and development of renewable energy systems; as the systems become more developed and therefore competitive, the government will reduce the feed-tariff. Currently Germany offers these feed-in tariffs for solar, wind, and biomass [23].

Incentives such as the feed-in tariff could have a great impact on what the costs for the investor would be when building a hybrid system. This program would be useful not only for people considering investing in rural areas, but also people considering investing to take advantage of these programs.

Using the same example discussed in the previous section, the following table was created, showing possible systems incorporating wind, solar, and biomass components in varying degrees. Assuming that energy costs $0.10/kWhr, the payback period for such a system was calculated.

Table 12 – Payback period for current system.

a	b	c	Daily kWhr Energy Conversion	Annual kWhr Energy Conversion	Dollar Output per year ($) at $0.10/kWhr	Payback Period (years)
0.2	0.6	0.2	21.9	7994	799.35	37.50
0.2	0.4	0.4	21.9	7994	799.35	37.50
0.2	0.2	0.6	21.9	7994	799.35	37.50
0.4	0.4	0.2	24.0	8760	876.00	34.25
0.4	0.2	0.4	24.0	8760	876.00	34.25
0.6	0.2	0.2	26.1	9527	952.65	31.49

It is obvious that with current values for solar panel costs, biomass costs, and the wind speeds in Palm Springs, CA, the payback period is extremely long (around 75 years). As discussed, prices are somewhat variable depending on government support, and improvements in technology could change the viability of such systems. To illustrate this point, the same calculations were done for a hypothetical location with wind speeds that are twice the wind speeds in Palm Springs, where the price of solar panels is cut in half (to $310) and 25% of the biomass costs are covered by the government (bringing the cost down to $1350/kW), as shown in table 13.

Table 13 – Payback period for hypothetical location.

a	b	c	Daily kWhr Energy Conversion	Annual kWhr Energy Conversion	Dollar Output per year ($) at $0.10/kWhr	Payback Period (years)
0.2	0.6	0.2	134.3	49020	4901.95	6.12
0.2	0.4	0.4	132.1	48217	4821.65	6.22
0.2	0.2	0.6	130.2	47523	4752.30	6.31
0.4	0.4	0.2	202.4	73876	7387.60	4.06
0.4	0.2	0.4	200.5	73183	7318.25	4.10
0.6	0.2	0.2	267.0	97455	9745.50	3.08

With these adjustments, the payback period is significantly shorter, (between 3 and 6 years). The assumptions for this analysis are not far fetched, they simply reflect improvements in manufacturing methods for solar panels and a government interest in encouraging investment in biomass. Palm Springs has low wind speeds compared to many locations; therefore it is not unreasonable to making an assumption that some location may have winds speeds that are twice those in Palm Springs.

This example demonstrates another important aspect of the tool created: it not only does energy conversion calculations for current costs, but due to the inputs being variable it can also be used to make predictions about possible future investments and can reflect conditions in multiple locations by modifying the inputs.

Limitations

Clearly, this is a simplified model for power generation from a hybrid system. For the wind data, the pricing model from NREL was used. However this model is partially based on a linear relationship between cost and height, in the form $y = mx + b$. Therefore at small investments the equation will still give a significant value for h, since even when the cost (x) is zero there will still be a non-zero value for y due to the intercept. This problem becomes less of an issue as the amount to be invested increases, but is certainly something to consider for smaller investments. Therefore there is some minimum amount of money that must be invested for this program to give an accurate estimate of the energy conversion. Additionally for the wind portion, the assumption is made that the cost of the turbine and therefore the height depended only on the cost of the tower and price of the blades, omitting the other components, such as the rotor and generator, among others. It is also assumed that the height of the turbine and diameter of the blades are equivalent, which is not necessarily true in real-world applications. As the blade diameter changes the energy conversion will also change, so the calculated values may differ from actual numbers for turbines of various heights.

For the biomass portion, this research looked only at a specific system, the BioMax 15. The analysis presented was modeled on this system because it was specifically designed for small-scale power production. However, other systems may operate differently and thus the values would vary from those used in the program. The BioMax 15 runs on woodchips as fuel, however many types of biomass exist. This program does not take into account the type of fuel or the availability of fuel in specific areas. For all three types of energy systems, certain factors were not accounted for. Installation costs and transportation costs are not currently incorporated in this design.

Currently the user needs to manually download the solar and wind information from NSRDB and NREL and then copy it into the model workbook to run the analysis. This would make it difficult for users who are not familiar with the program to use it. Clearly, this is an issue that needs to be addressed to make the user's experience a positive one.

Further Development

This is a project with a lot of potential to positively impact the lives of many people around the world. While the simplified model currently developed is only a small step towards the ultimate goal of this research, many additional steps could be taken to create a model that would account for many of the factors and variations that need to be considered before this program could be used to accurately predict costs. Additionally, changes to this program that allow the user to have more control and set more complicated parameters would make this tool more useful.

Based on the current limitations, the costing models used in this program need to refined and possible take into account factors such as transportation and operating costs.

Currently for a user to run the analysis, they need to manually download and transfer the data to the workbook to run the analysis. It is essential that this step become automated so that the user could just specify a location and the analysis would be performed without forcing the user to go through a series of complicated steps. Further advancements for the user need to be made. It would be ideal for the user to be able to set a minimum desired daily or even hourly level of energy conversion. It would also be interesting for the user to be able to turn off any component of the system and see how the other two or even one would work alone.

While there is room for a lot of improvement, this research is the first step on a path towards creating a tool that would help investors to wisely spend their money on systems that could provide electricity to areas currently not connected to an electrical grid. With every improvement, this research will come closer to realizing its ultimate objectives: to create a sophisticated tool that can help users invest wisely in environmentally responsible energy systems.

Conclusions

Overall, a simplified model for the optimization of a small, hybrid, decentralized power plant was developed through this research. The model takes into account the basic principles governing power production from wind, solar, and biomass systems. It gives a general idea of the trends and a reasonable first estimate of how to optimize the power output for a specified area. It can also reflect changes in pricing, such as reductions in production costs for the various components or government incentives to invest in renewable energy. There is certainly room for improvement and further research and work needs to be put into this project to make the projections more realistic. Keeping this in mind, it provides the foundation for what could be an extremely useful tool, providing the first step towards making electricity available to people around the world.

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Thesis Supervisor: Anil K. Kulkarni

Related Experience

Research Assistant at Center for Innovative Sintered Products, Penn State

Supervisor: Dr. Smid

Spring 2008 – Spring 2009

Awards

Dean's List – 5 Semesters – Fall 2007, Spring 2008, Fall 2008, Spring 2009, Fall 2010

Activities

Volé – Penn State Ballet Club	F. 2007 – Spr. 2010
SOMA – Students Organizing the Multiple Arts (Penn State)	F. 2006 – Spr. 2008
Schreyer Honors College Student Council	F. 2006 – Spr. 2008
Student Council PR Chair	F. 2008
SES – Society of Engineering Science	F. 2009 – Spr. 2010