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OPTIMIZATION OF ENERGY STORAGE IN A RENEWABLE PLANT: THE MISSING LINK IN FEASIBILITY

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ABSTRACT

Energy is considered the top global problem for the 21st century, and simultaneously many countries are striving for higher economic status, which requires more energy. That is why renewable development is necessary, and many remote areas do not have access to standard transmission lines. A program was developed that assesses energy needs and system cost for these types of locations, receiving power from wind, solar, and biomass. However, energy storage is the missing link in increasing the feasibility of a renewable hybrid plant. By storing energy for later use, the intermittency problem of solar and wind can be alleviated. Thus, the objective of this thesis sought to integrate a form of energy storage (valve-sealed lead acid batteries) into the existing program. The methods used included estimating excess energy generation by the wind turbine and solar panels, and iterations based on the battery bank energy capacity were performed. This energy was stored in the batteries on an hourly basis and met loads that the renewable sources could not by storing excess generation for later use. Essentially, the batteries store loads to displace loads at a later time. The user is able to adjust the battery model properties, and see results including battery system costs, efficiency, and total energy stored. An optimization algorithm, using user inputted weighted functions, chooses the best battery system for both the wind turbine and solar panels, respectively. A costing function including battery cost, installation fees, operation and maintenance, incentives, and inverters was implemented. It was found that using batteries as energy storage can cover 10-15% of the required load on average, up to 25% in some cases. As a result, this program provides an accessible and understandable way for someone to evaluate their needs for a renewable system based on their location, from its generation to storage to price.

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Chapter1: Introduction

As society transgresses through the 21st century, important decisions regarding energy use must be confronted for civilization to continue to its development. Energy can be harvested through various means, and typically we have relied on fossil fuels to power our vehicles, businesses, and homes. However, we have to reconcile that these are finite and polluting sources that will one day run out, and their use will become economically unfeasible as we have to use more sophisticated drilling and processing methods to make them usable as fuels. It is widely recognized that energy can be extracted from the sun or wind, but caveats for their implementation exist. These include their cost per kilowatt compared to conventional energy sources as well as the intermittency of solar and wind. The sun only shines for a portion of the day, the wind blows at varying times, and the intensity of the sun and wind are always in flux.

A way to rectify this problem is to utilize energy storage. In this method, the intermittency of renewables is less troublesome because the energy can be saved for use at a later time i.e. the energy received from the sun during the day can power a home at night. How can energy be stored? The possibilities includes storing heat in sources like rocks and water, flywheels, compressing air, batteries, or even dams and water towers. These will be delved into and discussed in this thesis. Specially, their application is assessed for rural or off-grid locations because they benefit the most from renewables. The reason being is that poorer countries do not have the resources to create a centralized electrical grid structure, and the energy losses in transmission lines can make electricity from nuclear or fossil fuels too costly.

Scope of Research

The underlying theme of this thesis is to find a suitable storage mechanism for renewable energy systems that can be applied anywhere but with a focus on off-grid remote locations. Hence, the emphasis will be on simple, low cost, and easy to implement technologies to an energy generation system that uses a combination of PV panels, wind turbines, and biomass. This thesis is in conjunction with an overall research project that creates a way for a layman to assess their energy needs, and the thesis will be used to find the best storage option based on user input and the energy load. Parameters such as the $/kWh, efficiency, life cycle cost, installation time, and storage capacity must be considered in order to create a program that can accurately pinpoint the best energy storage technology for any circumstance. Therefore, an optimization method must be employed in order to compare and contrast each storage type and select the appropriate one.

This will be accomplished by creating a background on energy storage technology, selecting the best one for the current research, and finding the main parameters to optimize. This will then be sync with the research project's existing program in Excel. The reason Excel is the software of choice is because it is a common program worldwide that can reach a larger audience, and it has a user interface many are familiar with. By using Excel, users will find assessing their energy needs is hassle free by not having to learn some new complicated or specialized software. Overall, this thesis will provide the reader with a thorough background on the emerging energy storage field. Furthermore, it will create an optimization program using numbers from published journals and projects in order to select the best energy storage technology that is applicable anywhere but focuses on rural off-grid areas.

Chapter 2: Literature Review of Storage Technology

The purpose of this section is to inform the reader of the energy storage applications that are out there and from there the appropriate choices for an off-grid application will be made. Overall, a review of the workings of each type of storage will be discussed along with relevant physical parameters, the scalability of each technology, installation time, system cost, examples of real world projects, and safety and environmental concerns will be discussed.

Pumped Hydro Storage:

Storing energy by pumping water is one of the oldest forms of energy storage. The basic principle behind this method is changing the elevation of water and storing it in some kind of reservoir, and then releasing it when there is energy demand. Power is produced from this method due to the change of the water's position in the natural gravitational field i.e. its potential energy. The primary components necessary amounts to water, a pump, reservoir, controller, and a turbine-generator system. Specifically, an upper reservoir holds the water which is attached to a level headrace which obtains water between the upper reservoir and flows it to the upper end of a penstock [33]. This penstock connects to the pump turbine system that is on the same shaft as the generator, and a tailrace tunnel that typically rises slightly to connect to the lower reservoir [33]. A layout of a conventional pumped hydro plant is shown in Figure 2-1. Power is generated when the turbine turns since the generator also turns.

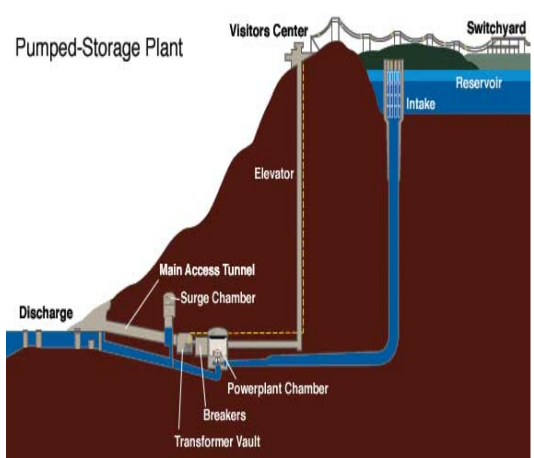

Figure 2-1: Pumped Hydro Reservoir [33]

It is feasible for this to be used in off-grid applications due to the low level of technology required, but it is typically restricted to the topography of the land. However, using water towers and even underground pumped storage have been proposed. The following is an overview of the potential uses for this storage technology as well as its limitations.

As of today, pumped hydro energy storage (PHES) is the one of the only energy storage methods that has been proven to work on large scale projects greater than 100 MW [11]. The other is compressed air storage [45]. There are over 300 plants in the world that has a capacity of over 95 GW [11]. Systems usually pump water during periods of off-peak power, and the energy is generated during peak periods [11]. The pumping is done during off-peak hours due to the lower cost of electricity [45]. Historically, PHES was seen as a complement to nuclear power because nuclear plants cannot be ramped up or down quickly in order to meet changing demand while PHES can. The lowered development of PHES in the United States occurred due to competition with cheaper gas-fired plants in the 1990s as a peak-load technology [45]. Furthermore, finding suitable sites that were affordable were arduous to come by [45].

There is a multitude of ways to implement a pumped hydro plant. In addition to the classic hydroelectric plant that drops water at a predictable rate, recent innovations use variable speed pump/turbine systems that utilize asynchronous motor-generators. This allows the plant operator to change the turbine rotation speed and thus the amount of energy generated which will increase efficiency. However, this improvement will add an extra $1000-1050/kW for a hydroelectric plant. Other possibilities include using a water tower combined with renewables that uses back to back voltage source converters (VSCs) to connect to the grid [47]. By using the VSCs, the water tower can store pumped water as an energy storage mechanism or provide power to balance the generation and load demands, and it only takes “several tens of seconds” to change from motor to generator mode and vice-versa [47].

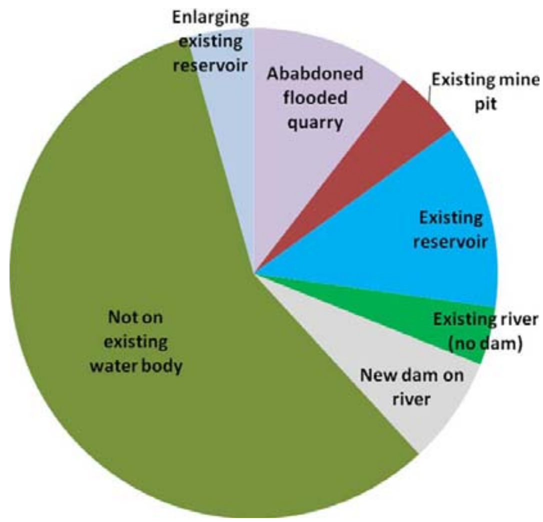

Figure 2-2: Different Types of Upper Pumped Hydro [45]

Currently, there are 32 permits in the process as of April 2010 in the United States. A special note though is that the designs now differ from the typical pumped storage using existing reservoirs or dams. In fact, less than a quarter of the proposed projects uses them and instead wishes to use underground caverns, quarries, and mine pits [45]. Figures 2-2 and 2-3 show the different site selections for PHES projects for both upper reservoir and lower reservoir projects [45]. An example of such a project is Mulqueeney Ranch located in California. Here recycled wastewater is utilized in the pumped storage system by aerating the water itself, sparing the fish population of exposure [45]. The Mulqueeney Ranch has a capacity of 280 MW. Other examples of pumped hydro projects are shown in Table 2-1.

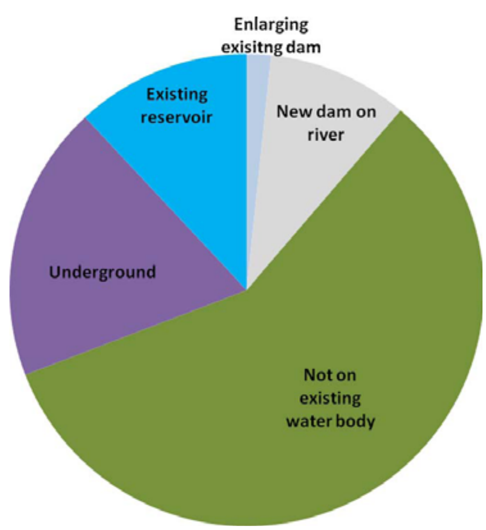

Figure 2-3: Different Types of Lower Pumped Hydro [45]

The main obstacles that PHES faces typically are permitting issues and environmental concerns. The rock of the reservoir must be suitable, and “unfractured igneous basement rock under low lateral stress is considered ideal” [33]. Other rocks that can be used include igneous extrusive, sedimentary, or metamorphic rock [33]. Furthermore, PHES that uses dams can affect the ecosystems of local aquatic life and create sediment buildup near the dam itself. Permitting may be tough to obtain with local opposition to changes to the scenery and possible electromagnetic field health concerns [33].

Plant Name	State	Power [GW]	Energy [GWd]	Avg. Head [m]	Eff. [%]
Bath County	VA	2.86	0.99	359	80
Ludington	MI	1.98	0.72	111	72
Raccoon Mountain	TN	1.53	1.31	273	77
Castaic	CA	1.28	0.50	326	67
Bad Creek	SC	1.07	1.00	350	–
Helms Pumped Storage	CA	1.05	7.67	490	74
Blenheim Gilboa	NY	1.00	0.50	335	75
Northfield Mountain	MA	0.94	0.44	227	75
Rocky Mountain Hydro	GA	0.85	0.24	197	84
Muddy Run	PA	0.80	0.46	108	71

Table 2-1: Pumped Hydro Project Statistics [33]

Thermal Storage:

In constructing a way to store energy for a PV array, there are two ways of accomplishing this. One is using a semiconductor material to create a photoelectric effect where light incident on a PV panel is converted into electricity. The other way is to capture the heat that is radiated onto the surface of a panel, heat a fluid or evacuated tube, and convect heat to some external source. Thus the principle of thermal storage for a renewable system is to store the heat transferred for use at a later time. There are a variety of avenues toward this end. The two general categories for thermal storage are sensible and latent methods [17]. Sensible thermal storage involves changing the temperature of the storage like rocks, water, and concrete; latent thermal storage holds the temperature constant, and uses a phase change of the storage material to store thermal energy [17]. Phase change material can include molten salts, ice, or water [17]. A primary difference is that phase change thermal storage has a better energy density than sensible storage [46]. A more in-depth look into each of these methods will be explored. This paper deals with PV panels, so a thermal system will need to inefficiently convert the electricity from the panels into heat first. Due to this, thermal storage will not be considered in the actual program.

Figure 2-4: Solar Trough vs. Solar Panels [22]

Molten salts are an effective phase change material, and a study done by the NREL in Golden, Colorado analyzed using molten salt with solar troughs. Note in Figure 2-4 how the trough differs in geometric shape from panels or parabolic troughs. Temperatures from the trough field can be between 400-500°C [22]. A drawback of using molten salt (also called salt hydrates) is the high freezing temperature, thus a high operating temperature must be maintained or there can be damage to the piping; high operation and maintenance challenges can occur from this [22]. The storage duration of the system is about six hours [22]. Table 2-2 below gives the cost per kilogram of cost along with the storage cost. A special concern in constructing a salt system is to account for the corrosion by the salt itself, so the correct piping must be chosen for each application [17].

Salt	Temperature Rise	Cost per Kg	Storage Cost
	°C	$/kg	$/kWh
Hitec (a) [142°C]	200	0.93	10.7
Solar Salt (b) [220°C]	200	0.49	5.8
Calcium Nitrate	200	1.19	15.2
[HitecXL] (c) [120°C]	150	1.19	20.1
	100	1.19	30.0
Therminol VP-1 (d)	100	3.96	57.5

a) 7:53 Na:K Nitrate, 40 Na Nitrite c) 42:15:43 Ca:Na:K Nitrate
b) 60:40 Na:K Nitrate d) Diphenyl/biphenyl oxide

NREL TES Workshop-Golden-Feb03

Table 2-2: Thermal Salt Properties [17]

Simple rocks the size of pebbles can be a useful path to storing heat. It is an easy and cheap way to store energy, and using a pebble bed of rocks with a simple air duct could be a solution. In a study at ETH Zurich, the efficiency of the operation can be over 90% under optimal conditions and have charging and discharging cycles of six hours [15]. Considering the bed dimensions, fluid flow rate, pebble material and diameter, the volumetric heat capacity is the most important parameter and not thermal conductivity [15]. It can be inferred that this property should be accounted for when sizing the overall capacity of the pebble bed. The larger the bed, the higher the cost will become to pay for the system. It would also make sense that the volumetric heat capacity will be of importance with the units of kJ/m^3K, so the energy stored will be based on the volume and its temperature. Advantages of rock beds include lower fabrication requirements compared to molten salts and steam, ambient pressure operation, and they can be connected right after the receiver, ridding the need for a heat transfer fluid [15]. Disadvantages include higher flow rates and surface areas for air compared to higher thermal conductive materials like molten salts or thermo-oils [15]. There are other ways of using rocks besides pebble beds. In an article by The Guardian, Cambridge researchers used “gravel batteries” that uses argon gas to heat gravel in silos when synced with a wind farm [20].

Concrete thermal storage is similar to rock bed storage and has an estimated energy density of 22 kWh/m^3 [5]. At the Institute of Technical Thermodynamics, a $20m^3$ concrete slab with an energy capacity of 400 kWh was built in Stuttgart [5]. In regards to molten salt technology, concrete is “expected to be an attractive option regarding investment and maintenance costs” [5]. Their concrete storage experiment is shown in Figure 2-5 which also uses a 50 MW solar trough field. The duration of the storage charging and discharging is in 6 hour cycles [5].

Figure 2-5: Concrete Thermal Storage [5]

Another similar thermal storage method is using a thermally stratified underground sand bed that is connected between a solar collector array and the home it heats. Figure 2-6 shows a simplified view of sand bed storage done at Virginia Commonwealth University. The hotter sand is at the top of the bed while the cooler sand is toward the bottom of the bed. Pumps push the cool and warm air to change the temperature of the sand bed.

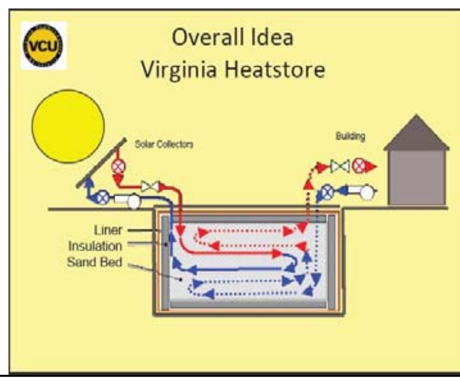

Figure 2-6: Sand Bed Thermal Storage [22]

Water can be used as a phase change storage medium since it undergoes two phase transitions [17]. Thus, there are thermal storage systems that use phase change involving ice while others use steam. Ice slurry can be used as both the storage medium as well as the heat transfer fluid [26]. Water flows into the TES (thermal energy system) at a temperature of 20^{o}C to 30^{o}C and cooled by the ice slurry in the TES [26]. The capacity of the experiment was 2.0 MJ (0.56 kWh) that could discharge as fast as 30 seconds [26]. Water can also be used as a sensible thermal storage material, and it acts as the heat transfer fluid as well [38]. Examples of this can be flat plate solar water heaters in India [38]. Furthermore, the heat transfer can be enhanced in the water if small pieces of copper or graphite composite are inserted into the water flow [9]. For water, latent thermal methods are superior to sensible as they can store 5-14 times more heat per unit volume and have lower heat losses as heat is absorbed to enact the phase change [38]. In the study at Devi Ahilya University, a tank latent water storage system was able to provide hot water all day with an efficiency of 45% [38]. Figure 2-7 shows the layout of the tank-in-tank design.

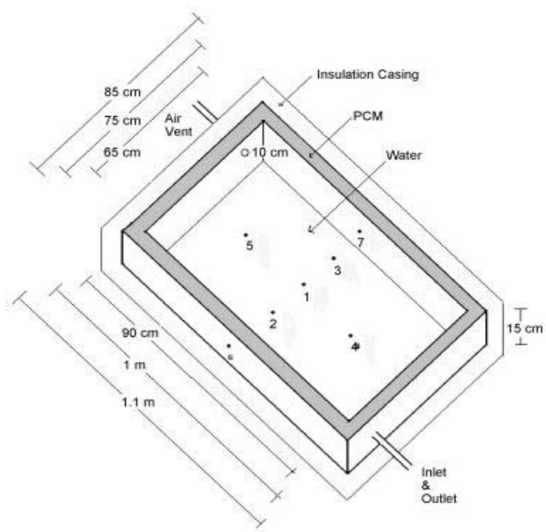

Figure 2-7: Latent Hot Water System [38]

Battery Storage:

Batteries are electrochemical energy storage devices, and it is one of the most common forms as well. A variety of batteries exist based on the element that constitutes each electrode. Examples include lead acid (PbA), zinc bromide (ZnBr), nickel cadmium (NiCd), vanadium redox (VRB), lithium ion (Li-ion), and sodium sulfur (NaS) batteries. Figure 2-8 shows a schematic for a typical battery with the figure depicting a NaS battery.

How does a battery work? Two electrodes are connected via. a circuit and salt bride to allow electron and ionic species flow. The positive electrode (Zn) will have the anode and oxidize as electrons leave through the circuit. A voltage is generated as the electron goes to the cathode on the reducing electrode (Cu). Here Cu reacts with Zn on this side by the ions flowing through the electrolyte. The electrolyte is a filter for ionic and insulator against electron flow. Chemical forces drive this reaction though the Gibbs free energy. Thus an electrochemical cell acts as a transducer between electrical and chemical energy. Also switching polarity occurs by imposing an opposite stronger voltage, and recharging occurs by reversing electron flow. Note that positive ions and electrons flow in the same direction while vice-versa for negative ions. As the battery is used, the chemical composition of the electrodes changes, and since it's based on the virtual reaction phase diagrams can be used to find the chemical thermodynamic properties [17]. This degradation does lead to the end of battery life too.

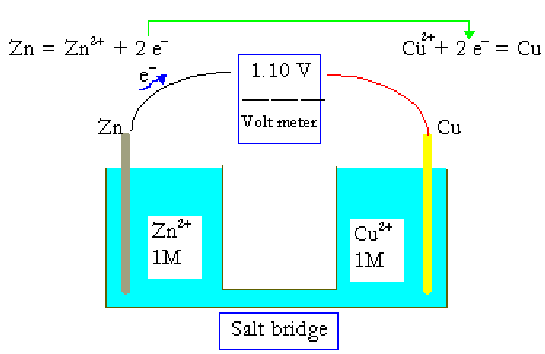

Figure 2-8: Operation of a Battery Cell [17]

One of the most common batteries for renewable energy systems is the lead acid battery. This is due to low cost and technological maturity despite drawbacks such as limited cycle life and low energy density [35]. Its lower cycle life can be attributed to corrosion during overcharging and electrode degradation [35]. A low energy density means that it will take more volume of batteries to provide energy, so the allotted battery space must be considered. The two main categories of lead acid batteries are flooded and valve regulated. According to the Trojan Battery Company, valve regulated batteries are better for remote applications since it does not require regular maintenance like water refilling that the flooded PbA batteries require [41]. Projects on PbA batteries in energy storage projects include a 10 MW, 40 MWh system in Chino, California. The system's overall efficiency was 72% with lead acid batteries that had at least 2000 deep discharge cycles, and the project as a whole met expectations [35]. Figure 2-9 shows the battery banks for the Chino project. In Germany, the BEWAG testing facility created a 17 MW, 14 MWh system that was able to provide over 7000 times its nominal storage capacity in a period of 9 years [43]. In conjunction with a stand-alone photovoltaic and biomass system, valve-regulated batteries were used for a simulation of energy needs in Nigeria, Africa [29]. The simulation itself found the 370 kWh battery bank to be sufficient in creating a stable energy source for a 1,056 solar panels with a rating of 24 volts [29].

Figure 2-9: Battery Storage in Chino, CA [35]

Lithium-ion batteries are in a nutshell superior to the lead acid battery in nearly every category but cost. Li-ion batteries have high cycle life, high energy density, and high efficiency. The high energy density means that it has found uses in portable electronics such as laptop batteries. However, its high energy density led to an explosion risk that did not enable it to be commercialized until Sony came up with a safe design [39]. The high cost of Li-ion batteries makes it unfeasible right now for energy storage applications. Recycling issues with Li-ion batteries include the cobalt the battery is composed of [39].

In sodium sulfur batteries, it has a high cycle life and energy density like its lithium ion counterpart. However, there are safety issues with NaS batteries due to the high operating conditions required. The temperature needs to be between 300°C to 350°C, so operation and maintenance costs will be more significant. Furthermore, it is highly reactive with the atmosphere, which can be dangerous, so appropriate the NaS system must be isolated from atmospheric conditions. Examples involving NaS batteries have been done by Sandia National Laboratory for a 1.2 MW project [31]. Note in Figure 2-10 the enclosure that was designed to make sure the NaS batteries are not exposed to the environment in order to maintain the necessary operating conditions. According to the California Energy Commission in May of 2011, the total installed capacity of NaS batteries amounted to 300 MW in 200 locations with the largest being 34 MW and 245 MWh [3].

Figure 2-10: Safety Enclosure for NaS Battery [31]

Nickel Cadmium batteries are low maintenance batteries but possess a low energy density [8]. According to the president of Cadex Electronics Inc., NiCd batteries are useful where long life span and price are paramount, but the components of it are toxic to the environment [8]. The Golden Valley Cooperative installed a 40 MW system in Alaska that supported 90,000 residents in -50°C temperatures, stored energy for 15 minutes, and costed $35 million [12]. At the Technical University of Ostrava, an off-grid PV/wind system used NiCd batteries to power a streetlight [27]. It was able to function in harsh condition at temperature of -23°C with a storage duration of 8 hours [27].

Vanadium redox batteries differ from the classic battery cell because "a flow battery pumps a solution of free-floating charged metal ions, dissolved in an electrolyte — substance with free-floating ions that conducts electricity — from an external tank through an electrochemical cell to convert chemical energy into electricity." [16]. This allows for nearly unlimited use since the chemical composition will not change, not require recycling, and it can be charged at the same rate it can be discharged [37]. In their experiment, 48 volt VRB discharges at 10 kW and with a storage capacity of 100 kWh [37]. While the upfront cost is higher, the reusability of VRB and flow batteries in general enable them to reduce the overall life cycle cost [37]. Figure 2-11 shows the 100 kWh system.

Figure 2-11: 100kWh Vanadium Battery System [37]

Another type of flow battery is the Zinc Bromide battery. With efficiencies of over 70% and an estimated cost of $400/kWh, the ZnBr battery can become one of the first flow batteries that will be able to compete with the lead acid battery [25]. The systems can vary between 50 kWh and 400 MWh in size and can store energy between 2 and 10 hours [25]. Projects involving ZnBr batteries include a joint project by Sandia National Laboratory and the Department of Energy that created a 400 kWh system synced with PV that could charge for 6 to 8 hours in remote locations. Also, Premier Power Corporation is creating a 50 kW system that is housed inside a 20 foot long heated enclosed space [3].

In terms of storage duration, batteries are best medium-term time spans of up to 15 minutes [3]. However, batteries can be reliable for hours or several days at the expense of a higher capital investment [3]. Other parameters that are endemic to batteries include its specific energy, cycle life, power density, discharge rate, and charge capacity. In terms of its capacity, the service life of a battery is defined as when the capacity drops to 80% of its initial capacity or it no longer works [3].

Flywheel Storage:

Using flywheels to store energy is an interesting alternative because the system can be made without harmful materials that other storage technology like batteries are. All that is required is a mass that can be turned on a shaft, and its angular kinetic energy stores the energy received from the shaft. The material chosen for a flywheel should be able to endure the centrifugal stresses caused by the high rotation rate [17]. Other parts of a system would include a generator, gearing, power electronics, and a container that protects against possible flywheel failure. The vessel itself is made out of steel and usually buried underground due to the high velocity a flywheel’s shattered pieces can travel [17]. The system works by having a motor spin the shafts in order to charge the flywheel, and it becomes a generator when the flywheel discharges. The discharge rate of flywheels for power requirements can be on the order of seconds or minutes [30].

Two equations of interest are Equation 2-1 and Equation 2-2, which are given below [17]. Both of these equations show how a flywheel's highest rotation rate and kinetic energy are a function of the material properties such as the maximum centrifugal stress the flywheel can withstand σ_{max}, radius R, density ρ, and shape factor K_m. To create a high performance flywheel that can work at as high of a stress as possible, they are reinforced with Kevlar or carbon, and its design creates a constant stress central region and high stress outer rim in order to improve its performance [17]. Storage values in these specialized flywheels can reach as high as 200 kJ/kg [17].

$$\omega max = \frac{1}{R}\left(\frac{2\sigma max}{\rho}\right)^{\frac{1}{2}} \tag{2-1}$$

$$\frac{Ekin}{mass} = \frac{\sigma max}{\rho} Km \tag{2-2}$$

Other ways of creating a better flywheel energy storage system can include using magnetic bearings for the shaft to reduce wear, and by creating a low pressure vacuumed flywheel chamber which can lower air drag that reduces its angular momentum [30]. The efficiency of these systems can be over 90% [30]. Beacon Power Corp. has created a 100 kW storage facility that uses a vacuum chamber and magnetic bearings as well as rim technology that can prevent cracks from centrifugal forces [30].

Magnetic Energy Storage:

Superconducting magnetic energy storage (SMES) is a developing technology that stores electrical energy in a magnetic field by using a superconducting coil [30]. Since superconductivity for materials is a function of its temperature, applications are cryogenically cooled to temperatures below minus 269^{o}C; the benefits of a low temperature makes the material's resistance to electric current non-existent which can enable efficiencies of up to 97% [30]. It would make sense to create magnetic technology since the energy conversion is electrical in nature and not chemical to electrical, mechanical to electrical, etc.

Figure 2-12: 200kW Magnetic Storage [30]

The sizes of the system can be upward of 10 MW but research aims to create large scale storage of up to 2000 MW [30]. The cost of the system is still preliminary since the research in this field is still in its infancy, but costs of $550/kW have been estimated [30]. The cost increases greatly by installing the necessary capability for the magnetic storage material to resist the high mechanical forces induced by large magnetic fields [17]. ACCEL is one company developing magnetic storage technology that is 200 kW in capacity [30]. A SMES plant would require worker protection from the extremely low temperatures, and a method to control and mitigate the magnetic radiation to the surrounding environment [30]. System components would include a DC power input, an inverter for AC current, and a control system [17].

Supercapacitor Storage:

Capacitors in electrical circuits store charge, and supercapacitors (also known as ultracapacitors or double-layer capacitors) create a larger electrode surface area that allows more charge to be stored [30].The advantages of supercapacitors include very quick charge and discharge rates, have an efficiency upward of 98%, and minor degradation over many life cycles. Energy densities are believed to be upward of 60 Wh/kg with over 300,000 cycles [24]. As of 2003, the cost of supercapacitors were still quite costly with a range of 35000-1200 $/kW [30]. A supercapacitor can be seen in Figure 2-13.

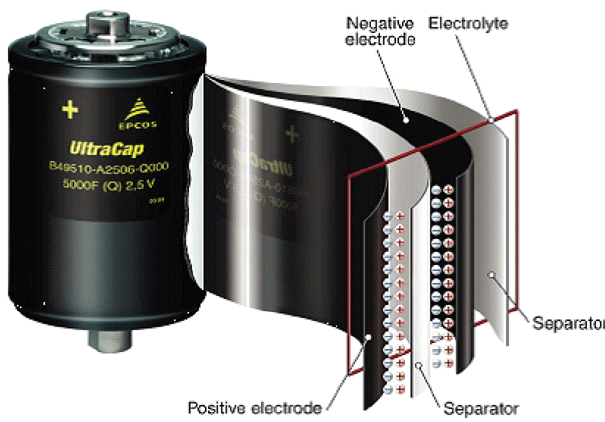

Figure 2-13: Supercapacitor Storage [30]

Supercapacitors were used in a study where they would smooth out the power fluctuations that inevitably occur as the wind changes. It was found that a correctly sized supercapacitor storage is based on its low-voltage ride through (LVRT) capability of the DC bus it reinforces [1]. Other projects included using valve-regulated lead acid batteries combined with a supercapacitor in a photovoltaic generation system [13]. Figure 2-14 shows a configuration for a PV-supercapacitor system. The supercapacitor itself is used to provide large quick bursts of energy while the lead acid battery releases it over a longer time span [13]. It was found "from the simulations performed the addition of a supercapacitor bank will increase the battery SOC for peak and pulse current loads" [13]. Numerous studies have looked into applying supercapacitors for public rail lines. One done by the University of West Bohemia investigated supercapacitors for absorbing the kinetic energy caused when a trolley brakes [32]. The energy can then be used for acceleration by either attaching the supercapacitor directly onto the vehicle or placing it at the tram line where there is an instability in trolley line voltage [32]. A rough return on investment found it to be only 2 years [32]. Projects by the Laboratory for Electromagnetic and Electronic Systems investigated the so-called ultracapacitors that use carbon nanotubes to enhance the surface area of the capacitor and allowing it to store more charge [24].

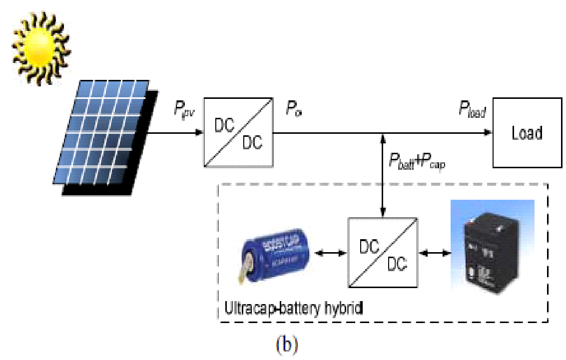

Figure 2-14: PV-Supercapacitor Schematic [13]

Hydrogen Storage:

Hydrogen will see a more pronounced role in energy generation and storage as the technology matures. Hydrogen and oxygen fuel cells can be used to generate electricity by using a catalyst or combustion with an efficiency of 60% but up to 80% if cogeneration is used with the waste heat from the fuel cell [17]. The hydrogen itself is produced through a steam reforming process with methane to remove impurities such as sulfur [17]. Furthermore, electrolysis can be performed on water by enacting a voltage between two electrodes; the hydrogen gas will form on the negative electrode while oxygen gas will be on the positive electrode [17]. Since it has the potential to be used as a fuel, energy will be able to be stored and transported in ways similar to petroleum fuels are today. High pressure tanks of 5000-10,000 psi are employed in steel or composite containers [17]. A Dynetek 5000 psi storage container is shown in Figure

2-15. Next, hydrogen can be liquefied by cooling it below 20.3K and storing it in a thermally-insulated tank, but the liquefaction can consume 30-40% of the energy content of the hydrogen [17]. Finally, hydrogen can be stored in metal hydrides by hitting the protons (H+ ions) into the interstitials of these solid electrical conductors [17]. However, an issue with use in automobiles stems from the metal hydrides' high weight, which impacts fuel economy.

Figure 2-15: High Pressure Hydrogen Tanks [14]

In a study by Griffith University in Australia, a PV array is synced with a hydrogen fuel cell system coupled with an electrolyzer. The authors believed that the technology is scalable from several hundred watts to hundreds of kW for industrial scale [10]. A schematic of the system is shown in Figure 2-16. A feature of this design is that the metal hydride stores excess PV input energy by using the electrolyser to create hydrogen from the PV current. The hydrogen storage utilized is a metal hydride system with AB_5 using a Mischmetal [10]. The hydrogen is stored in the metal hydride for use when the sun may not be shining or it is night time [10]. The study found that high energy density metal hydrides can compare or exceed the performance of Li-ion batteries owing to the lower volume requirements.

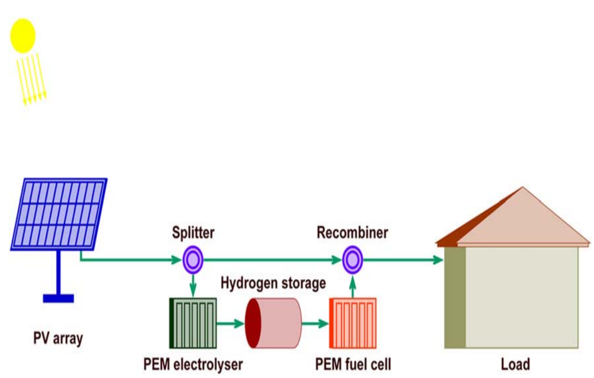

Figure 2-16: PV with Fuel Cells as Storage [10]

There are hurdles to adequate deployment of hydrogen as a fuel source for a remote renewable energy system. It was found that a standardized refilling process would be superior to merely exchanging an empty tank for a full one due to transportation and reinstallation requirements [14]. Also, the refilling procedure and equipment used should be similar across the whole spectrum of gas suppliers [14]. High pressure storage tanks need to become feasible by being more cost and code friendly while running at longer times for stationary applications [14].

Compressed Air Energy Storage:

Storing energy with air requires compression using underground mines, caverns, or even normal piping [30]. Figure 2-17 shows how wind can be stored using compressed air storage. The wind turbine uses a compressor to both cool the air and put it underground for later. Then a recuperator releases and mixed the air with natural gas followed by an ignition of the mixture in order to heat up the air. Finally, the hot air turns a gas turbine producing the needed electricity. A round trip efficiency of 60% is the norm [42]. A downside to CAES is that it usually requires suitable underground areas, but many of them are occupied by gas and coal generation facilities [30].

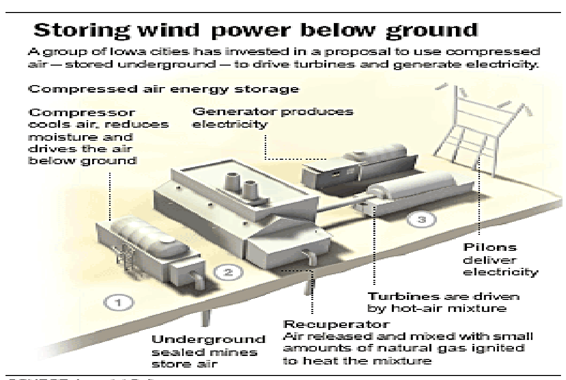

Figure 2-17: Wind-Compressed Air System [18]

As would be expected, the gas turbine setup is useful for primarily utility scale deployment, yet smaller systems under 50 MW are emerging. For these CAES systems, pipes from normal gas transmission may be used as the energy storage device [21]. This is because they are larger in diameter at 48" and can work at pressures up to 2500 psi which exceeds the requirement for regular combustion turbines [21]. The estimated cost of these type of plants is ball parked at $700-$750/kW [21]. Another estimate is $525/kWh [30].

As of 2007, there are only two operational compressed air storage plants in the world. The first was built in Hundorf, Germany with a capacity of 290MW; the other plant in Alabama costed $65 million [30]. Nonetheless, this is a mature technology and new projects such as the Iowa Stored Energy Plant will support a wind farm of 75-150MW and an adjoined CAES plant rated at 200 MW. The excess energy from the wind turbines will be used to pump the air for storage [30]. Other projects study small scale CAES for it technical characteristics [42] while another used a wind-diesel system where excess wind energy would be stored in a CAES medium in order to turbocharge a diesel generator for off-grid applications [18].

Chapter 3: Optimization Review

The overarching aim of this research project is to select the best energy storage for each application. How can the storage medium be sized such that the system's load needs are met at a reasonable cost? Ultimately, the idea will be to store the minimum amount of energy necessary to adequately power everything while making sure the cost is not absurd. The reasoning for storing only the minimum is due to the fact that the cost per kilowatt-hour is the primary concern for remote applications with end users whom may not have sufficient funding. In the case that the cost is growing too much for the specified application, a tradeoff much be made between system reliability and cost, specifically the net present value. To accomplish this, optimization must be employed in the software such that both goals are attained. Before delving into the optimization for this research, it is imperative to conduct a literature review of the available energy storage software out there along with the optimization techniques employed. This section will seek to provide the overview of this field of study. As a result, it should be noted that technical parameters such as optimizing battery discharge or other physical properties will not be considered, but the optimization of the amount of energy stored and how much it costs will be.

First, the techniques of optimization will be considered. For the energy generation system, the meteorological data is used since both solar and wind deal with intermittency issues. Some use Typical Meteorological Year data while others are based upon the worst month for solar and wind, respectively [48]. In using TMY data, the size of the PV panels and wind turbines are derived from the "yearly average monthly method" which is simply the wind speed and solar irradiance averaged by the month over a year span [34]. Protogeropoulos uses the worst month method based on the worst performance months for solar and wind separately and sizes the system accordingly to choose the single worst month for a hybrid PV-wind system. By doing this, the maximum area occupied by the panels and turbines are considered [28]. Disadvantages of this optimization techniques is that heavy computational effort is needed, and it depends on wind data that may not exist.

Graphical construction methods are frequently used to optimize a stand-alone renewable energy system. For instance, one study sought to minimize the cost of the system by considering a PV-battery setup [6]. By using a graph of cost, the point of tangency on the graph will show the relationship between the optimal number of PV arrays and batteries [6]. A downside to this approach is that it only considers a limited number of parameters used as the number of panels and batteries but not the panel slope or hub height of the wind turbine [48].

Probability methods are employed in sizing the storage of renewable systems. Since there is not a steady or predictable supply of power, probability density functions are useful to approximate the expected loads. Some use two-event probability distributions [7] while others used three-event distributions in order to match the actual energy distribution more accurately [4]. Other probability techniques include using the convolution technique, which accounts for the fluctuating nature of renewables and eliminating the need to have time-series data [40].

Iteration is another optimization technique that is utilized in evaluating off-grid energy systems. In a study by Yang, the capacities of PV panels, wind turbines, and the battery bank are optimized such that the lowest levelized cost of energy is found [44]. This is accomplished by iteratively looking at all possible configurations. Other iterative approaches included trying to make the difference between the generated power and demanded power as close to zero as possible [23]. This creates several possible combinations of solar, wind, and batteries with the lowest cost being selected as the optimal mix. By using linear programming techniques, the solutions are not perfect owing to the lack of insight into the exact best but instead relying on discrete iterations.

Finally, artificial intelligence can be undertaken to optimize an energy system with storage using Genetic Algorithms, Artificial Neural Networks, and Fuzzy Logic [48]. Genetic algorithm use stems from their ability to be suitable for non-linear systems. An artificial neural network (ANN) is a mathematical model with its roots in biology where artificial neurons are connected, and the information exchanged between them helps provide the data for optimizing the system itself [48].

A variety of software is already in existence trying to balance a system comprising of renewable energy, usually a hybrid solar-wind system, and a suitable storage. For example, HOMER (Hybrid Optimization Model for Electric Renewables) is an NREL software which uses hourly load, constraints, and environmental data to optimize the system in terms of the net present cost. The background algorithms and calculations are not available for the end user to see [48]. It has the ability to model more components such as wind turbines, hydraulic turbines, PV panels, AC & DC loads, electrolyzers, hydrogen tanks, fuel cells, and boilers [2].

The Renewable Energy Research Laboratory (RERL) at the University of Massachusetts created the HYBRID2 software whose strength is its precision. Time intervals can be done anywhere from 10 min to 1h [48]. The NREL (not RERL) recommends using HOMER to optimize the overall system and use HYBRID2 to improve the specifics [48]. Specifically, it models different wind turbines, PV panels, diesel, and battery storage coupled with power conversion devices [2]. Furthermore, it can also model things like fuel cells or electrolyzers [2].

Another software program is called HOGA, which was developed at the University of Zaragoza in Spain. A Genetic Algorithm is used that can have mono-objective or multi-objectives using 1h time intervals [48]. One can optimize systems that involve PV panels, batteries, wind turbines, hydraulic turbines, AC generator, hydrogen tank, inverter, and fuel cells [4]. The components that are considered are very similar to the ones considered in the HOMER program.

ES-Select is a tool developed by Sandia National Laboratories that has more of an energy storage focus than the other software that concentrate on the whole system. In ES-Select, the user enters in the capacity of the system, grid connection, financial parameters, and uses a Monte Carlo simulation methods in order to select the best storage for the user in terms of $/kW or $/kWh [48]. Additionally, one can choose the loading requirements over a day's period by the storage i.e. use thermal storage in the day and battery storage at night. While other programs focus on primarily batteries, ES-Select allows the user to choose from batteries (PbA, NiCd, Li-ion, ZnBr, VRB), compressed air, pumped hydro, flywheel, supercapacitors, and hot or cold thermal storage.

Solar Homes created the HYBRIDS application which determines a suitable renewable fraction and consider the economics using the net present cost. Using the daily-average load, HYBRIDS uses Microsoft Excel to evaluate one configuration at a time using a multitude of variables [48].

Chapter 4: Program Development

The overall purpose of this thesis is to produce a program that enables end-users to evaluate their energy storage needs from a renewable energy plant. In order to accomplish this objective, the algorithm for the energy storage must sync with an existing Excel-based program. The following details the basic inner workings of the current program as well as the approach taken in trying to reconcile the energy generation with the subsequent storage.

Selection of Storage Technology

First, the choice of energy storage must be made. All of the aforementioned energy storage technology could be possible choices, but there are limiting factors to most. In order to make the program accessible to many, the most wide-reaching energy storage choice will be made. Based on this, storage from super magnets, supercapacitors, hydrogen, and flow batteries are not feasible at this time due to cost and the fact they are still in development. They are not commercially-proven enough to pursue.
Others like pumped hydro and compressed air depend on the location's geography including a reservoir with adequate height change or a cavern, respectively. Flywheel storage is an interesting choice due to its quick discharge rate and environmentally friendly storage, but the capital costs associated with the expensive magnetic bearings and levitation system make it unfeasible. Furthermore, there is concern with the safety of containing flywheels with very high angular speeds. Note that comparison on energy storage technology can be found in Appendix 1 for further reader interest.

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Finally, thermal storage is useful for heating systems involving solar panels and storage with rock beds, concrete, or ice. This can take care of energy loads involving space heat and air conditioning. However, this program deals with electricity generation. While thermal storage can be potentially used to generate electricity, other technology is superior at this point in time.

Batteries are the most common way to store electricity for renewable plants, and the battery choices are many as seen before. The NaS battery requires a high operating temperature around 310-350^{o}C (Table A-3 in Appendix 3) and will not be used. Tables 4-1 and 4-2 outline the basic properties of four primary batteries: lead acid (PbA), lithium ion (Li-ion), sodium sulfur (NaS), and vanadium redox (VRB). As can be seen, the PbA battery, as an energy cell, is smaller in comparison to the Li-ion, NaS, and VRB in categories like cycle life and energy density. However, the PbA battery is a mature technology that is cheaper on the system cost than the other batteries. Furthermore, lead acid batteries are the power sources of choice for off-grid power, telecommunications equipment, and car start-up systems. For reasons of cost and technological maturity, the lead acid battery will be used to store energy from excess renewable generation.

Table 3. Battery technology characteristics (based primarily upon [10] and [11] and/or other sources as noted).

Battery type	Pb–A		Li-ion		Na–S	VRB
	Power cell	Energy cell	Power cell	Energy cell		
Cycle life (cycles @ % SOC variation)	50 to 200 @ 80% [30], 1000's for shallow cycles [31]	200 to 1800 @ 80% [13] and [30]	3000 @ 80% [13]	3000+ @ 80% [13]	4500 @ 80%, 2500 @ 100% [74]	10,000 to 12,000+ @ 100% [86] >270,000 @ few % [89]
Specific energy (Wh kg^{-1})	30 to 50 [30]	30 to 50 [30]	75 to 200 [10] and [13]	75 to 200 [13]	150 to 250	10 to 30 [86]
Specific power (W kg^{-1})	300[a]	75[a]	2400 [103]	75 to 300[a]	150 to 230 possible, commercial ~30 [74]	N/A
Energy density (Wh L^{-1})	50 to 80	50 to 80	200 to 500 [103]	200 to 500	150 to 250	16 to 33
Power density (W L^{-1})	300 to 400	10 to 100	4500 [103]	1500	N/A	N/A
E/P ratio (kWh kW^{-1})	**0.13**	**0.5**	**0.025 to 0.075**[a]	**0.27 to 0.6**[a]	**6**[74]	**1.5 to 6+** [89]
Self-discharge per day	<0.5% [13]	<0.5% [13] and [30]	0.1–0.3%	0.1–0.3%	20%[b]	Negligible

Table 4-1: Battery Comparison

Cycle efficiency	63 to 90% [13] and [104]	63 to 90% [13] and [104]	80 to 98%[a][13]	80 to 98%[a][13]	75 to 90% [13] and [104]	75 to 80%
Format	Cylindrical	Prismatic	Cylindrical	Prismatic	Tall cylindrical	Separate tanks
Active material phase	Solid	Solid	Solid	Solid	Liquid	Liquid
System level cost (US$ kWh^{-1})	200 to 600	200 to 600	600 to 1200 [13]	600 to 1200 [13]	350	150 to 1000
Maturity level	Mature	Mature	Commercial	Commercializing	Commercializing	Developed
Notable characteristic	Modular	Modular	Sealed, modular	Sealed, modular	High temperature	Flowing liquids

a Based on the authors' laboratory results from testing several different power and energy cells.

b Although heat input requirement is ~20% of battery capacity, thermal losses are mostly or entirely counteracted by internal I^2R losses and therefore little to no actual parasitic discharge is observed.

Table 4-2: Battery Comparison (continued)

User Inputs

The existing program seeks to establish the necessary generation from renewable sources such as wind, solar, and biomass. Meteorological data from the NREL allows the user to find both the solar and wind resource for their locale. The data works by taking measurements at every hour for both wind and solar, and the respective average hourly wind speeds and solar incident radiation are found in Table 4-3. By simply copy and pasting the raw data into an Excel file, the program will automatically calculate how much energy is generated by the wind turbine or solar panels per hour.

Wind Profile			Solar Profile	
Daily			Daily	
hour of day	avg. wind speed (m/s)		hour of day	avg. hourly incident radiation (Wh/m2)
midnight - 0	7.40		midnight - 0	0.00
1	7.53		1	0.00
2	7.58		2	0.00
3	7.44		3	0.00
4	7.13		4	0.00
5	7.52		5	0.00
6	7.57		6	0.00
7	7.52		7	0.00
8	7.04		8	0.00
9	7.45		9	91.00
10	7.38		10	224.50
11	7.22		11	234.00
noon-12	7.11		noon-12	415.00
13	6.99		13	441.50
14	6.77		14	309.50
15	6.65		15	189.50
16	6.76		16	180.50
17	6.85		17	47.00
18	6.84		18	0.00
19	6.88		19	0.00
20	6.96		20	0.00
21	7.01		21	0.00
22	7.07		22	0.00
23	7.19		23	0.00

Table 4-3: Wind and Solar Profiles

There is flexibility in the user-input interface to allow for modifications if their model of wind turbine or solar panel differs from the base models. This can be done because they can change the battery parameters and biomass properties.

SOLAR	
area per solar panel (m2)	1.63
module efficiency (decimal)	0.144
max power (W)	235
module price per panel ($/panel)	$294
inverter cost ($/panel)	$35
cost of installation ($/kWh)	$3,600
cost of O&M ($/kWh)	$0.009

Table 4-4: Solar Inputs

Table 4-4 shows how the solar panel model takes into account generic properties such as its area, module efficiency, and costs including panel, inverter, operation and mainteance, and installtion. In a similar manner, Table 4-5 shows the various inputs for the wind turbine that can also be freely adjusted to meet the needs of the operator. It has wind turbine properties like cut-in speed, cut-out speed, its rated power, swept area, and costs. Furthermore, there are external factors that must be accounted for like the air density and particularly the hub height. This is due to the wind shear effect where wind speed increases as you go up since fluid speed at the ground is zero due to the no-slip principle.

WIND	
air density (kg/m3)	1.225
rated wind speed (m/s)	16
rated power (MW)	0.85
hub height for wind speed data (m)	100
wind turbine height (m)	100
blade radius (m)	26
swept area (m2)	2124
Cost of Generator ($/kW)	$600
Cost of Turbine ($/m^2)	$424
Exponent for power law	0.14
cut-in wind speed (m/s)	4
cut-out wind speed (m/s)	25
Cost of Turbine $	$900,000
cost of O&M $/kWh	$0.015
wind installation ($/kW)	$340

Table 4-5: Wind Inputs

Next, the biomass is easily found knowing the costs of installing the system, the cost of fuel, and how much energy can be extracted for every pound combusted. Table 4-6 shows these in addition to the incentives, years of payment on system, and what fraction of the day the system must operate and supply power.

BIOMASS			ADDITIONAL PARAMETERS	
cost of biomass facility ($/kWh)	$1,800			
cost of biomass fuel ($/ton)	$20		minimum % of time electricity is supplied at all times(decimal)	1
fuel conversion (kWh/lb of fuel)	0.0125		incentive solar - $/kWh	$0.000
			number of years valid	10
cost of O&M ($/kWh)	$0.020		incentive wind - $/kWh	$0.000
cost of installation ($/kWh)	$35		number of years valid	10
			incentive biomass - $/kWh	$0.000
			number of years valid	10
			incentive - lump sum	$0
			years for payment	10

Table 4-6: Biomass and Incentives

Now that the generation information is known, the energy storage needs to be specified. Using the main properties of a battery, the excess energy from the wind turbine and solar panels can be stored. Note that there are things not taken into account such as depth-of-discharge because there is no knowledge of how the energy stored will be used. It can go to small electronics or large machines, all of which affect how much, how quickly, and how often power is taken from the battery bank. It is for variations such as these that it's best to treat the battery as a black box where energy comes in and energy comes out based on the "battery charge-discharge efficiency", shown in Table 4-7 Along with the usual inputs for cost and installation, the cells "Weighted Value of Excess kWh" enables the user to decide between battery bank efficiency or effectiveness. By entering a higher ratio for excess kWh, they do not there to be left over energy in the battery bank at the end of each day. After their input, the "Weighted Value of Solar Load" is simply the difference between the weighted excess kWh and one. If they place a higher emphasis on the solar load, this implies they want as many batteries as feasibly possibly to lower the load. By using more batteries to store more wind energy, less panels will be needed. Furthermore by storing excess solar energy, less biomass will be needed resulting in overall cost reductions.

ENERGY STORAGE			
Battery Charge-Discharge Efficiency	0.9		
Batttery Cost ($/battery)	20		
Battery Energy (kWh/battery)	0.351		
Weighted Value of Excess kWh	0.3	Adjust percentage of "Weighted Value of Excess kWh" (between 0 and 1)	
Weighted Value of Solar Load	0.7		
Incentives for Batteries: $/kWh	10		
Number of Years Valid	10		
Cost of O&M ($/kWh)	0.015		
Cost of Installation ($/kWh)	200		
Inverter Cost ($/battery)	1		

Table 4-7: Battery Inputs

Finally, the required load is manually entered in for each hour of the day as shown in Table 4-8. With all of this data in place, an energy assessment can be performed on the incoming energy needs, possible storage, and energy demand.

Since this thesis centers on the energy storage, a brief overview of the existing program will be done. Before the storage was added, the energy needs were evaluated using the wind turbine, solar panels, and biomass. A single wind turbine uses the average wind speed data to approximate energy produced through the wind. Then this was balanced by installing enough panels to absorb enough energy when the sun was out. This base case uses only wind and solar energy, not biomass. Consequently, it was the case that uses the maximum number of panels required to satisfy the load.

Load Profile	
Daily	
Hour of day	Avg. Req. Load (kW)
midnight - 0	120
1	120
2	120
3	120
4	140
5	150
6	320
7	440
8	300
9	310
10	360
11	300
noon-12	330
13	300
14	380
15	350
16	380
17	360
18	320
19	350
20	280
21	240
22	240
23	200

Table 4-8: User Required Load

An iterative process was then undertaken where the maximum panels case was considered the base case with 100% panels, and each iteration would use 10% less panels until there would no solar panels. In the scenario with 0% solar panels, biomass is used to supplant the load not met by the wind turbine. Each iteration would meet the inputted load with a certain combination of solar panels and biomass in combination with the wind turbine. The optimized version is based on the combination with the lowest levelized cost of energy. Then the specifics of the number of panels and pounds of biomass used are provided to the user in the "Results" sheet of the program. From this, people in off-grid or remote locations can use this program to find the best combination of renewables to power their homes for the lowest cost.

What then is the need for the storage if power needs and lowest price are found? The answer to this question lies in the excess energy generated. Since wind and solar are intermittent and the average loads they provide change, the hourly power from either source can exceed the required hourly load. This means that there is wasted energy which lowers the efficiency and potentially the cost of the entire system. It makes sense then to use batteries to capture that energy for use at a later point. That is why storage is necessary for a renewable plant. It can reduce the number of solar panels needed to satisfy the load. Furthermore, storing energy for later use will allow less biomass to be used since it is typically used at nights when there's no solar resource. As a result, the system can be sized smaller with fewer emissions due to the lower amount of biomass.

Wind Battery Bank:

Now the energy storage algorithm and its development will be discussed. The best way to describe the process is by analyzing the energy flow through the system itself. That is, energy from its generation to storage to usage will be analyzed as they occur. Since the data is on an hourly basis, the energy flows will be based on one hour intervals. Beginning with the wind turbine, Table 4-9 shows the energy produced by the wind turbine based on the average wind speed and found via. the power in the wind (Equation 4-1).

$$P_{wind} = 0.5\rho A v^3 \qquad (4\text{-}1)$$

COMBINATIONS FOR % OF LOAD			
hour	kWh Needed (User Input Load)	Turbine Produces (kWh)	Remaining kWh Needed w/Turbine
midnight - 0	120	268	-148
1	120	282	-162
2	120	288	-168
3	120	273	-153
4	140	240	-100
5	150	281	-131
6	320	287	33
7	440	282	158
8	300	230	70
9	310	273	37
10	360	266	94
11	300	249	51
noon-12	330	237	93
13	300	226	74
14	380	204	176
15	350	194	156
16	380	204	176
17	360	212	148
18	320	212	108
19	350	215	135
20	280	223	57
21	240	228	12
22	240	234	6
23	200	246	-46

Table 4-9. Wind Turbine Production

This is subtracted from the required load such that we have the first energy flow:

$$\text{RequiredLoad}(h_i) - \text{WindTurbinePower}(h_i) = \text{RemainingRequiredLoad}(h_i) \qquad (4\text{-}2)$$

The “remaining kWh needed with Turbine” is the RemainingRequiredLoad. Positive values indicate that the wind production in that hour does not sufficiently meet the required load on its own. Thus, solar panels and possibly biomass will also be needed. Negative values mean that there is an excess in wind energy generation (i.e. WindTurbinePower > RequiredLoad). This energy will be stored in the wind battery bank, shown in Table 4-10 below. Note that all of the negative values in the “remaining kWh needed with Turbine” of Table 4-9 are included in the column “Battery Storage from Excess Wind (kWh)”. The absolute values were taken since this is a positive energy into the batteries.

The “Excess Total (kWh)” of Table 4-10 is simply the sum of the excess energy produced by the wind turbine. The “Number of Batteries Needed” finds the amount of batteries that can store that amount of energy by knowing an individual battery’s energy content (kWh/battery). The “Size of Wind Battery Bank” in this iteration is equal to total excess wind energy, so this is 100% battery case is analogous to the 100% solar case for the solar panel iterations. All battery bank iterations are based on this primary case, so there is a battery bank iterated at 90%, then 80%, and so on in 10% intervals. However, a 907.569 kWh bank from 2585.6667 batteries is not realistic, so the “Actual Size of Bank (kWh)” rounds it down to the nearly units spot in order to provide an even number for the energy content of the battery bank. Then the corresponding number of batteries is denoted by “Actual Number of Batteries”.

Battery Storage from Excess Wind (kWh)	Excess Total (kWh)	
148.0460097		908
161.7820561		
168.0342045	Number of Batteries Needed	
152.7003447		2585.666755
100.1872655		
130.8014652	Size of Wind Battery Bank (kWh)	
0		907.569031
0		
0	Actual Size of Bank (kWh)	
0		900
0		
0	Actual Number of Batteries	
0		2565
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
46.01768531		

Table 4-10: Input from Wind and Battery Bank

In summary, the content of Table 4-10 sought to size a battery bank base in terms of its energy capacity and number of needed batteries, knowing the amount of excess wind energy produced. Note that each iteration possesses the same excess wind energy input, and each iteration is performed to find the combination of storage that best needs of performance and efficiency.

Actual Storage (kWh)	Load Remaining before Batteries (kWh)
133.2414087	0
278.8452592	0
430.0760433	0
567.5063535	33
624.2361446	158
583.5476061	70
513.9616215	37
477.3298707	94
382.8336701	51
331.4804339	93
238.6909039	74
164.7843546	176
0	156
0	176
0	148
0	108
0	135
0	57
0	12
0	6
0	0
0	0
0	0
41.41591678	0

Table 4-11: Wind Battery Bank Storage and Load

Referring to Table 4-11, the “Actual Storage (kWh)” column takes into account how much energy can actually be absorbed in the battery bank itself. First, there are natural inefficiencies due to resistive wires, natural discharge rates, and other second law principles that demonstrate that 100% of the excess wind energy cannot be absorbed. This each hourly excess wind energy generation is added to “Actual Storage” after being multiplied by the charge-discharge efficiency ζ, input by user to create the second energy flow, Equation 4-3:

$$\text{WindRemainingLoad} \times \zeta = \text{WindBankInput (kWh)} \tag{4-3}$$

Furthermore, energy stored in the bank from the previous hour must be accounted for, so the input energy and stored energy are summed together to find the term in the “Actual Storage” column, given by Equation 4-4.

$$\text{WindBankInput} + \text{WindEnergyStored} = \text{ActualStorage (kWh)} \tag{4-4}$$

Load Remaining before Batteries (kWh)	Adjusted Load Remaining before Solar (kWh)
0	0
0	0
0	0
33	0
158	0
70	0
37	0
94	0
51	0
93	0
74	0
176	10.78412422
156	156.2655383
176	176.4176447
148	147.9291687
108	108.4385986
135	135.3881845
57	56.96639601
12	12.09702638
6	5.91126521
0	0
0	0
0	0

Table 4-12: Load Adjusted for Wind Bank Discharge

Next, the required load by the buildings feeding off the renewable plant must be adjusted again. First, the wind turbine supplanted part of the load. This is done in Table 4-12 above. Now, the hourly excess wind energy stored in the battery bank will discharge to provide energy for other hours where there are still non-zero loads. Note that technically there is a depth of discharge associated with batteries. However, not knowing what the user will be using to power the plant, this is not accounted for in this algorithm. The “Load Remaining before Batteries (kWh)” are the positive values from the “Remaining kWh w/ Turbine” column in Table 4-9. The battery bank discharges energy to reduce the load further, given in the “Adjusted Load Before Solar (kWh)”. The logic of the this column is explained with if-else logic.

```
If RemainingRequiredLoad >0
                If (Actual Storage > RemainingRequired Load)
                        AdjustedLoadBeforeSolar = 0
                Else
                        AdjustedLoadBeforeSolar = RemainingRequiredLoad – Actual Storage
        Else
                AdjustededLoadBeforeSolar = 0
```

In words, if there is more energy in the battery bank than needed for the load, the adjusted load before the solar panels is 0. If not, the battery bank will discharge to take care of as much of the load as it can before emptying out.

Final Battery Storage before Solar Battery Bank (kWh)	Actual Final Battery Storage (kWh)
133	133.2414087
279	278.8452592
430	430.0760433
534	534.0676057
466	465.8262874
514	513.9616215
477	477.3298707
383	382.8336701
331	331.4804339
239	238.6909039
165	164.7843546
-11	0
-156	0
-176	0
-148	0
-108	0
-135	0
-57	0
-12	0
-6	0
0	0
0	0
0	0
41	41.41591678

Table 4-13: Battery Bank Storage after Load

The storage in the battery bank after each load must be re-evaluated. That is "Actual Storage" must change to account for the portion of the required load it displaced. In equation form, the "Final Battery Storage before Solar Battery Bank (kWh)" is found as follows:

$$\text{FinalWindBatteryStorage (kWh)} = \text{ActualLoad} - \text{RemainingRequiredLoad} \quad (4\text{-}5)$$

If the case RemainingLoad > Actual Load, there would be negative energy stored in the battery storage system which does not make physical sense. The actual energy stored is either the positive result of Equation 4-5 or zero if the result is negative. Thus, "Actual Final Battery Storage (kWh)" of Table 4-13 is the actual energy now stored in battery bank after both the excess wind energy input and load output for that hour have occurred. The results displayed in the "Actual Final Battery Storage" are the storage values taken as input for the battery bank for the next hour, which will then have excess wind energy added in. Then the next hourly load will be subtracted, and the process repeats itself.

Excess Energy Stored by Batteries (kWh)	Excess kWh from Wind Bank	
133.2414087		41.41591678
145.6038505		
151.2307841	Total Excess Energy Stored (kWh)	
137.4303102		816.8121279
90.16853896		
117.7213187	Percent Excess Energy Utilized	
0		90
0	Note that the greatest amount	
0	can't be 100% due to the	
0	charge-discharge efficiency.	
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
0		
41.41591678		

Table 4-14: Excess Energy Stored by Batteries

It would be useful to know how much energy is being absorbed by the battery bank every hour. This can be found by taking the difference in the bank's energy capacity before and after the excess wind energy is added. This is given by Equation ().

$$\text{ExcessEnergy}(h_i) = \text{ActualLoad}(h_i) - \text{FinalBatteryStorage}(h_{i-1}) \qquad (4\text{-}6)$$

The preceding hour's final battery storage (FinalBatteryStorage(h_{i-1})) is how much energy is stored in the bank before the next hour's excess wind energy input. The ActualLoad(h_i) is the energy in the bank after the excess wind is added in. The results are compiled in the "Excess Energy Stored by Batteries (kWh)" column of Table 4-14.

Since the battery bank will not absorb all of the excess energy provided to it, a way has been provided for the end user to be aware of how much percent of the excess energy is utilized. This is done by totaling together the results of the "Excess Energy Stored by Batteries" column, representing the excess energy stored, divided by the total excess energy generated by the wind turbine ("Battery Storage from Excess Wind" of Table 4-10). This ratio is the percent of excess energy absorbed, shown by Equation 4-7 and represented by "Percent Excess Energy Utilized" in Table 4-14

$$\text{PercentExcessEnergyStored} = (\text{Total Excess Energy Stored by Batteries} / \text{Total Excess Energy Generated}) * 100\% \quad (4\text{-}7)$$

At this point, the algorithm has analyzed the energy flows through the battery storage. As a result, we know the energy stored by the batteries stored every hour (based on the average required loads) as well as the hourly load that remains to be taken care of by the solar panels and biomass. This process is repeated for each iteration of battery banks in succession of 10% intervals. From there, the best choice must be found. Note that this will find the optimally sized battery bank for the excess wind energy, not excess solar energy. That will be considered separately.

Optimizing the right choice will be based on two parameters: efficiency and load displaced. The efficiency is taken as how much energy is stored in the bank at the end of the day. If there's excess energy left over, then there are more batteries than is needed to store energy. The energy left over after each day for each iteration is listed under the "Excess kWh" column of Table 4-15 Note that each iteration is identified by the left-hand column of the table. The load displaced is dictated by the load remaining after the wind battery bank discharges (the "Adjusted Load Remaining before Solar" column of Table 4-12). The daily total of this column is taken for each iteration and displayed in the "Total Solar Load Left Over" column of Table 4-15.

Percent Batteries Used out of Maximum	Excess kWh	Total Solar Load Left Over
100%	41.41591678	810.1979465
90%	41.41591678	643.148284
80%	41.41591678	810.1979465
70%	41.41591678	810.1979465
60%	41.41591678	894.4340911
50%	41.41591678	984.4340911
40%	41.41591678	1074.434091
30%	41.41591678	1164.434091
20%	41.41591678	1254.434091
10%	41.41591678	1372.15541

Table 4-15: Excess Energy and Remaining Load

Ideally, the system should have no excess energy at the end of the day and displace as much of the required load as possible. Therefore, the "Excess kWh" and "Total Solar Left Over" columns are ranked such that the lowest entry is ranked #1 and the highest entry ranked #10. These are denoted by "Ranking of Excess kWh" and "Ranking of Solar Load" columns of Table 4-16.

Ranking of Excess kWh	Ranking of Solar Load
1	2
1	1
1	2
1	2
1	5
1	6
1	7
1	8
1	9
1	10

Table 4-16: Rankings of Excess Energy and Load

Next, the rankings are assigned a weighted value in an inverse manner. That is, a number 1 ranking will receive 10 points, a number 2 ranking will get 9 points, and so on until the number 10 ranking which receives 1 point. Table 4-16 shows the results of the weighted values.

Weighted Value of Excess kWh	Weighted Value of Solar Load
10	9
10	10
10	9
10	9
10	6
10	5
10	4
10	3
10	2
10	1

Table 4-17: Manual Weighting of Rankings

To make it more user accessible, these weighted values will be multiplied by the ratios inputted by the user at the beginning as shown in Table 4-17. These were called the “Weighted Value of Excess kWh” and “Weighted Value of Solar Load” from Table 4-7. Therefore, if the user wants the batteries to take care of more of the load, they use a higher weight for the solar load, thereby using a higher percentage of the excess energy. The values in Table 4-17 are multiplied by these ratios to provide the value of the entries in Table 4-18 below.

User Weighted Value of Excess kWh	User Weighted Value of Solar Load
3	6.3
3	7
3	6.3
3	6.3
3	4.2
3	3.5
3	2.8
3	2.1
3	1.4
3	0.7

Table 4-18: User Weighting of Rankings

Next, these weighted values are added together by summing each iteration's entry for "User Weighted Value of Excess kWh" and "User Weighted Value of Solar Load" and the results compiled in the "Weighted Sum of Energy Loads" column of Table 4-19. The best optimized choice is the entry with the highest sum, and "Max Weighted Sum" finds this value from all of the possible choices.

Weighted Sum of Energy Loads	Max Weighted Sum
9.3	10
10	
9.3	
9.3	
7.2	
6.5	
5.8	
5.1	
4.4	
3.7	

Table 4-19: Selection of System from Weightings

Now the algorithm finds the iteration with the number of batteries that corresponds to the highest weighted sum. Table 4-20 shows how this is done. By comparing the entry in the "Max Weighted Sum" to the entries in the other column of the table, the one's that match up find the number of necessary batteries. If they don't match up, an arbitrary value of 1E+20 is used. If the entry in the "Max Weighted Sum" column matches multiple entries, then the results with the minimum number of batteries will be chosen in the "Locate Choice with Lowest # Batteries" column of Table 4-20.

Filter Battery Banks	Locate Choice with Lowest # Batteries
1E+20	2308
2308	
1E+20	
1E+20	
1E+20	
1E+20	
1E+20	
1E+20	
1E+20	
1E+20	

Table 4-20: Locate System's Battery Count

Now that the correct number of batteries for the application are found, the load for that iteration will be used for the solar panels. Using an if-else function, the "Adjusted Load Remaining Before Solar" column corresponding to the iteration with the optimized battery number is imported to the "Load to go to Solar (kWh)" column of Table 4-21. Additionally, the total excess energy stored and percentage excess energy stored for that iteration is also displayed along with the cost of the batteries.

Load to go to Solar (kWh)	Cost of System ($)
0	46160
0	
0	Total Excess Energy Stored (kWh)
0	816.8121279
0	
0	Percent Excess Energy Utilized
0	90
0	
0	Note that the greatest amount
0	can't be 100% due to the
0	charge-discharge efficiency.
0	
0	
176.4176447	
147.9291687	
108.4385986	
135.3881845	
56.96639601	
12.09702638	
5.91126521	
0	
0	
0	
0	

Table 4-21: Optimized Remaining Load and Cost

Solar Battery Bank

At this point, the energy has flowed from the wind turbine to the wind battery bank, and now there is a load that still remains to be handled by solar panels and biomass. The “Load to go to Solar” column is input as the “Remaining kWh needed w/ solar and turbine” column of Table 4-22. The formula in the column takes the difference between the remaining hourly load and the hourly solar power produced in the neighboring column. Positive values indicate that there is still a load not satisfied whereas a negative value is indicative of excess solar energy production. This energy will then be sent to the solar battery bank, and the optimized solar bank will be determined in the same manner as the wind battery bank.

	#solar panels=	5164
hour of day	solar power prod. (kWh)	Remaining kWh needed w/ solar and turbine
midnight - 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	110	-110
10	272	-272
11	284	-284
noon-12	503	-503
13	535	-359
14	375	-227
15	230	-121
16	219	-83
17	57	0
18	0	12
19	0	6
20	0	0
21	0	0
22	0	0
23	0	0

Table 4-22: Solar Panel Production

There is a main point of difference between the solar battery bank iterations an d the wind battery bank. In the plant, there is only one wind turbine, and ten iterations (the 10% intervals) were done for the wind battery bank. For the solar panels, there are ten iterations of the number of panels used and each will have ten corresponding iterations of solar battery banks. That means that 100 iterations of solar battery banks will be performed, bringing the total battery bank iterations to 101 figuring in the wind bank. In the end though, there is one optimized wind bank, and an optimized solar bank for each solar panel iterations, totaling 10 solar-battery combinations. A screenshot showing the situation is provided in Table 4-23. Each major column is optimizing the solar battery system for a specific solar panel iteration.

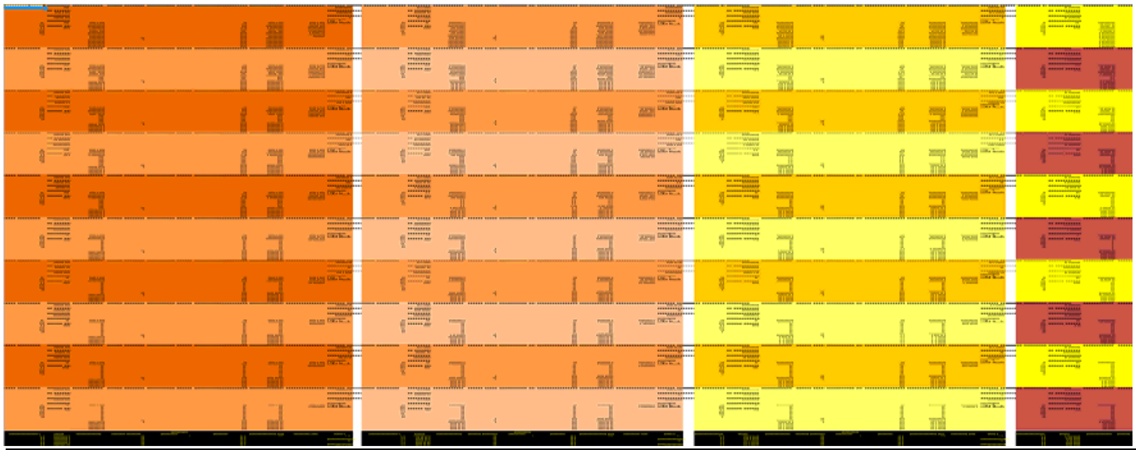


Table 4-23: Solar Bank Iterations

Biomass

Finally, after evaluating the energy storage capabilities of the solar panels, there may still be loads left over after factoring in the solar battery bank. Therefore, biomass is utilized to carry all remaining loads. The load outputted from the optimized solar bank goes to the biomass (same as the "Load to go to Solar" column of Table 4-21). In this case, it is represented as the "Load to Biomass (kWh)" column of Table 4-24. The biomass is essentially the final step in the road since the "lbs of biomass needed" entries' find how much biomass is needed to take care of the existing load. This ensures the required hourly loads for the building using the renewable plant are satisfied.

Load to Biomass (kWh)	lbs of biomass needed
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
18	1400
110	8830
85	6835
113	9079
51	4101
12	968
6	473
0	0
0	0
0	0
0	0

Table 4-24: Biomass Production

To reflect briefly, a wind turbine produced power in order to accommodate a prescribed hourly load. If excess power was generated, a wind battery bank is used to store this power. The bank will then displace more of the required load before going resorting to solar panels. Sizing the bank stems from iterations based on the number of batteries. The optimal system chosen is one that simultaneously satisfies as much of the load as possible while having minimal left over stored power at the end of the day. Solar panels and a solar bank carry more of the load. Finally, biomass will carry the remaining load to reach the required energy production. At this point, an Excel sheet was made detailing the energy summary from the calculations. Table 4-25 outlines the main points of interest in energy production: how much was made, how much of each, and did it do its job? Included is the energy production from wind, solar, and biomass ("total kWh") in addition to the "Remaining Load (kWh)" column, which sees if biomass met the final load. That is, the whole column should be zero because that would mean oil or gas will be needed to meet any non-zero loads. In addition, the right-hand column finds the contribution (in kWh) from each renewable source as well as the total remaining load, which again should be zero.

total kWh	Remaining Load (kWh)	remaining kWh/day	0.00
268.05	0.00	total biomass kWh	0
281.78	0.00	total lbs of biomass	0
288.03	0.00	total tons of biomass	0.00
272.70	0.00	total solar kWh	2585
240.19	0.00	total wind kWh	5852
280.80	0.00		
286.56	0.00		
281.59	0.00		
230.41	0.00		
383.67	0.00		
537.62	0.00		
532.28	0.00		
740.23	0.00		
761.23	0.00		
579.57	0.00		
423.43	0.00		
422.37	0.00		
269.04	0.00		
211.56	0.00		
214.61	0.00		
223.03	0.00		
227.90	0.00		
234.09	0.00		
246.02	0.00		

Table 4-25: Energy Summary

Costing Function

The system has been optimized for the necessary ratios of renewable generation and storage. There are 11 total iteration that have been done. Referring to Table__, each iteration (1-11) has the same optimized wind battery bank while each individual iteration has its own optimized solar battery bank. A costing function calculates the total cost of the system based on the number of components needed, inverters, operation and maintenance, and incentives. Furthermore, data from the energy summary sheet provides information on total eneryg production and remaining load to be met.

Options	Cost of System	Cost of System with Incentives ($)	Average Total kWh per Day	Remaining kWh/day
1-wind and max solar	$33,259,119.12	$33,073,101.12	26304.39	0.00
2-wind + 90% # of sola	$30,789,442.67	$30,479,398.67	24326.75	0.00
3-80% of # solar	$27,833,773.26	$27,562,747.26	22348.62	0.00
4 - 70% of # solar	$24,881,822.51	$24,648,806.51	20370.98	0.00
5-60% # solar	$22,182,291.00	$21,902,235.00	18392.85	0.00
6-50% # solar	$19,170,118.75	$18,948,064.75	16414.71	0.00
7-40% # solar	$16,298,547.04	$16,087,497.04	14437.08	0.00
8-30% # solar	$13,576,783.70	$13,357,753.70	12490.36	0.00
9 - 20% # sollar	$14,005,919.35	$13,864,883.35	11682.15	0.00
10 - 10% # solar	$16,646,548.92	$16,611,520.92	11575.56	0.00
11 -no solar	$19,774,092.87	$19,751,076.87	11563.18	0.00

Table 4-26: Cost Calculations

From there, the annual payment can be made based on knowledge of the number of years of payment for the loan. This is simply the total cost of the system divided by the years in the payment. The total energy production per year ("kWh/yr") is the energy production per day multiplied by 365 days in a year. The cost of energy is the annual payment divided by the "kWh per year" column. Finally, the "min COE" optimizes the system in terms of cost by selecting the system with the lowest cost of energy. Thus, the system can adequately meet the required load along with providing the iteration that is the most cost effective. All of these results are displayed in Table 4-27.

Annual Payment	kWh/Yr	COE ($/kWh)	min COE	0.29
$3,307,310.11	9601102.123	0.34447		
$3,047,939.87	8879265.304	0.34326		
$2,756,274.73	8157245.788	0.33789		
$2,464,880.65	7435408.969	0.33151		
$2,190,223.50	6713389.453	0.32625		
$1,894,806.47	5991369.937	0.31626		
$1,608,749.70	5269533.118	0.30529		
$1,335,775.37	4558979.946	0.29300		
$1,386,488.34	4263983.663	0.32516		
$1,661,152.09	4225078.414	0.39316		
$1,975,107.69	4220559.537	0.46797		

Table 4-27: Cost Optimization

Program Output

Now that the system has been chosen, the user can be informed of the results through a separate worksheet in the program. Essentially, the program works as a black box where they add their inputs on one sheet and see their results on the other. All of the other sheets are the background calculations, and the storage aspect has been developed as part of this research. The results that the user sees is displayed below in Table 4-28. It informs them of the number of batteries needed for storage, the expected energy that will be stored in the battery bank, and the percentage of excess energy utilized. By knowing these, the end user can know how much they will need for both the wind turbine and solar panels. If they are dissatisfied with the number of batteries or amount of energy stored, they can change the inputs parameters from Table 4-7 to change preference to amount of the load carried by batteries (which will increase the number of batteries used and percent energy utilized. Or, they can give preference to the efficiency of the battery bank, which will lower the number used. However, they shift their results though, the overall program algorithm ensures that their load will still be met for the lowest reasonable cost, even if the number of batteries changes. Ultimately, the end user has a trade-off between price tag and effectiveness, and this program allows them to change their inputs for numerous possible results.

Wind Battery Bank:	
Number of Batteries for Wind Battery Bank	2308
Total Excess Energy Stored from Wind Turbine (kWh)	817
Percent of Excess Energy Utilized for Wind Bank	90
Solar Battery Bank:	
Number of Batteries for Solar Battery Bank	684
Total Excess Energy Stored from Solar Panels (kWh)	240
Percent of Excess Energy Utilized for Solar Bank	68

Table 4-28: Battery Summary

Finally, it would be useful for anyone using this program to know how much energy the batteries are storing as a percentage of the total required load. Table 4-28 shows the percent of excess energy utilized but not the percent of the load achieved by battery storage. Thus, Table 4-29 was implemented.

% of Load Stored by Batteries	18.5
% of Load met by Wind	27.7
% of Load met by Solar	37.2
% met by Biomass	16.5
Total %:	100

Table 4-29: Percent of Load by Source

The percentages were figured based on the conservation of energy from the starting load all through the turbine, the battery banks, the solar panels, and biomass. The portion of the energy pie achieved by each technology is the difference between the load before and after. Mathematically, this can be represented by Equations 4-8 through 4-12. As indicated in the table, the total percentage will sum to 100%, satisfying conservation of energy.

LoadBeforeTurbine – LoadAfterTurbine = Energy provided by Wind Turbine (4-8)

LoadAfterTurbine – LoadAfterWindBank = Energy provided by Wind Bank (4-9)

LoadAfterWindBank – LoadAfterSolar = Energy provided by Solar Panels (4-10)

LoadAfterSolar – LoadAfterSolarBank = Energy provided by Solar Bank (4-11)

LoadBeforeSolarBank – LoadAfterBiomass = Energy provided by Biomass (4-12)

Note that the energy is not generated by the batteries, but instead they store excess energy for use at a later time. Knowing the energy provided by each, the percentage is simply the ratio of each individual energy contribution to the total required load. Figure 4-1 is provided to the user, so they can see the relative percentages in graphical form.

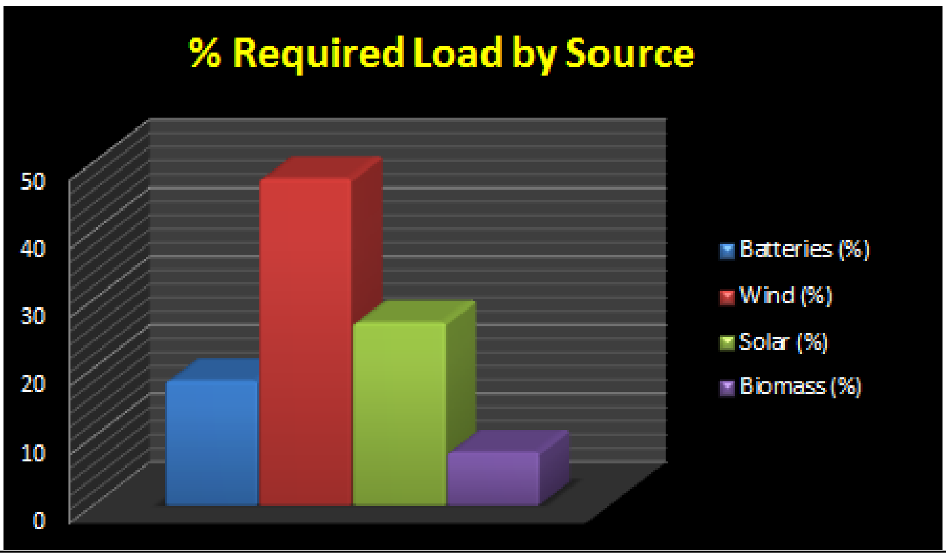


Figure 4-1: Bar Graph of Load Percentages by all Sources

Using graphics makes it easier for the user to compare different parts of the system in an easier manner than reading numbers. So a pie chart was created for the total costs of biomass, solar, wind, and batteries, seen in Figure 4-2. The costing of both includes operation and maintenance, installation, inverter, technology costs, and incentives.

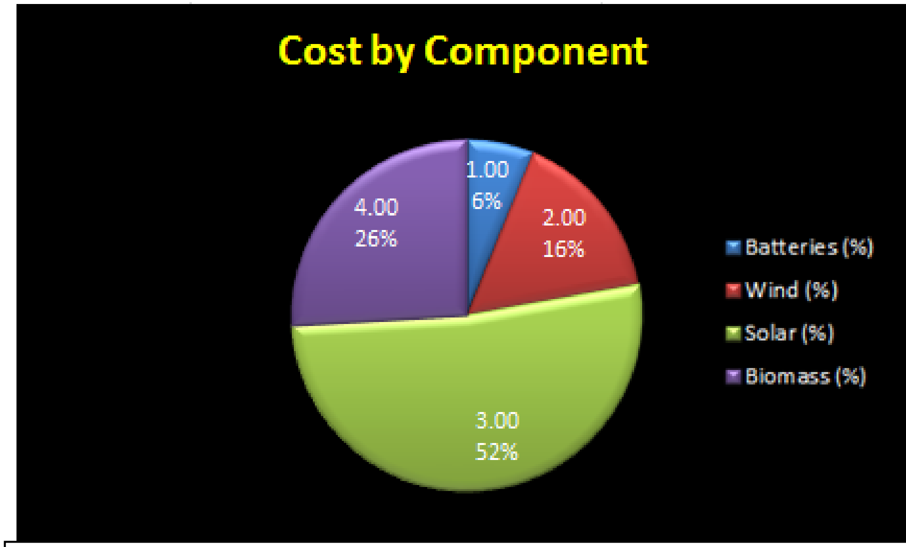


Figure 4-2: Pie Chart of Relative System Costs

Chapter 5: Results

Since the physical basis of the program's algorithm was based on energy flows, it must be ensured that the required load is always taken care of. Also, we must know the relative contributions of each. As a result, different trials were run to verify its operation. A generic load profile that has the inputs of Table 5-1 is used. The battery used is a UPG 45976 sealed lead acid battery. It has an energy capacity of 0.420kWh.

kWh Needed (User Input Load)
120
120
120
120
140
150
320
440
300
310
360
300
330
300
380
350
380
360
320
350
280
240
240
200

Table 5-1: Base Load Profile

The storage results displayed the following in Table 5.2:

Wind Battery Bank:		**% of Load Stored by Batteries**	
Number of Batteries for Wind Battery Bank	1929		22.7
Total Excess Energy Stored from Wind Turbine (kWh)	817	**% of Load met by Wind**	
Percent of Excess Energy Utilized for Wind Bank	90		75.7
Solar Battery Bank:			
Number of Batteries for Solar Battery Bank	1405	**% of Load met by Solar**	
Total Excess Energy Stored from Solar Panels (kWh)	540		1.1
Percent of Excess Energy Utilized for Solar Bank	90		
		% of Load met by Biomass	
			0.5
		Total %:	
			100

Table 5-2: Storage Results for Base Case

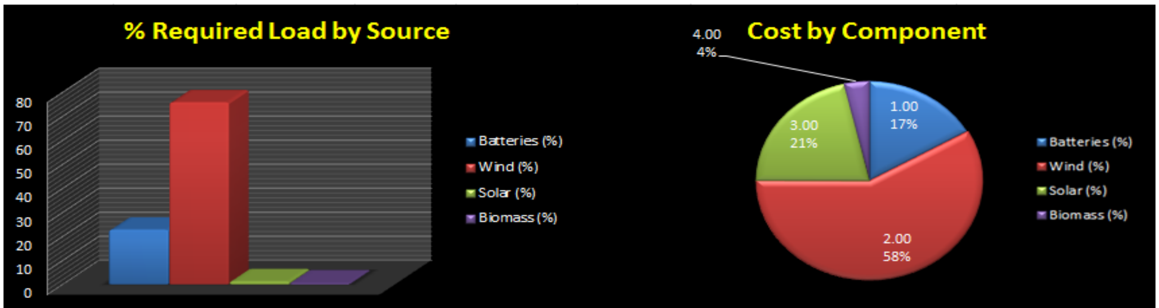


Figure 5-1: Results for Base Case

A check was done to see how the program would respond to odd inputs. All of the hourly loads in Table 5-1 were multiplied by 2.3167, and the following results were found in Figure 5-2. Using an odd decimal is done to see if the numbers of the program work out such that the total percentage of energy contribution is 100%, and it does work as expected. Table 5-3 shows that the right-hand column does indeed sum to unity, and Figure 5-2 shows the costs of the system.

Wind Battery Bank:		**% of Load Stored by Batteries**	
Number of Batteries for Wind Battery Bank	24		18.2
Total Excess Energy Stored from Wind Turbine (kWh)	12	**% of Load met by Wind**	
Percent of Excess Energy Utilized for Wind Bank	90		38.6
Solar Battery Bank:			
Number of Batteries for Solar Battery Bank	6548	**% of Load met by Solar**	
Total Excess Energy Stored from Solar Panels (kWh)	2750		29.9
Percent of Excess Energy Utilized for Solar Bank	70		
		% of Load met by Biomass	
			13.3
		Total %:	
			100

Table 5-3: Storage Results with Odd Input

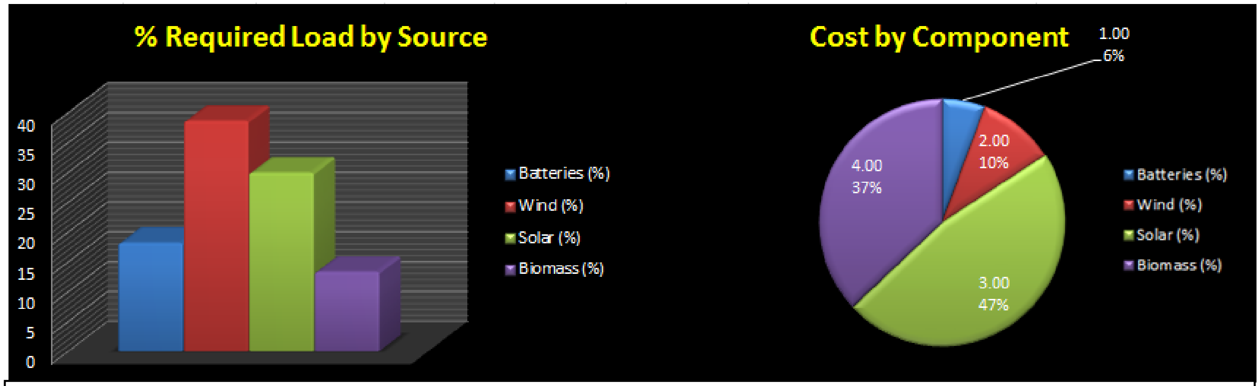


Figure 5-2: Results of Case with Odd Input

Next, if all of the inputs of Table 5-1 were cut in half, the wind turbine can fulfill all energy requirements, which is confirmed with Table 5-4 and Figure 5-3, which shows nearly 100% contribution from wind energy alone.

Wind Battery Bank:		**% of Load Stored by Batteries**	
Number of Batteries for Wind Battery Bank	596		0.0
Total Excess Energy Stored from Wind Turbine (kWh)	250	**% of Load met by Wind**	
Percent of Excess Energy Utilized for Wind Bank	9.663796992		100.0
Solar Battery Bank:			
Number of Batteries for Solar Battery Bank	0	**% of Load met by Solar**	
Total Excess Energy Stored from Solar Panels (kWh)	0		0.0
Percent of Excess Energy Utilized for Solar Bank	0		
		% of Load met by Biomass	
			0.0
		Total %:	
			100

Table 5-4: Storage Results with 0.5 Factor

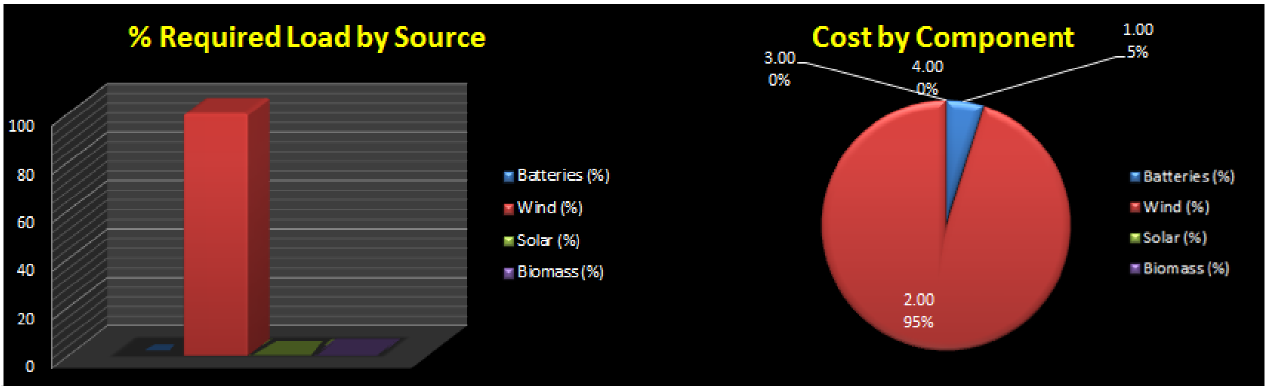


Figure 5-3: Results for Case with 0.5 Factor

Finally, the other end was checked by multiplying the inputs by one million each. Obviously, such a load profile is unrealistic, but this checks the validity of the algorithm at various values. Table 5-6 displays the results of these large input loads.

Wind Battery Bank:		**% of Load Stored by Batteries**	
Number of Batteries for Wind Battery Bank	0		25.0
Total Excess Energy Stored from Wind Turbine (kWh)	0	**% of Load met by Wind**	
Percent of Excess Energy Utilized for Wind Bank	0		0.0
Solar Battery Bank:			
Number of Batteries for Solar Battery Bank	6316207120	**% of Load met by Solar**	
Total Excess Energy Stored from Solar Panels (kWh)	2652806990		47.0
Percent of Excess Energy Utilized for Solar Bank	20		
		% of Load met by Biomass	
			28.0
		Total %:	
			100

Table 5-6: Storage Results with Large Load

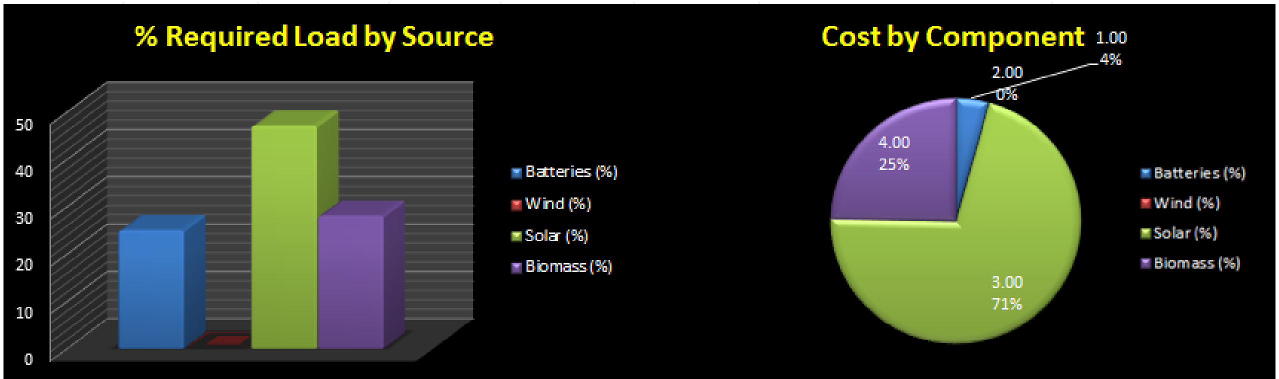


Figure 5-4: Results for Case with 1 Million Factor

As would be expected, Figure 5-4 shows how the solar panels generate the majority of the energy generation while the single wind turbine, which provides the same energy as the other trials, is sensibly a small fraction. Furthermore, the battery storage from excess wind energy is 0%, which is accurate since all of the wind production is used for the load. Also, for higher input loads, the energy supplied by batteries rose to 25%. Now, the percentage supplied by batteries can fluctuate since it depends on the locale where the hybrid plant is installed. With more solar insolation or higher wind speeds, more energy can be stored in the batteries and thus less panels or biomass will be needed. So, these trial runs of the program are not indicative of boundaries since the user inputs determine the results.

On an additional note, the battery banks tended to store energy during two periods: the early hours past midnight and the mid-afternoon hours. Since wind output over a day is continuous on average, the wind battery bank stored energy when there were low load requirements in that hour, which is typically past midnight. The wind bank's energy was discharged for loads in the morning that are due to people getting up and going about their day. For the solar battery bank, it was charged during peak sun hours, from 10AM-4PM. Then after the sunset, the solar batteries would discharge for energy requirements in the night hours before bed. Between the wind turbine, solar panels, and batteries, there is enough energy being generated or discharged to satisfy loads for all hours of the day. That means that biomass is used for hours where there are unusually high loads, including the early morning or evening hours.

Based on these trials runs, the program has been confirmed to operate correctly since any inconsistency would have created a total percentage that would not equal 100%. This did not occur in any trial, and also the remaining load was always zero. As a result, the end user can receive an approximation of their energy generation and storage capabilities based on the average loads.

Chapter 6: Limitations and Further Development

Program Limitations

The primary limitation in this program is optimizing in terms of discrete iterations. Since the capacity of the each battery bank iteration depends on the highest possible energy capacity, there will be 10 discrete battery system capacities. As a result, the optimal system in this program is a choice of one of these. However, that is only ball parking the battery bank with the ideal energy capacity. This would involve iterations that use permutations about each possibility and then "jog" in the direction of either permutation until the optimal capacity is found.

The storage itself is based on the energy per battery, the input excess energy, and the "charge-discharge efficiency". In this program, this efficiency was used as a blanket variable for all possible battery inefficiencies, but it does not take into account the specifics such as natural discharge rate. Next, the operating properties, like state of charge and voltage, change with age of the battery. This aspect is not accounted for. Additionally, since we do not know the electronics or buildings hooked up to the renewable plant, we cannot know the depth of discharge which is dependent on how much power an electronic needs in a certain span of time.

The ranking systems are based on the each battery system iteration's excess kWh and remaining solar load. In the scenario where multiple iterations, say 7 are tied at. That means that the number 2 in the system is ranked at number 8 which lowers its relative rankings since a 2 would usually get 9 points.

Further Development:

As mentioned before, the discrete iterations are best rectified by using some initial value based on the excess energy generation and then using permutations to jog to the ideal battery bank energy capacity. The permutations would check and optimize the percent excess utilized in addition to the load covered by the battery bank. The user inputs can still be used to weigh each category relative to the other, so if the user prefers efficiency they weighh the amount of energy stored more heavily.

The battery storage itself can be refined to include specific properties instead of the blanket variable charge-discharge efficiency. That way, the battery performance can be more accurately judged. Also, battery degradation and decrease in performance should be factored in.

The average loads inputted can be specified by declaring what types of devices they use, how much energy is needed, and how fast. Average loads are useful for knowing how much energy to generate, but it is not useful in evaluating battery storage performance. By inputting each device that needs power, the battery bank can factor in its depth of discharge because if too much power is demanded in too short of a time span, the battery will not work. However, this program assumes the battery bank can empty out entirely.

Finally, a function can be developed where the user can declare how much percent of the excess energy they want stored by the batteries. If they declare 100%, more batteries will be used but there can be potential cost savings since less solar panels are used. Right now, the program’s weighting functions can be used to change the excess energy percentage stored, but there is no way to directly work with it.

Chapter 7: Conclusion

There is a plethora of regions with no access to energy due to the lack of existence of an electrical grid. Because of this, renewable sources such as solar and wind can be used on site to create power. The purpose of this research was to develop an algorithm that would calculate energy storage needs using valve-sealed lead acid batteries. Energy storage is useful because it allows a way to overcome the intermittency of the wind and sunshine and use extra generation to supplant the load. This can result in cost savings since battery systems are cheaper than wind turbines and solar panels. For the program, a user inputs wind and solar data, renewable technology data, financial information, and required load data on a spreadsheet. The background calculations find the energy generated by each source as well as the amount of energy stored in the batteries from excess wind and solar energy. An optimization algorithm for the battery bank based on discrete iterations, a rankings system, and weighting functions finds the system that best meets the needs of the end user. Further optimization in terms of the system's cost find the cheapest solution to their energy needs. In the end, a program has been developed that allows people from all walks of life to evaluate the potential of a renewable energy system, creating a threshold from which everyone can increase the overall quality of their living conditions with clean energy.

Appendix A

Comparison of Energy Storage Technology

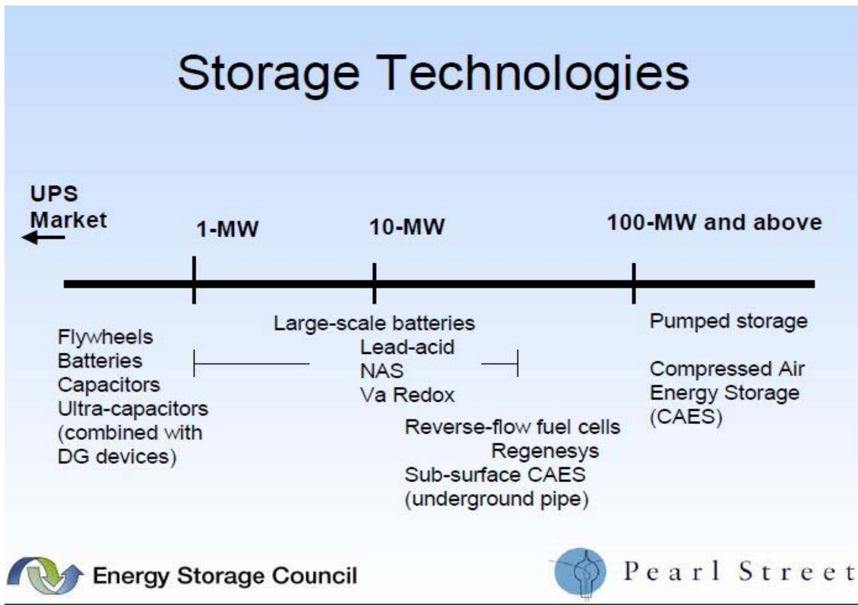


Figure A-1: Scale of Energy Storage Technology

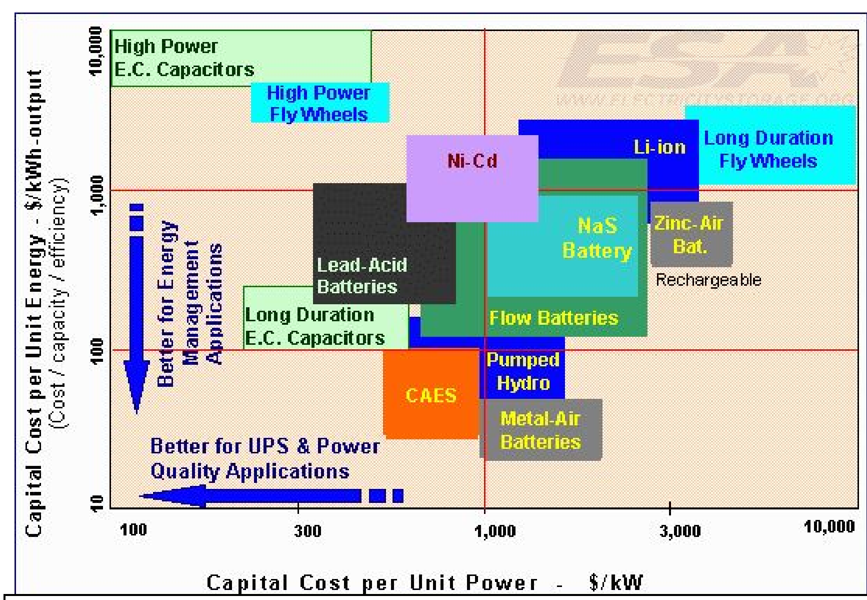


Figure A-2: Cost per Energy vs. Cost per Power

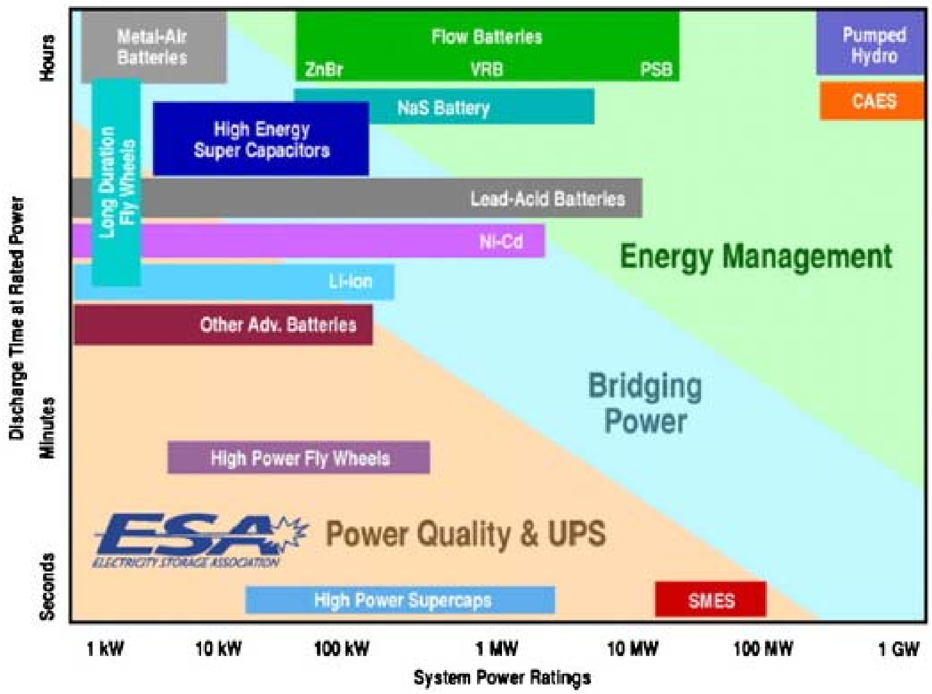


Figure A-3: Energy Storage Discharge by System Ratings

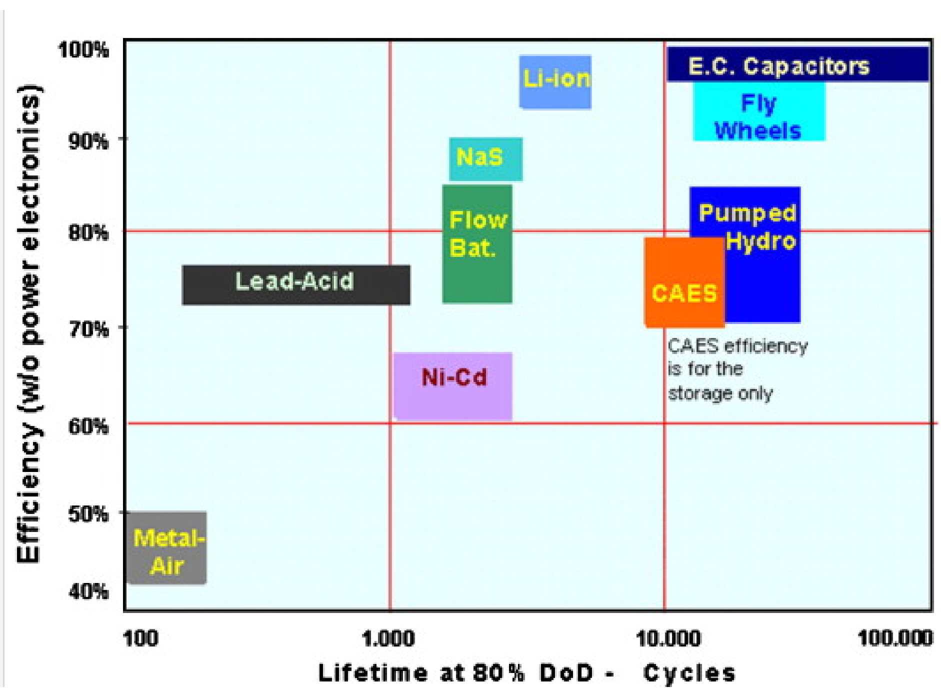


Figure A-4: Storage Efficiencies by Discharge Cycles

Table 3. Battery technology characteristics (based primarily upon [10] and [11] and/or other sources as noted).

Battery type	Pb–A		Li-ion		Na–S	VRB
	Power cell	Energy cell	Power cell	Energy cell		
Cycle life (cycles @ % SOC variation)	50 to 200 @ 80% [30], 1000's for shallow cycles [31]	200 to 1800 @ 80% [13] and [30]	3000 @ 80% [13]	3000+ @ 80% [13]	4500 @ 80%, 2500 @ 100% [74]	10,000 to 12,000+ @ 100% [86] >270,000 @ few % [89]
Specific energy (Wh kg^{-1})	30 to 50 [30]	30 to 50 [30]	75 to 200 [10] and [13]	75 to 200 [13]	150 to 250	10 to 30 [86]
Specific power (W kg^{-1})	300[a]	75[a]	2400 [103]	75 to 300[a]	150 to 230 possible, commercial ~30 [74]	N/A
Energy density (Wh L^{-1})	50 to 80	50 to 80	200 to 500 [103]	200 to 500	150 to 250	16 to 33
Power density (W L^{-1})	300 to 400	10 to 100	4500 [103]	1500	N/A	N/A
E/*P* ratio (kWh kW^{-1})	**0.13**	**0.5**	**0.025 to 0.075**[a]	**0.27 to 0.6**[a]	**6**[74]	**1.5 to 6+** [89]
Self-discharge per day	<0.5% [13]	<0.5% [13] and [30]	0.1–0.3%	0.1–0.3%	20%[b]	Negligible
Cycle efficiency	63 to 90% [13] and [104]	63 to 90% [13] and [104]	80 to 98%[a][13]	80 to 98%[a][13]	75 to 90% [13] and [104]	75 to 80%
Format	Cylindrical	Prismatic	Cylindrical	Prismatic	Tall cylindrical	Separate tanks
Active material phase	Solid	Solid	Solid	Solid	Liquid	Liquid
System level cost (US$ kWh^{-1})	200 to 600	200 to 600	600 to 1200 [13]	600 to 1200 [13]	350	150 to 1000
Maturity level	Mature	Mature	Commercial	Commercializing	Commercializing	Developed
Notable characteristic	Modular	Modular	Sealed, modular	Sealed, modular	High temperature	Flowing liquids

a Based on the authors' laboratory results from testing several different power and energy cells.

b Although heat input requirement is ~20% of battery capacity, thermal losses are mostly or entirely counteracted by internal I^2R losses and therefore little to no actual parasitic discharge is observed.

Table A-1: Comparison of Battery Technology

Components	η_i	α_5
1 PV (mc-Si)	0.12–0.13	
2 Charge regulator	0.90–0.95	
3 Batteries[a]		
Li-ion	0.85–0.95	
NaS[b]	0.75–0.83	
PbA	0.70–0.84	
NiCd	0.65–0.85	
NiMH	0.65–0.85	
VRB[c]	0.60–0.80	
ZnBr[d]	0.60–0.73	
PSB[d]	0.60–0.65	
4 Inverter	0.92–0.94	
5 Air conditioning		3

Table A-2: Efficiency of Batteries

Table 4. Ambient temperatures for battery operation and factors for temperature corrected battery service life

Technology	Temperature (°C)	$\sigma_{30\,°C}$	$\sigma_{35\,°C}$	$\sigma_{40\,°C}$	$\sigma_{45\,°C}$	$\sigma_{50\,°C}$
Li-ion	−20 to 50	0.72	0.55	0.40	0.30	0.23
NaS[a]	−40 to 50	1.0	1.0	1.0	1.0	1.0
NiCd	−50 to 50	0.90	0.80	0.73	0.65	0.57
NiMH	0 to 40	0.85	0.75	0.65	0.52	0.35
PbA	−30 to 40	0.69	0.51	0.37	0.25	0.14
PSB	−40 to 50[b]	1.0	1.0	1.0	1.0	1.0
VRB	15 to 40[c]	1.0	1.0	1.0	N/A	N/A
ZnBr	10 to 40[c]	1.0	1.0	1.0	N/A	N/A

Sources: [12], [23], [30], [31] and [32]; Note: σ = temperature correction factor. Change in service life relative 25 °C for battery cycle life and float service life. N/A = not applicable.

a The battery operating temperature is 310–350 °C for the NaS battery.

b Heat generated in the battery prevent the electrolytes from freezing.

c Optimal operating temperature is 25–30 °C. Heat exchanger has to be operated at T> 30 °C.

Table A-3: Operating Temperatures of Batteries

Appendix B

Battery Specifications

UPG STAY POWERED®

Sealed Lead-Acid Battery

UPG No. 45976

UB12350

Maintenance-Free

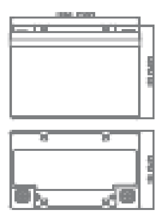
Absorbant Glass Mat (AGM) technology for superior performance. Valve regulated, spill proof construction allows safe operation in any position. Approved for transport by air. D.O.T., I.A.T.A., F.A.A. and C.A.B. certified. U.L.® recognized under file number MH 20567.

Specification

Nominal Voltage			12 volts
Nominal Capacity			77° F (25° C)
20-hr. (1.75A)			35.00 Ah
10-hr. (3.26A)			32.55 Ah
5-hr. (5.95A)			29.75 Ah
1-hr. (21.00A)			21.00 Ah
Approximate Weight			23.2 lbs (10.5 kgs)
Internal Resistance (approx.)			10mΩ
Shelf Life (% of normal capacity at 77° F (25° C))			
3 Months	6 Months	12 Months	
91%	82%	64%	
Temperature Dependancy of Capacity			(20 hour rate)
104° F	77° F	32° F	5° F
102%	100%	85%	65%

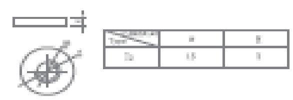
Charge Method (Constant Voltage)	
Cycle Use (Repeating Use)	
Initial Current	12.25 A or smaller
Control Voltage	14.5 - 14.9 V
Float Use	
Control Voltage	13.6 - 13.8 V

Physical Dimensions: in (mm)



L: 7.70 in (195.5 mm)
W: 5.12 in (130 mm)
H: 6.26 in (159 mm)
TH: 6.26 in (159 mm)
Tolerances are +/- 0.04 in. (+/- 1mm) and +/- 0.08 in. (+/- 2mm) for height dimensions. All data subject to change without notice.

Terminals



Constant Current Discharge Characteristics Unit:A (25°C, 77°F)

F.V/Time	5MIN	10MIN	15MIN	30MIN	1HR	2HR	3HR	4HR	5HR	8HR	10HR	20HR
9.60V	122.0	89.0	63.0	38.0	19.8	12.0	8.5	6.6	5.4	3.8	3.5	1.9
10.20V	108.0	81.0	56.0	36.0	18.6	11.0	8.3	6.4	5.3	3.8	3.4	1.8
10.50V	104.0	77.0	53.0	35.0	18.0	10.8	8.1	6.3	5.3	3.7	3.3	1.8
10.80V	100.0	73.0	50.0	34.0	17.0	10.5	7.9	6.2	5.1	3.6	3.3	1.8
11.10V	96.0	69.0	46.0	33.0	17.0	10.2	7.6	6.0	5.0	3.5	3.1	1.7

Constant Power Discharge Characteristics Unit:W (25°C, 77°F)

F.V/Time	5MIN	10MIN	15MIN	30MIN	1HR	2HR	3HR	4HR	5HR	8HR	10HR	20HR
9.60V	1297.0	946.0	666.0	403.0	229.0	134.0	98.0	76.0	63.0	44.0	40.0	21.7
10.20V	1194.0	901.0	623.0	399.0	216.0	128.0	96.0	75.0	62.0	43.0	39.0	21.1
10.50V	1175.0	876.0	599.0	397.0	209.0	125.0	93.0	73.0	61.0	43.0	39.0	20.9
10.80V	1160.0	853.0	576.0	396.0	203.0	122.0	91.0	72.0	60.0	42.0	38.0	20.7
11.10V	1139.0	825.0	550.0	393.0	200.0	122.0	90.0	71.0	60.0	42.0	37.0	20.1

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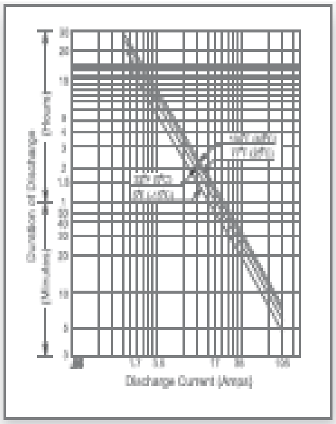
UPG No. 45976

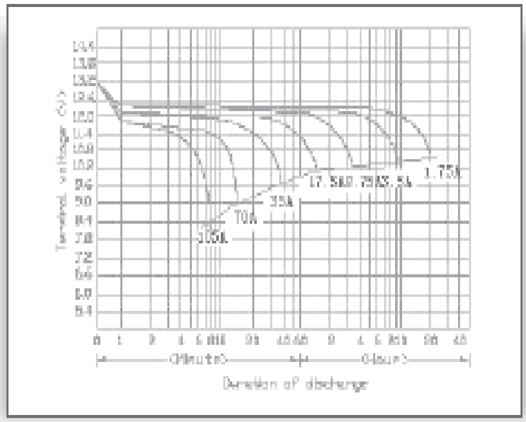
UB12350

Maintenance-Free

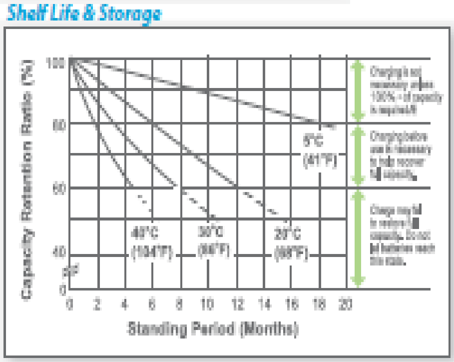
Discharge Time vs. Discharge Current



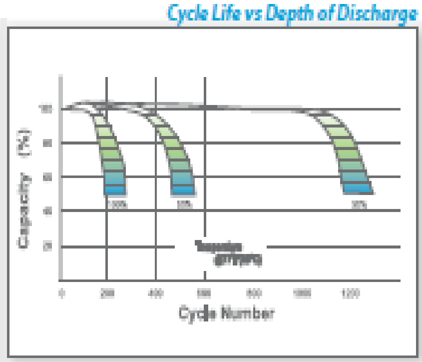
Discharge Characteristics



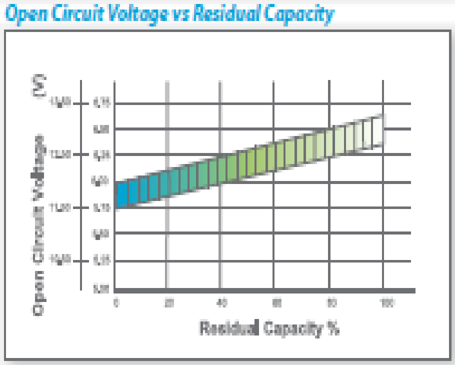
Shelf Life & Storage



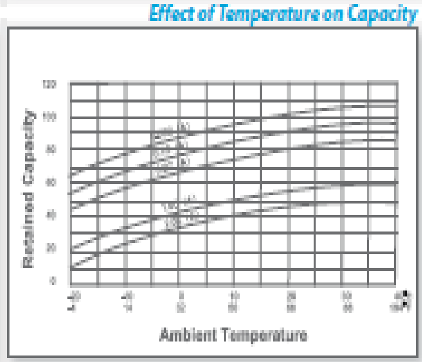
Cycle Life vs Depth of Discharge



Open Circuit Voltage vs Residual Capacity



Effect of Temperature on Capacity



Charge Current & Final Discharge Voltage

Application	Charge Voltage(V/Cell)			Max.Charge Current
	Temperature	Set Point	Allowable Range	
Cycle Use	25°C (77°F)	2.45	2.40~2.50	0.35C
Standby	25°C (77°F)	2.325	2.30~2.35	

Final Discharge Voltage V/Cell	1.75	1.70	1.60	1.30
Discharge Current(A)	0.2C>(A)	0.2C<(A)<0.5C	0.5C<(A)<1.0C	(A)>1.0C

Appendix C

User Manual

Introduction:

The purpose of this program is to help people evaluate their energy needs if they wish to set up a renewable system. This software can be used by anyone wishing to do this, but this tool was particularly made for remote hybrid plants. Using wind, solar, and biomass, the hybrid plant produces energy and stores excess in batteries. After the user inputs their daily hourly loads, this program will calculate how much of the load is taken care of by wind, solar, biomass, and batteries. It uses an optimization process to find the best sizing of each type that is also the lowest in cost. A summary of the cost of each part of the system as well as total plant cost can be found on the "Results" worksheet. The following details how to operate the program.

Wind Data (for U.S. Locations):

1) **Go to http://www.nrel.gov/electricity/transmission/wind_integration_dataset.html**
2) Select "Eastern/Wind Dataset" or "Western Wind Dataset" depending upon your location
3) Select "Obtain the Eastern Wind Dataset" in the gray box on the next page.
4) Click the link "data use disclaimer agreement" in the gray box entitled "How to Download and Unzip the Data".
5) Read agreement, select "I agree", and hit Submit. The directory that opens contains the Excel files with numerous site numbers.
6) You will need a site number, so enter this directly into the URL bar: ftp://ftp2.nrel.gov/pub/ewits/TimeSeries/LandBased/EWITS_site_info.xlsx

7) Open the document from the link. Knowing your latitudinal and longitudinal coordinates, you can find you site number.

8) Download the zip file from the directory that contains the site number you have. Locate your site's data.

9) Copy and paste the data directly into the program on the sheet called "WindData", pasting in the upper left corner.

10) Copy and paste the resulting average wind speeds on that sheet into the "Inputs" sheet under "Wind Profile"

Solar Data (for U.S. Locations)

1) Go to NSRDB http://rredc.nrel.gov/solar/old_data/nsrdb/

2) Select "National Solar Radiation Database 1991-2010 Update"

3) Select the link for "1991-2010 Update"

4) Scroll down to "Data" and select "NSRDB solar & filled meterological fields"

5) Select your state by letter, and find the corresponding site number for you location.

6) Use a zip file program to download and unzip the file

7) Select the sheet with your site's data and copy and paste it to the "SolarData" sheet in the program in the upper left corner of the sheet

8) Copy and paste the average solar data into the "Inputs" sheet under "Solar Profile"

Components

The wind turbine, solar panel, and battery models along with the biofuel of choice will change the inputs. The following is an example of how to find a wind turbine, solar panel, and biomass.

Example:

1) Go to sharp model spec sheet for desired model

2) http://www.sharpusa.com/SolarElectricity/SolarProducts/ResidentialSolarProducts.aspx

3) Get area, max power, efficiency

4) Get price from somewhere…example

5) http://www.ecobusinesslinks.com/solar_panels.htm

6) For inverter simply search for an inverter that is a reasonable number of Watts, note price (i.e. consider your needs)

7) Wind turbine cost in our program is measured as $/m2

8) Prices are often in $/kW in reports etc. simply multiply the rated power times the $/kW to get an idea of the total price for the wind turbine. Get the spec sheet for the desired turbine, divide by the swept area

9) http://eetd.lbl.gov/ea/ems/reports/lbnl-5119e.pdf to see price trends over time

10) Get specs for wind turbine, including blade radius, cut-in and cut-out speed, rated power

11) http://www.vestas.com/en/wind-power-plants/procurement/turbine-overview/v112-3.0-mw.aspx#/vestas-univers

12) Biomass costs – specific to each system - example

13) http://www.fpl.fs.fed.us/documnts/techline/biomass-for-small-scale-heat-and-power.pdf

Wind Inputs:

Go to the Inputs sheet of the program and enter the following information in the appropriate cells. The cost information can be found from a contractor quote.

a. Rated Wind Speed [found on turbine spec sheet]

b. Rated Power [found on turbine spec sheet]

c. Hub Height for Wind Data [found in data sheet]

d. Wind Turbine Height (m) [found on turbine spec sheet]

e. Blade Radius (m) [found on turbine spec sheet]

f. Swept Area (m^2) [found on turbine spec sheet]

g. Cost of Generator ($)

h. Cost of Turbine ($)

i. Cut-in Wind Speed (m/s) [found on turbine spec sheet]

j. Cut-out Wind Speed (m/s) [found on turbine spec sheet]

k. Cost of Turbine ($)

l. Cost of Operation and Maintenance ($)
m. Wind Installation Cost ($)

Solar Inputs

Go to the Inputs sheet of the program, and enter the following for the solar inputs. The cost information can be found by a quote from a renewable contractor.

a. Area per Solar Panel (m^2)
b. Module Efficiency
c. Module Price per Panel ($/panel)
d. Inverter Cost (S/panel)
e. Cost of Installation ($/kWh)
f. Cost of Operation and Maintenace ($/kWh)

Biomass Inputs

The following parameters will also be entered on the Inputs sheet of the program, and the costing information must be found from a contractor quote or some other outside estimate.

a. Cost of Biomass Fuel ($/ton)
b. Cost of Biomass Facility ($/kWh)
c. Fuel Conversion (kWh/lb) [found on biofuel spec sheet]
d. Cost of Operation and Maintenance ($/kWh)
e. Cost of Installation ($/kWh)

Battery Inputs

Go to the Inputs sheet of the program, and enter the following for the battery inputs. The cost information can be found by a quote from an electrical contractor.

a. Battery Cost ($/battery)
b. Years of Battery Life
c. Battery Energy (kWh/battery)
d. Inverter Cost (S/battery)
e. Cost of Installation ($/kWh)
f. Cost of Operation and Maintenance ($/kWh)

Incentive Inputs

1) Continuing on the Inputs sheet, enter the incentive information for each technology.

a. Incentive Solar ($/kWh)
b. Incentive Wind ($/kWh)
c. Incentive Biomass ($/kWh)
d. Incentive Batter ($kWh)
e. Years Solar Incentive Valid
f. Years Wind Incentive Valid
g. Years Biomass Incentive Valid
h. Years Battery Incentive Valid
i. Lump Sum Incentive [for all incentives that fall outside the others]

Required Load Input

Finally, estimate your hourly load data. That is, your energy use each hour over the course of a day. This can be done using an electric bill. Enter the data into the "Load Profile" section on the Inputs sheet of the program.

Results

The results of your inputs are automatically calculated on the "Results" sheet of the program. The pink boxes denote the cost information as well as number of components for wind, solar, batteries, and biomass. The green box "Grand Total for Energy Plant" outlines the total cost of the system, including incentives. The blue boxes outline the hourly production of wind, solar, and biomass. Also, the "Remaining Load" column represents how much of the hourly load is left over after the plant. If your load is covered by renewables, the cells' value will be zero. The battery information can be found in the black cells, which displays the excess energy generation by wind and solar that is absorbed by the batteries. Also included is the number of batteries, the % of the load taken care of by each source, and the cost breakdown by category (solar, wind, biomass, and battery).

How it Works

The inputs are used to calculate the generation by the wind turbine first. Then the wind turbine's excess energy is stored by a wind battery bank. This discharges and takes care of more of the load. The solar panels are used next for the load and generate power based on how much sun is shining. Excess solar energy production is stored by a solar battery bank, which discharges to take care of the load that solar could not. If there is still an hourly load remaining after all of these, the biomass is used to make up the difference. That way, every hourly load will always be taken care of.

There are many possible combinations of the four to do this, so which to choose? This program's algorithm iterates based on certain factors and uses weighting functions to find the best system. The best system is the one that satisfies all loads for the lowest cost. After performing iterations on batteries, solar, and biomass, the best system is determined by the lowest levelized cost of energy. The levelized cost of energy is the annual payment divided by the annual energy production. The results of these calculations are displayed on the "Results" sheet for users to see.

Bibliography

[1] Abbey. (2007). Supercapacitor Energy Storage for. *IEEE*, 769-776.

[2] Agustin, B. (2009). Simulation and optimization of stand-alone hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, 2111-2118.

[3] Alaska Energy Authority. (2009). *Energy Storage Review*. Fairbanks: Alaska Energy Authority.

[4] Bagul. (1996). Sizing of a stand-alone hybrid wind-photovoltaic system using a three-event probability density approximation. *Solar Energy*, 323-335.

[5] Bahl. (2010). *Concrete Thermal Energy Storage for Solar*. Stuttgart: German Aerospace Center.

[6] Borowy. (1996). Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. *IEEE Transactions on Energy Conversion*, 367-375.

[7] Bucciarelli. (1984). Estimating loss-of-power probabilities of stand-alone photovoltaic solar energy systems. *Solar Energy*, 205-209.

[8] Buchmann. (2003). Batteries bear the digital load's burden. *Wireless Systems Design*, 42-44.

[9] Cabeza. (2002). Heat transfer enhancement in water when used as PCM. *Applied Thermal Engineering*, 1141-1151.

[10] Cohen. (IEEE). Hydrogen Delivery and Storage Options. *Renewable and Sustainable*, 262-266.

[11] Deane, G. M. (2010). Techno-economic review of existing and new pumped hydro energy storage plant. *Renewable and Sustainable Energy Reviews*, 1293-1302.

[12] Eckroad. (1991). Review of Engineering Design Consideration for Battery Energy Management Systems. *IEEE Transactions on Energy Conversion*, 303-309.

[13] Glavin. (2008). A Stand-alone Photovoltaic Supercapacitor. *IEEE*, 1688-1695.

[14] Gray. (2011). Hydrogen storage for off-grid power supply. *International Journal of Atomic Energy*, 654-663.

[15] Hanchen. (2011). High-temperature thermal storage using a packed bed of rocks e Heat transfer. *Applied Thermal Engineering*, 1798-1806.

[16] Hobby. (n.d.). *Sandia National Laboratories researchers find energy storage "solutions" in MetILs* . Retrieved August 11, 2012, from Sandia.gov: https://share.sandia.gov/news/resources/news_releases/metils/

[17] Huggins. (2010). *Energy Storage.* New York: Springer.

[18] Ibrahim. (2010). Study and design of a hybrid wind–diesel-compressed air energy. *Applied Energy*, 1749-1762.

[19] Ilinca. (2008). Energy storage systems—Characteristics and comparisons. *Renewable and Sustainable Energy Reviews*, 1221-1250.

[20] Jha. (2010, April 26). *Giant gravel batteries could make renewable energy more reliable*. Retrieved August 11, 2012, from The Guardian: http://www.guardian.co.uk/environment/2010/apr/26/gravel-batteries-renewable-energy-storage

[21] Kamath. (n.d.). *Energy Storage Technology Overview.* Knoxville: EPRI PEAC.

[22] Kearney. (2003). *Overview on use of a Molten Salt.* Golden: NREL.

[23] Kellogg. (1998). Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems. *IEEE Transactions on Energy Conversion*, 70-75.[24] Laboratory for Electromagnetic and Electronic System. (n.d.). *Carbon Nanotube*

Enhanced Ultracapacitors. Retrieved August 11, 2012, from MIT.edu: http://lees.mit.edu/lees/ultracapacitors.htm

[25] Lex. (1999). *The Zinc/Bromine Battery System for Utility and Remote Area Applications.* Wauwatosa: Power Engineering Journal.

[26] Lin. (2010). Ice Slurry Thermal Energy Storage System. *AIAA/ASME Joint Thermophysics and Heat Transfer Conference* (pp. 1-10). Chicago: AIAA.

[27] Misask. (2010). *Off-grid Power Systems.* Ostrava: Technical University of Ostrava,.

[28] Morgan. (1997). 'ARES'—A refined simulation program for the sizing and optimisation of autonomous hybrid energy systems. *Solar Energy*, 205-215.

[29] Munthe. (2009). *A Hybrid Renewable Energy System for a Rural Area in Africa.* Delft: Delft University of Technology.

[30] Naish. (2008). *Outlook of Energy Storage Technologies.* Bruxelles: European Parliament.

[31] Nourai. (2009). Utility-Scale Energy Storage. *Transmission & Distribution World*, 80.

[32] Pavel. (2009). The Energy Storage System with Supercapacitor for Public Transport. *IEEE*, 1826-1830.

[33] Pickard. (2011). The History, Present State, and Future Prospects of Underground Pumped Hydro for Massive Energy Storage. *IEEE*, 473-483.

[34] Protogeropoulos. (1997). Sizing and Techno-Economical Optimization for Hybrid Solar Photovoltaic/Wind Power System with Battery Storage. *International Journal of Energy Research*, 465-479.

[35] Rodriguez. (1989). Operating experience with the Chino 10 MW/40 MWh battery energy storage facility. *Energy Conversion Engineering Conference* (pp. 1641-1645). Rosemead: IEEE.

[36] Rosen. (2011). *Themal Energy Storage.* West Sussex: Wiley.

[37] Schreiber. (2012). Practical and commercial issues in the design and manufacture of vanadium flow batteries. *Journal of Power Sources*, 483-489.

[38] Shukla. (2009). Solar water heaters with phase change material thermal energy. *Renewable and Sustainable Energy Reviews*, 2119-2125.

[39] Sorenson. (2007). *Renewable Energy Conversion, Transmission, and Storage.* Academic Press.

[40] Tina. (2006). Hybrid solar/wind power system probabilistic modelling for long-term performance assessment. *Solar Energy*, 578-588.

[41] Trojan Battery Company. (n.d.). *Comparing Deep-Cycle Flooded Batteries to VRLA Batteries*. Retrieved August 11, 2008, from Trojanbatteryre.com: http://www.trojanbatteryre.com/Tech_Support/ComparingFlood2VRLA.html

[42] Villela. (2010). *Compress Air Energy Storage Systems for Stand-Alone Off-Grid.* Tucson: IEEE.

[43] Wagner. (1997). Large lead/acid batteries for frequency regulation, load levelling and solar power applications. *Journal of Power Sources*, 163-172.

[44] Yang. (2008). Battery behavior prediction and battery working states analysis of a hybrid solar–wind power generation system. *Renewable Energy*, 1413-1423.

[45] Yang. (2011). Opportunities and barriers to pumped-hydro energy storage in the United States. *Renewable and Sustainable Energy Reviews*, 839-844.

[46] Yilmaz. (2011). Preparation of phase change material–montmorillonite composites suitable for thermal energy storage. *Thermochimica Acta*, 39-46.

[47] Zhou. (2010). Current status of research on optimum sizing of stand-alone hybrid. *Applied Energy*, 380-389.

[48] Zhou. (2010). Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. *Applied Energy*, 3642-3651.

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