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1. Executive Summary

Nowadays, the renewable energy industry has increased due to higher concerns on environmental and global warming issues. Every day, the world is striving on creating a superior and more reliable source of energy that will not only benefit society, but will protect the environment as well. Hence, the market for solar, wind, hydro, and geothermal power is rapidly growing and potentially becoming a major source of energy in the world. With that in mind, the goal of the project is to introduce a method of integration and control for a renewable energy system, which is able to take two different sources at different times, such as Photovoltaic (PV) panel and Wind Turbine respectively. In addition, the system will be portable enough to be transportable outside the United States of America due to the objective of the project which is to provide power to an underprivileged community located in South Africa.

The intention is to create an efficient, robust and low cost charge controller with a maximum power point tracking (MPPT) algorithm to obtain the highest efficiency for the entire system. The method of implementation consists of bringing two renewable power generation sources into a single integrated hybrid energy system, that will input either solar or wind. In addition, components such as an inverter will be used to convert DC power to AC. A storage system made of batteries is used to distribute energy when the output power of the solar or wind source is not significant enough to maintain the energy demand by the user. Most importantly a main controller is designed to control, monitor, and display important information about the control system such as power input, power output, battery levels and to successfully take care of the health of the entire system.

In order to execute a hybrid charge controller that can capture different input sources, a switch will be embedded into the design, thus the system will recognized which source of power, solar or wind, has been connected. Also, different sensors such as voltage, current and temperature, will be added in different parts of the system, and be fed into the microcontroller. The charge controller will read in the data from some of those sensors and use the MPPT algorithms programmed in it to compute the maximum power point. That power will then be delivered to the battery and/or the user. The topology employed in the design of the charge controller, will be able to control the buck and boost converters to extend the life time of the batteries. Temperature sensors will be used to supervise the ambient conditions of main components, in order to deliver the desirable output power and maintain a long lasting system.

Lastly, the main goal is to create a reliable, robust and high efficiency structure that can benefit the underprivileged community and last longer than five years. Ultimately, the entire project will consist of a solar panel, MPPT charge controller,

inverter, battery bank, and a distribution system that will have contact with the end user, and bring joy and entertainment to many South Africans that lack of the enormous privilege of electricity.

2. Description

2.1 Motivation

The primary motivation for this project is the idea of giving back to the community. This project will help provide cheap electricity from a renewable energy source to the Pomolong Township located near Harrismith, South Africa. This Township is unable to afford electricity from the grid and is without power for their community center. Their community center is where this township comes together for education and entertainment. The community center has a computer, a projector and some lights. During the day the community center acts as a school for the children and adults in the township and at night it is a place of refugee to relax from the stresses of everyday life and to enjoy a quick movie. The electricity harvested by from renewable energy sources such as solar or wind power, will be used to supply electricity to the community center so that this community center can be used to its full potential.

Another major motivation for this project is that it will be a charging station for portable electric devices. Many travelers and local only have cellular phones as a means of communication to the outside world. There are very few places in Pomolong that are capable of recharging people's cellular phone or any other portable electric devices. This project will provide a central place for most visiting and living in Pomolong to recharge their cellular phones and stay connected. By building a small power station that has the ability to reliably and efficiently harvest energy from renewable energy sources, store that electricity, and distribute it in multiple usable forms, this township will be able to grow.

2.2 Objectives

The main purpose of this project is to introduce the integration and control of renewable energy in an electric power system. Selecting a Photovoltaic (PV) panel or a small wind turbine, a green renewable energy model will be used to develop control methods to control the dynamic process and the efficiency of the system. In addition it is required to provide sufficient power to a community center located in Southern Africa. The method of implementation consists of bringing either one of two types of renewable power generation devices into a single hybrid energy system. In addition an inverter will be used to convert DC power to AC. A storage system will be used to distribute power when the output power of either the solar or wind sources are not significant enough. In addition a charge controller will be added to regulate this power. As a result, the optimal goal we are striving to achieve is the design of a robust power source integration that it includes low cost, sustainable and reliable components, which will be installed in a small community in Southern Africa. Since this community has not source of power, they cannot take any technological advantage that it might be available to them. Having no source of power, they find it difficult to acquire new skills and knowledge as compare to most civilized cities; limiting them to continue their learning at a slower and antique pace.

Finally, we will develop this project so that it can generate enough electricity, at the lowest possible cost, to power a projector and a computer at the South Africa community center which could be used for educational and recreational purposes for the people in this small community. If there are enough teams working towards this community, the power attained will be greater and therefore, a greater diversity of devices could be powered to assist the people in the village.

2.3 Location

As mentioned above, the main purpose of the design is to develop a sustainable energy platform that will support energy needs of the Pomolong Township located near Harrismith, South Africa. It is important to conduct research on the place and area of the design will be located because there are several variables that can affect the system, from weather conditions to animal or vegetation harm, which can damage any component and negatively impact its surroundings.

The design will be established at a small community center inside the Pomolong Township. In South Africa the term township usually refers to the underdeveloped urban living areas that from the late 19th century until the end of Apartheid, were reserved for non-white citizens. This project will be installed on the city of Harrismith, geographically shown in Figure 1 below because is the nearest city to the Pomolong Township, which is roughly 314 kilometers from Johannesburg and 315 kilometers from Durban.

The geographical setting of the area will help us understand for planning the components we will purchase for the system. Even though, we are designing a system to have durability and functional elements, we have to keep in mind that a part could fail or stop working; therefore we will research different vendors and suppliers near Harrismith area, which offer solar and wind energy system component replacement and services. One of the challenges we will encounter is finding parts that will match the African standards, this will give the system the most usability with easy to repair parts in case of unexpected failure.

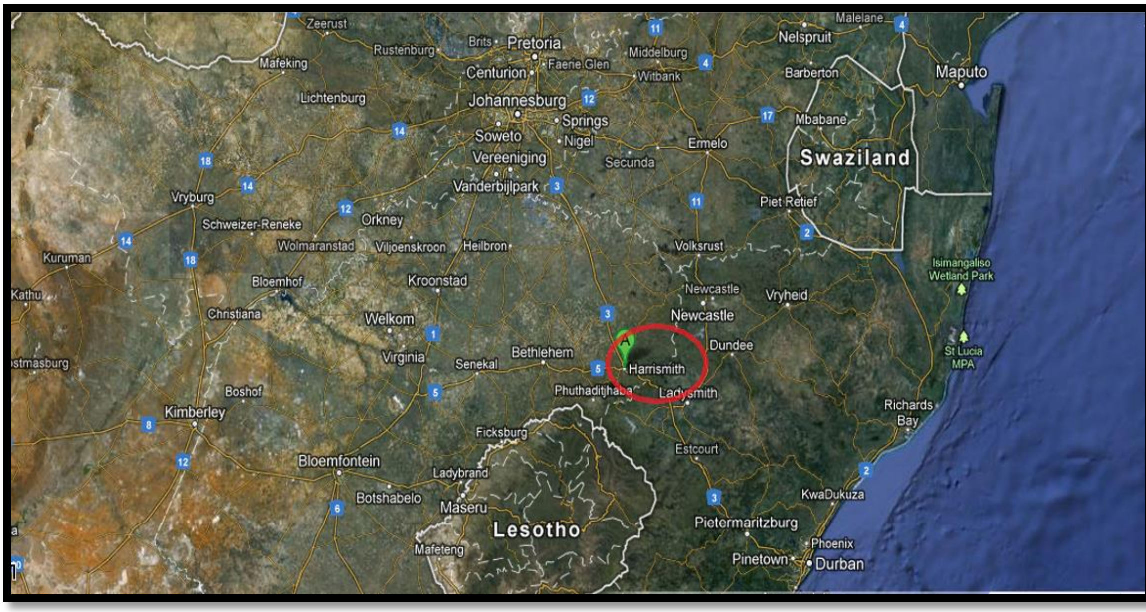

Figure 1 Harrismith, South Africa

In addition, we will take into account the monthly distribution of average daily temperatures represented below in Figure 2. The average midday ranges from 58°F in June to 76°F in January. [3]

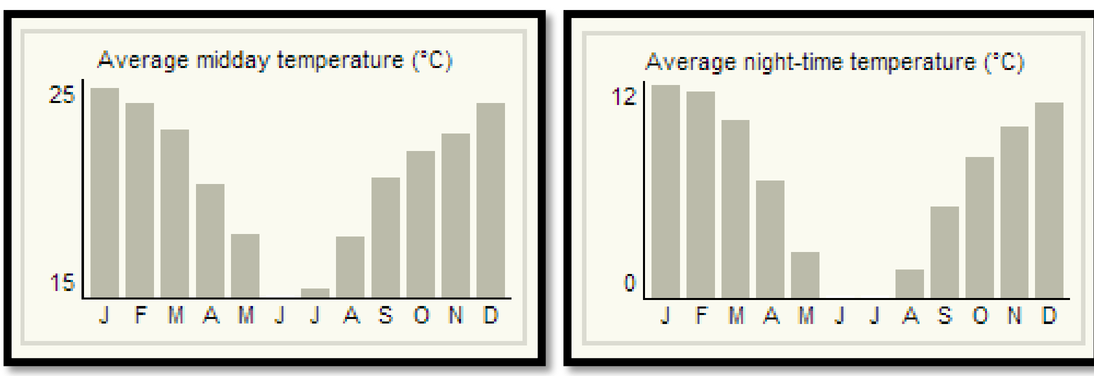

Figure 2 Average Temperature

The reason we examine the climate it is because we want to provide the most efficient system for this community, and the weather and temperature conditions are a huge factor on the functioning and longevity of the systems. Also, we will choose the appropriate components that fit the environment setting. As an example, the batteries perform according their surrounding temperature. As the temperature goes down, the battery capacity (amps per hour) is reduce, and vice versa. The standard rating for batteries is at room temperature - 25 degrees C. The battery capacity drops 20% at freezing point and 50% at approximately -22 degrees. Also, at higher temperatures, such as 50 degrees C, battery capacity would be about 12% higher, than regularly. Another variable within the batteries is the charging voltage which changes with temperature as well. It will vary from about 2.74 volts at -40 degrees C to 2.3 volts at 50 degrees C [6]. If the system is placed outdoors, then it is recommendable to have a charge controller with a temperature compensation embedded in it. In this project, the charge controller and the battery bank will be placed inside of a structure, and also there are not extreme changes in the climate, therefore the system will be secure and not affected by the temperatures. Other components such as charge controller, inverter and fuses are going to be chosen and design taking into account the above temperatures. The most important feature is how effectively the charging method is in relation to the temperatures, and most likely the batteries are the ones that become more affected by this than the other components. Lastly, the fog which occurs in the area is not a cause of concern for the system as it does not alter the operating conditions to be other than having the air mass to be measured at AM1. Table 1 shows the average hours of sunlight year around. There about 9-10 hours of sun light daily and an average of solar irradiance on the area of 1900-200kWH/m^2, which will provide larger amount energy and charge the battery bank in a faster rate.

Table 1 Average of Climate per Month

Month	Average Air Temperature (°C)	Average Hours of Sunlight (hours)	Average Wind Speeds (Knots)
January	22	8	9
February	22	8	7
March	22	8	8
April	18	8	8
May	17	9	8
June	13	9	10
July	13	9	9
August	16	10	10
September	20	10	11
October	22	9	11
November	22	8	10
December	22	8	10

This project is providing both wind and solar power systems to supply power to the community center, it is important to study the wind speeds as well, on this particular area in order to understand how effective our system will be. The area where the system is to be implemented is relatively flat with an approximate elevation of 1636 meters with a slope of 2 degrees. This will be needed when placing the wind turbine at the location for better energy absorption. In the above table, it can be seen the average of wind speeds in Knots per month.

Besides the protection and life of all the components, the knowledge of the wind speeds is to have an idea of how much energy is going to be supply when the turbine is plugged into the charge controller and battery bank. Overall, the climate in this area of South Africa is stable and not extreme, which makes is a good location for the entire system. However, all of the components will have conditions for extreme temperatures and climate changes that can be reliable and will not affect the system.

2.4 Requirements and Specifications

Table 2 Requirement and Specifications

Input Power	
Source	Wind Power or Solar Power
Open Circuit	Power source needs to be able to handle a open circuit disconnect
Short Circuit	Will result in an immediate disconnect or blown fuse
Communication to Source	None
DC Voltage	15VDC-40VDC
AC Voltage	Not Supported
Maximum Power	<1000W

Table 3 Requirement and Specifications

Charge Controller	
Input Voltage	15VDC-40VDC
Output Voltage	22VDC-30VDC
Max Input Current	<67A
Max Output Current	<48A
Efficiency	>90%
Switching Frequency	220 Khz
Max Duty Cycle	100%
Min Duty Cycle	0%
Charge Stages	3 (Bulk, Absorption, Float)
Over Current Protection	Yes
Over Voltage Protection	Yes

Table 4 Requirement and Specifications

MPPT Algorithm	
Algorithm	Perturb and Disturb
Convergence time	<.5ms
Stages Used	Bulk Only
Voltage Boundaries	22VDC-30VDC

Table 5 Requirement and Specifications

Battery Bank	
Quantity	2 (12VDC)
Capacity	105AHr
Terminal Voltage	24VDC
Bulk Stage Charge	22VDC-30VDC
Absorption Stage Charge	28VDC
Flow Stage Charge	24VDC (Trickle Charge)
Operating Temperatures	-40 C° to 60 C°
Number Of Cycles at 50% Discharge	1000 Cycles

Table 6 Requirement and Specifications

Desulfator	
Supplied Voltage	12VDC

Table 7 Requirement and Specifications

Inverter	
Input Voltage	20VDC-30VDC
Output Voltage	110Vrms at 60Hz
Continuous Power	2500W
Surge Power	5000W
Peak Efficiency	95%
Full Load Efficiecy	90%
Overheat Protection	Yes
Remote Control	Yes

Table 8 Requirement and Specifications

Output Power	
AC Voltage	110Vrms at 60Hz and 220Vrms at 60Hz
DC Voltage	5VDC (USB port)
Maximum Total Power	1000W
American Standard Sockets	2
European Standard Sockets	2
USB ports	2

2.5 Budget

Specific Part	General Part Name	Cost per Part ($)	Number Parts	Total Cost ($)
MSP430 Launch Pad	Microprocessor	4.3	1	4.3
TCA6416A	I/O Expander	0	1	0
ADS1246	Analog to Digital Conv.	0	2	0
PCB Board	PCB Board	33	2	66
HUF75545P3	MOSFET	2.28	4	9.12
AGM 31M	Battery	276.46	1	276.46
AIMS PWRINV2.5K24	Inverter	279	1	279
Enclosure Materials	Enclosure Materials(est.)	60	1	60
HQPR MC4	Input Connector for PV and Wind	9.99	1	9.99
BS-546	European Socket	2	1	2
NEMA Socket	American Socket	2	1	2
WF-098	USB Power Socket	2.77	1	2.77
THG-1000	110VAC to 220VAC Transformer	29.08	1	29.08
SW-S65P	Solar Panel	250	1	250
LCD-09395	LCD Display	25	1	25
Temperature Sensor	Temperature Sensor	0.9	5	4.5
Littelfuse 0498080	Fuses	4	1	4
EC025M24	Fans	10.95	4	43.8
Miscellaneous	Electrical Components: Resistors, Capacitors, Inductors, Wiring, Internal Connectors, Solder, ect.	85	1	85
			Total	1153.02

2.6 Milestones

In order to monitor the overall progress of this project the team will set several tasks with assigned specific dates. In this way, the team will be able to finish the project in a timely fashion during the following two semesters. The milestones that will be used will establish reference points, marking major accomplishments in the development of the project. These milestones will consist of the realization of required research, the completion of required paperwork and documentation, the waiting time for the acquisition of parts, the building phase, the testing phase, and presentation of the final product. The research and work needed to accomplish this project will be distributed based on the individual preferences and interests of each group member and at the same time making sure that each member be responsible for equal amounts of work.

The expected duration for each stage of this project is depicted in the following chart which the team will use as a guide to effectively track and accomplish the intention of this project.

Date	Task
08/20/2012	Define Project • Goals and Objectives • Area of Interest
08/31/2012	Research • Location and Climate Conditions • Renewable Energy Sources • Charge Controller • Microcontroller • Battery technologies and charging states • Control and Monitoring Devices • Grounding and system protection • Safety Regulations
09/11/12	Finish Initial Project and Group Identification Document
10/05/12	Design • Hardware Diagrams and Schematics • Software and Algorithms Diagrams
10/30/2012	Design and determine required hardware/parts: • PV Panels • Buck and Boost Controller • LCD • Charge Controller • Power Inverter • Step up Transformer • Wiring and Connectors • Battery Bank

	• Temperature, Voltage, and Current Sensors • Heatsink
12/05/12	Finish Final Documentation
01/30/2013	Prepare Initial Presentation
02/15/2013	Building Phase: • Buck and Boost Converter • Charge Controller PCB • Power Inverter • LCD integration
02/25/2013	Assembly of Prototype
02/30/2013	Programming: • Charge Controller • PV Panel Controller and Regulator • Maximum Power Point Tracking Controller • Wind Turbine Controller and Regulator
3/11/13	Testing Phase: • Make Sure Prototype Works as Specified • Test Integrity of the System Under Several Conditions
04/15/2013	Prepare for Final Presentation

3. Research

3.1 Related Projects

In the last century projects relating renewable energy and sustainability have grown rapidly. Designs of solar and wind generation have been very common among industry and academia. Many university students have linked towards this field for the popularity and common need in society, and are working on improving such systems each time. The implementations of a MPPT charge controller it is the main focus on this type of projects for efficiency and reliability purposes. This project will not only encompass the design of an efficient charge controller, but it will be able to recognized which source of power has been input it into the system, either solar or wind, and use it as a charging method to the batteries. Similar projects have been done in the past, but there were not any that incorporated the recognition of different input sources into their design. This is a significant feature to this project because there are going to be multiple energy sources implemented in the small community in South Africa. A previous senior design project conducted by students at the University of Central Florida in the Fall of 2011 provided insight into a solar project that followed all the requirements of a UCF Engineering senior design. The Solar Knights project incorporated a small solar panel design and a charge controller with maximum power point tracking system, and was referenced for documentation style. [1]

Also, there is another similar project was accomplished last summer 2012 by a group of students at the University of Central Florida. The Intellaturbine group built a maximum power point tracking system by utilizing two wind turbines, charge controller, converters, and data acquisition that will be used to increase the efficiency of the system. This documentation provided a different approach to be able to implement the wind generation as one of our source. [2]

Even though there has been multiple projects done in this area of energy sustainability, the focus was narrowed down to only two to three projects, due that it was necessary to relate to the most accurate information for this project. In order to provide the user with a system that can intake either solar or wind power source, there was a deeper analysis on the each stand alone system. The solar provided insights on performing a solar source charge controller, as well wind source. Regardless of the majority of systems being created for improvement or innovation, this project encompasses unique and challenging features such implementing a hybrid system keeping in mind that the goal is to provide a reliable and long lasting system for the unprivileged community in South Africa. The project will follow the specific senior design requirements and will be base on the demand of the end user.

3.2 Solar Energy

Solar Energy is considered to be one of the most abundant and cleanest renewable energy sources available on earth. The term renewable energy refers to any source of energy that could be replenished in a relatively short period of time. Since solar energy represents one of the cleanest and sustainable forms of energy, it is expected that the world will experience a huge expansion in solar power development over the next years. As shown in Figure 3, in the year 2011 solar energy accounted only for 2% of the total energy produced via renewable sources in the US. However, this form of energy is expected to grow by up to 400% over the next five years according to the European Photovoltaic Industry Association (EPIA). [3]

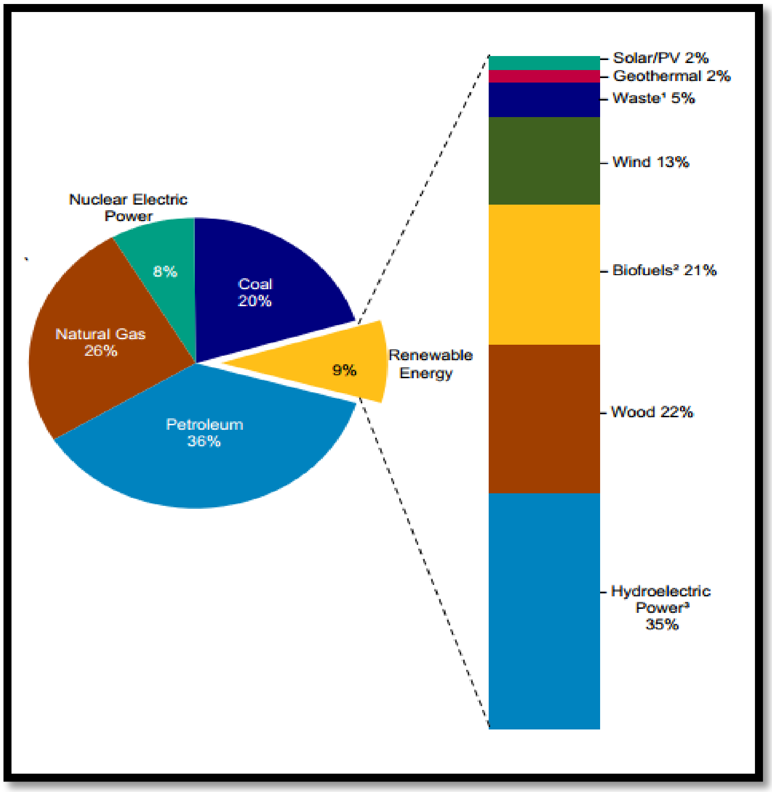

Figure 3 Total energy consumption in the US for the year 2011

According to Figure 3, about 9% of the total energy consumed in 2011 in the United States was from renewable sources and they account for about 13% of the energy production. Even though this represents only a small portion of the energy produced, the United Stated was the world's largest consumer of renewable energy such as, hydroelectric power, Wood, wind energy, bio fuels, waste, geothermal, and photovoltaic panels. The renewable share of total world energy consumption is expected to rise from 10.2% to 14.2% in 2035 according to the Energy Information Administration (EIA).

3.2.1 Photovoltaic Effect

A solar panel is a packaged connected assembly of photovoltaic cells. Solar panels use light energy; that is, photons from the sun to generate electricity through a photovoltaic effect. Therefore, these solar panels are often referred to as Photovoltaic (PV) panels. Solar energy applications are based in the exploitation of the photovoltaic effect. The photovoltaic effect, takes place when solar radiation (photons) is induced over extrinsic semiconductor materials. The energy received from the photons, creates a chaotic movement of electrons in the interior of the semiconductor material. That is, the electrons in the valance band break the bond that keep them tied to an atom. For each bond that is broken we get a free electron and a hole (lack of electron in a broken bond) to move inside the semiconductor material. This movement of electrons and hole in opposite directions is what generates electric current, as shown in Figure 4.

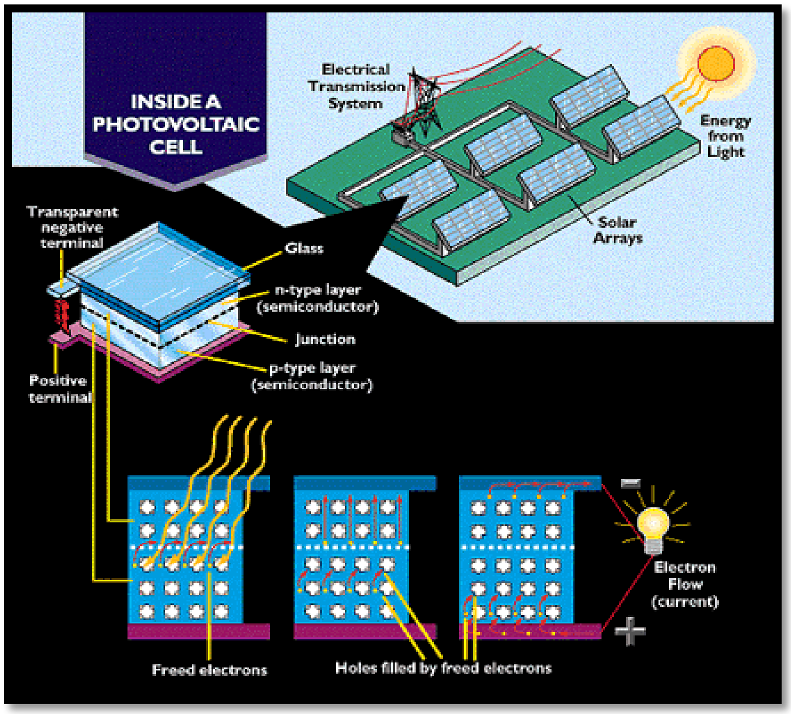

Figure 4 the operation of a Photovoltaic Cell:

There are many types of solar panels. One of the most common are Monocrystalline silicon (mono-silicon or single silicon), Polycrystalline silicon (multicrystalline, multi-silicon, ribbon), Thin film (amorphous silicon, cadmium telluride, copper indium gallium (di)selenide), BIPV (building integrated photovoltaics), and Solar hot water (thermal) panels. [7]

3.2.2 Harvesting Methods

3.2.2.1 Monocrystalline Silicon Panels

As of right now, these are the most efficient type of solar panels. They are also the most widely used photovoltaic technology, this type of solar cells represent more than 90% of the actual market. This type of photovoltaic technology was first developed in 1955. Monocrystalline silicon solar cells are designed to direct the loose electrons in a circuit as electricity. The voltage of each cell depends on the cell's internal electric field. These types of solar cells are cut into thin wafers from a singular continuous crystal grown in a laboratory to achieve a high degree of purity. This technique is often referred to as the Czochralski process. [7] The cells are laminated using tempered glass on the front and plastic on the back. These are joined using a clear adhesive. Monocrystalline photovoltaic cells can be distinguished by their uniform appearance and are usually dark blue or black. Monocrystalline cells have the highest efficiency of any cells on the market under standard operating conditions. The efficiency rates of Monocrystaline solar panels are typically 15 to 20%. [7]

Their high efficiency means they have the smallest footprint for their output, so we can maximize power output when roof space is limited. In other words, Monocrystalline silicon solar panels are space-efficient when compared to other solar panels technologies. That is, the user will get the most watts per square foot when using this technology. Since these solar panels yield the highest power outputs, they are a good choice when limited space is an issue. For example, Monocrystalline silicon solar panels can produce up to four times the amount of electricity as thin-film panels. Because of the higher efficiency level these panels tend to perform better than polycrystalline solar panels at low-light and low-temperature conditions and have been proven to last longer than the rest of the silicon technology panels. In fact, these types of panels are estimated to last at least 25 years.

Because of the production process of these type of solar panels in which a lot of silicone material is wasted, monocrystalline cells are more expensive that other cells. Also, monocrystalline cells don't perform as well as polycrystalline cells or thin film under higher temperatures (more than 25°C). All cells are subject to 'de-rating' as the ambient temperature increases, and monocrystalline cells tend to produce less at higher temperatures than the other technologies. Another drawback is that the Czochralski process is used to produce these solar cells and it results in large cylindrical ingots. Four sides are cut out of the ingots to make silicon wafers. Therefore, a significant amount of the original silicon ends up as waste. However, the higher price of these panels is justified by the returned energy cost that these panel produce during their long serving life. Therefore, this will be the technology of choice for our renewable power generation system.

3.2.2.2 Polycrystalline Silicon Solar Cells

The first solar panels based on polycrystalline silicon, which also is known as polysilicon (p-Si) and multi-crystalline silicon (mc-Si), were introduced to the market in 1981. Unlike monocrystalline-based solar panels, polycrystalline solar panels do not require the Czochralski process. One key advantage of these types of solar cells over monocrystalline cells is that the process used to make them is simpler. The reason polycrystalline solar panels are less expensive than monocrystalline solar panels, is because of the way the silicon is made. Basically, the molten silicon is poured into a cast instead of being made into a single crystal. Also, Polycrystalline solar panels tend to have higher heat tolerance and therefore perform better than monocrystalline at high temperatures. Heat can affect the performance of solar panels and shorten their lifespan. However, this effect is minor and in most applications it does not need to be taken into account.

It is worth mentioning that because of the lower silicon purity polycrystalline solar panels have, they are not quite as efficient as monocrystalline solar panels. The efficiency of polycrystalline solar panels is typically between 13 to 16%. Moreover, in order to output the same electrical power as we would with a solar panel made of monocrystalline silicon, we would need to cover a larger surface and therefore making these panels much less space efficient than the monocrystalline ones.

3.2.2.3 Thin Film Solar Panels

The term "Thin film solar panels" refers to the fact that these types of solar panels use a much thinner level of photovoltaic material than mono-crystalline or multi-crystalline solar panels. Thin film solar cells consist of layers of active materials about 10 nm thick compared with 200- to 300-nm layers for crystalline-silicon cells. It is worth mentioning that these types of solar panels are much lower in price but they also have lower module efficiency than silicon based solar panels. In fact, the efficiency of thin film solar cells is roughly ½ of monocrystalline solar cells. The three most common photovoltaic materials used in mass production of thin film modules are the following:

3.2.2.3.1 Amorphous Silicon

Amorphous Silicon photovoltaic panels were the first thin film modules to be commercially produced. Amorphous silicon is the non-crystalline form of silicon. Amorphous silicon panels are formed by vapor-depositing a thin layer of silicon material – about 1 micrometer thick – on a substrate material such as glass or metal. The thickness of the solar cell is just 1 micron, or about 1/300th the size of mono-crystalline silicon solar cell. This technology is often used in small electronic applications such as calculators. Panels made from amorphous silicon then to have a efficiency of about 7 to 9%. One key advantage of this technology is its higher resistance to heat. Actually, amorphous silicon is the most developed thin film technology to-date.

3.2.2.3.2 Cadmium Telluride

Cadmium telluride is the first and only thin film photovoltaic technology to surpass crystalline silicon panels in price per watt of power. One key advantage of cadmium telluride is that it absorbs sunlight at close to the ideal wavelength; capturing energy at shorter wavelengths than what is possible with silicon based photovoltaic panels. Also, cadmium is a very abundant material and is produced as a byproduct of other industrial metals.

There are some drawbacks in using this type of technology to build photovoltaic panels. First, lower efficiency levels. Cadmium telluride solar panels currently achieve no more than 10% efficiency which is much lower than the typical efficiency of silicon based solar panels. Secondly, there is very limited supply of Tellurium. Tellurium is an extremely rare element; therefore, the availability of tellurium will eventually limit the production of photovoltaic panels made with this material. Also, Cadmium is one of the top deadliest and toxic materials known to man. Cadmium telluride is toxic if ingested, if it is dust is inhaled, or even if it is handled improperly; that is, without appropriate gloves and safety precautions. Actually, there are some concerns about the future of cadmium telluride based photovoltaic panels due to the very limited availably of Telluride and increased concern about long term toxic effects of Cadmium.

3.2.2.3.3 Copper Indium Gallium Selenide (CIS/CIGS)

Copper Indium Gallium Selenide solar panels have been under development for more than twenty years. One of the first companies to support this type of technology was the Walton Family (CITATION). Copper Indium Gallium Selenide based solar panels have showed to have the most potential in terms of efficiency compared to other thin film technologies. In fact, modules based on CIGS technology are estimated to have an efficiency of at least 10%. One key advantage of this thin film technology is that these solar cells contain less amount of toxic material, especially when compared to Cadmium Telluride solar cells.

There are some drawbacks about using solar panels based on CIGS and one of them is higher total costs. Theses solar cells cannot draw as high wattage from sunlight as monocrystalline and polycrystalline panels do, which requires more installation space for the same amount of power. Although panel costs (which account for around 50% of the total installed price) have been declining as a result of more efficient manufacturing and economies of scale – installation costs have remained about the same. Consequently if we need to install twice as many panels to get the same results – the overall cost advantages of lower panel prices disappear quickly.

3.2.3 Photovoltaic Panel Performance

The performance of a photovoltaic panel is measured in kilowatt hours per kilowatt peak (kWh/kWp), which translates as the number of electrical units of energy (kWh) the panel will produce during the brightest light.

The electrical performance of a photovoltaic panel depends on many environmental conditions. Factors that affect solar array efficiency include:

3.2.4 Temperature

Solar panel temperature is one of the most important factors to take into account when designing a photovoltaic system because temperature will greatly affect how much electricity we can obtain from our system. In fact, in some cases high temperatures can reduce power output by as much as 25%. However, as previously discussed, some photovoltaic technologies are more affected than others by temperature. Generally, photovoltaic panels based on silicon are the ones most affected by high temperatures. If we look at the manufactures data sheet for solar panels we will see a term called temperature coefficient. One good example is a solar panel with a temperature coefficient of -0.45%. What this means is that for each degree above 25C, the maximum power produced by the photovoltaic panel will be reduced by 0.45%. By contrast, on a sunny day when temperatures are lower than 25C, the amount of electricity we could get from the photovoltaic panel would actually increase above its maximum rated level. In other words, the warmer the solar panel the less power it can produce. The power loss due to temperature is dependent on the type of solar panel technology being used. For example, solar panels based on silicon such as monocrystalline and polycrystalline panels will usually have a temperature coefficient between -0.44% and -0.50%. Thin film based solar panels tend to perform better under higher temperatures. For example, amorphous silicon solar panels usually have a temperature coefficient of -0.34% and Cadmium Telluride solar panels have a temperature coefficient of about -0.25%.

3.2.5 Solar Irradiance

Taking into account solar irradiance is a key factor in order to build an appropriate photovoltaic system for a specific location. Irradiance is a measure of the electromagnetic energy that reaches the earth's atmosphere per second, per meter. Irradiance can be understood as a stream of photons. Each photon contains a certain amount of energy, and all electromagnetic radiation consists of these photons. Generally, speaking the smaller the wavelength the more energy is contained in the photon.

It is important to take into account solar irradiance for the location where the photovoltaic system will be installed because photons release the energy produced in the sun when it comes in contact with the solar panels and in doing so they cause electrons to move and electricity to be produced. The following Figure 5 shows the average annual solar radiation in South Africa:

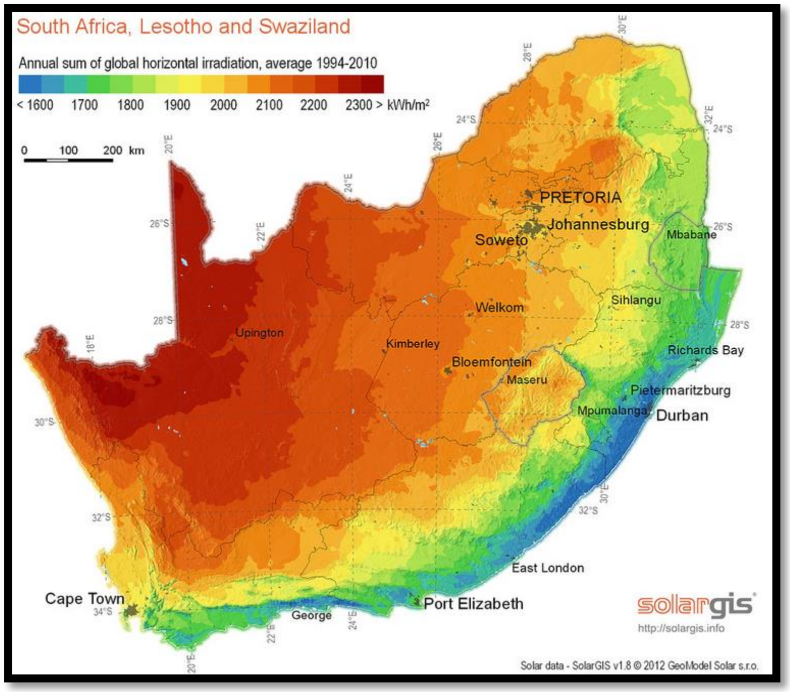

Figure 5 Average of Annual Solar Radiation

It is worth mentioning that, each Photovoltaic panel is rated under industrial Standard Test Conditions (STC) of solar irradiance of 1,000 W/m² with zero angle of incidence, solar spectrum of 1.5 air mass and 25°C cell temperature. Electrical characteristics from manufacturers include maximum rated power, open circuit voltage, short circuit current, maximum power voltage, maximum power current, and temperature coefficients.

3.3 Wind Energy

Wind power is the conversion of wind energy into a more useful form of energy. Wind power is produced by using wind generators (also called wind turbines) to harness the kinetic energy of wind. This form of energy is gaining worldwide popularity as an alternative energy source manly because it represents an inexhaustible supply of renewable energy and it does not cause pollution. However, wind energy still only provides less than one percent of the global energy consumption. Wind has been used as a source of generating energy for decades making it one of the oldest forms of renewable energy.

3.3.1 Turbine Components

The purpose of wind turbines is to convert the kinetic energy in the wind into mechanical power. Then, the mechanical power produced is converted by a built in generator into electrical energy to power businesses and homes.

First, the wind turns the blades of the wind turbine and these blades, at the same time, are connected to a shaft. The rotating shaft spins a built in generator and electricity is generated. A typical a wind turbine is composed of the following components:

- *Anemometer:* This device measures wind speed. Wind speed is by far the most important factor in determining if a wind turbine will produce enough power for our application. Anemometers collect data and are responsible for the process of steering the wind turbine into the wind in order to obtain maximum efficiency. In other words, anemometers have a control function for the wind turbines. These are usually placed on top of the wind turbines.

- *Brake:* There are usually two types of braking systems in wind turbines. The first one is electrical braking and this is accomplished by dumping energy from the generator into a big load resistor. In this way, the kinetic energy generated by the turbine is dissipated as heat. On wind turbines there is also a mechanical braking system which consists of a drum or disc brake in order to hold the wind turbine at rest.

- *Controller:* This device communicates constantly with the anemometer which transmits the data collected from measuring the wind speed. Usually, this controller starts the turbine at wind speeds between 8 to 16mph. At a specific speed, generally above 65mph, the controller shuts the wind turbine off in order to keep it from overheating.

- *Gear Box:* The gear box connect the low-speed shaft to the high-speed shaft in order to convert the rotational speed of the rotor from about 10rpm to about 1200-1500rpm which is the rotational speed needed by most generator to generate electrical energy.

- *Generator:* This device is the one responsible for converting the rotational movement to electrical energy. There are mainly three types of generators that could be in a wind turbine.

  One of them is the Induction Generator induction generators produce electricity when their shaft is rotated faster than the synchronous frequency of the equivalent induction motor. Generally speaking, these types of generators are electrically and mechanically simpler than other generator types. Induction generators require an external supply to produce rotating magnetic flux. The external supply can be supplied from the generator itself, once it stars producing power or sometimes a capacitor bank is used to supply it. A gearing is required in order to use this type of generator because induction motors need to run above

1500rpm to start generating power. The other types of generators are the Permanent Magnet Alternators. These types of generators have one set of electromagnets and one set of permanent magnets. Usually, the permanent magnets are mounted on the rotor and the electromagnets on the stator. Permanent magnet alternators are usually very efficient 60% to 95%. One advantage of this type of generators is that they do not require a controller as other generators. Another type of generators is the Brushed DC motor generators. These types of generators are typically used in small applications such as wind turbines for single homes. On a brushed DC motor, the electromagnets spring the rotor with the power coming from what is called the commutator. In this way, a rectifying effect is created and therefore and DC output is obtained from this process. It is worth mentioning that this is not a very efficient way to rectify the power we could get from the wind turbine. Unfortunately, this is the only way to get the power out of the rotor. Typically, a brushed motor generator has efficiency between 50% and 70% at most. One key advantage of brushed motor generators is that they do not require any gearing as induction generator do; making their construction simpler and therefore very common for home built wind turbines applications.

- *Tower:* supports the motors, drive train, and the blades. The tower is one of the most important parts in a wind turbine. It raises the wind turbine so that its blades safely clear the ground and so it can reach the cleaner, stronger winds at higher elevations. As a general rule, it is better to go for as high a tower as makes economic sense. At higher elevations the wind is usually much stronger. Power output from a wind turbine is a function of the cube of the wind speed so even small increases in wind speed from a taller tower can have a huge impact on energy production. The decision of what height tower to use is based on the cost of taller towers versus the value of the increase in energy production resulting from their use. Another reason for going with a taller wind tower is that the air at higher elevations is generally less turbulent. At lower elevations, the wind can often become quite turbulent due to obstructions from buildings and trees which in turns puts more stress on the wind turbine and will cause it to wear out faster. Generally, is recommended to install a wind turbine on a tower with the bottom of the rotor blades at least 30 feet above any obstacle that is within 300 feet of the tower. Usually, the tower is one of the most expensive components in a wind generation system. It can be well over half the cost of the overall system. There are a couple of approaches when building a wind turbine tower.

    - *Free Standing Towers:* requires a solid foundation because they have no guy wire. One of their main advantages is their small footprint created on their construction. This type of towers are usually implemented on large scale projects, they are not commonly used in smaller systems due to their high construction cost. Because these type of towers cannot be laid down they usually include a built-in ladder so that someone can climb the tower to do maintenance on the turbine.

- *Guyed Towers:* These types of towers are held in place with guy wires. The tower itself is often just a long steel pole which is 30 to 100 feet tall. There are usually three or four guy lines made of steel cable which run from the top of the tower to guy anchors on the ground which hold the tower in place. Guyed towers are often the least expensive type of wind tower and are often an excellent choice for a small residential scale wind turbine projects. It is worth mentioning that this type of tower takes up a considerable amount of space because the guy wires extend well beyond the base of the tower.

Actually, wind energy is one of the lowest priced renewable energy technologies available today. In fact, according to the US department of energy, wind energy cost between 4 and 6 cents per kilowatt-hour, depending upon the wind resource and project financing of the particular project. [8]

3.3.2 Types of Wind Turbines

There are two basic types of wind turbines currently being used today. One of them are the horizontal-axis turbines, and the other type are the ones that use a vertical-axis design. A horizontal-axis wind turbine has its blades rotating on an axis parallel to the ground. On the other hand, a vertical-axis wind turbine has its blades rotating on an axis perpendicular to the ground. There are a number of available designs for both and each type has certain advantages and disadvantages. However, compared with the horizontal-axis type, vertical-axis wind turbines are not as common and widely available. Figure 6 Horizontal Axis and Vertical Axis wind turbines shows the two types of wind turbine axis.

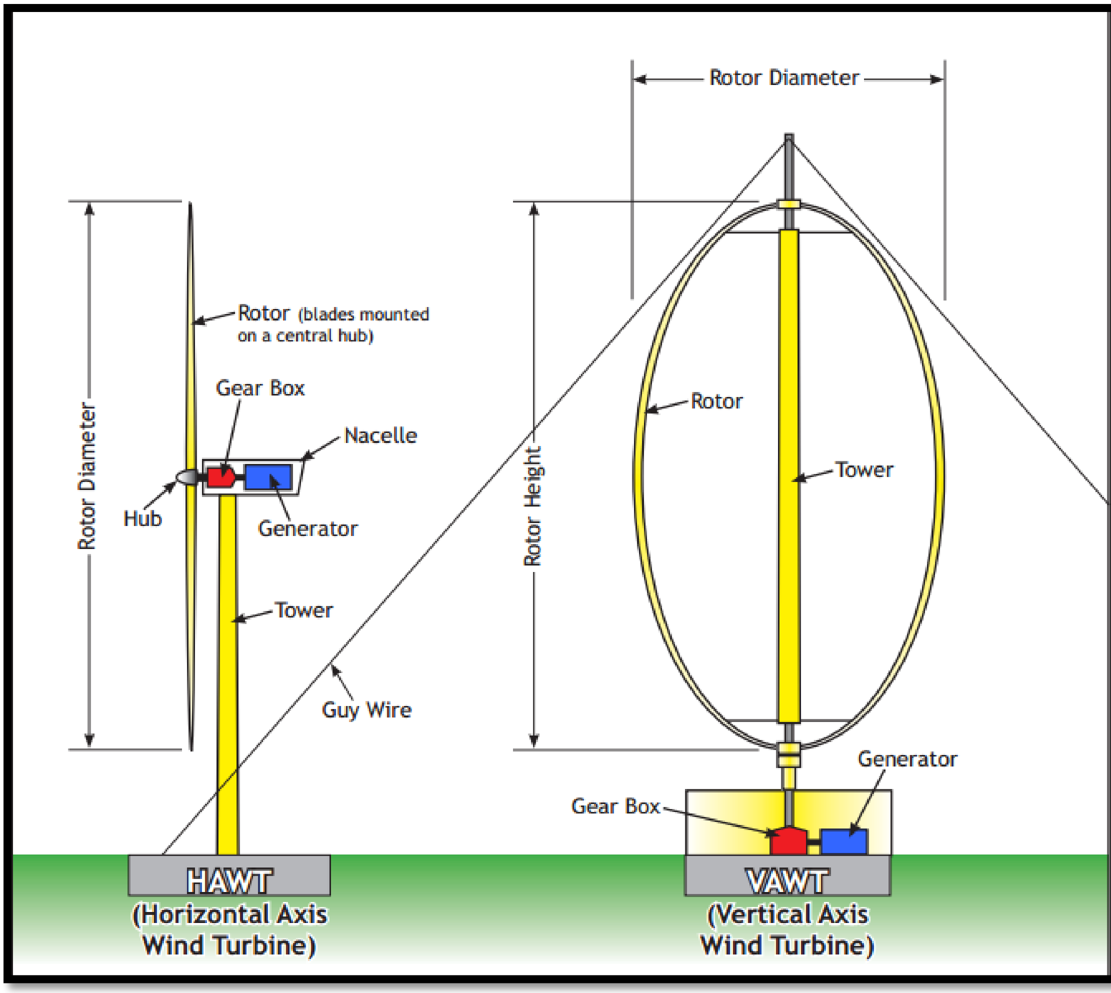

Figure 6 Horizontal Axis and Vertical Axis wind turbines

3.3.2.1 Vertical Axis Wind Turbines

This type of wind turbines are not as common as horizontal-axis wind turbines.. Vertical-axis wind turbines have existed for centuries and one of the oldest designs was used around 1000b.c which is called the Persian windmill. In this design, half of the sails are exposed to the wind which is pushed downward, causing the windmill to rotate. The Persian windmill was used mainly used to grind grain and pump water. One advantage of vertical axis wind turbines (VAWT) is their independence of wind direction in order to function. It means that the design can be seriously simplified, making them a great choice for developing countries due to their low cost.

One disadvantage of vertical-axis wind turbines is that they do not take advantage of the higher wind speeds at higher elevations above the ground as horizontal-axis wind turbines do.

Savonius Wind Turbine: Another example of a vertical-axis wind turbine is the Savonius wind turbine. The Savonius wind turbine was invented by Sigurd Johannes Savonius in 1922. [9]

The purpose of this turbine is to convert the force of the wind into torque on a rotating shaft.. This turbine is S-shaped when viewed from above. Because of the curvature, the blades experience less drag when moving against the wind than when moving with the wind. In this design, the differential drag is what causes the Savonius turbine to spin slowly but it yields a high torque. Because of their relatively slow rotational speeds, the Savonius wind turbine is not suitable for generating electricity on a large scale. Usually, this design is mainly used for grinding grain and pumping water.

Flap Panel Wind Turbine: Another example of a vertical-axis wind turbine is the Flap Panel wind turbine. The flap turbine is a type of turbine where the blades are made of movable flaps. In this design, when the sail is moving in the downwind direction, the flaps will close and in this way the flaps will not allow air to pass through the sail. On the other hand, when the sail is moving in the upwind direction the flaps will be open and allow air to flow through the sail. One key advantage of this type of wind turbine is that the flaps are operated by the wind and consequently there is no need for complicated mechanisms.

Darrieus Wind Turbine: The Darrieus wind turbine is one of the most famous vertical-axis wind turbines. This design was invented in 1931 by J.M. Darrieus. [9]

The Darrieus wind turbine is characterized by its C-shaped rotor blades. One key advantage of this type of wind turbine is that it does not need to be turned into the wind because the blades rotate about a vertical axis. Also, because of the shape of the blades they experience high centrifugal forces. One of the most important advantages of the Darrieus wind turbine is that the generator and controls are all located at ground level; therefore, making maintenance and repairs more accessible and economical to perform.

One big disadvantage of using this technology is that the Darrieus turbine is not self-starting. It needs to start turning before the wind rotates it. Therefore, if the turbine stops during low speed wind, it will not self-start once the wind speed increases. In some designs, an induction motor is used in order to start rotating the turbine.

Giromill Wind Turbine: A giromill wind turbine uses the same principal as the Darrieus turbine to capture energy, but in this design the blades are straight and individually attached to a vertical-axis. The blades are attached to the central tower by horizontal supports. Giromill wind turbines are characterized by their

H-bar shape. One key advantage of this turbine is that it works well under turbulent wind conditions. A giromill turbine is usually cheaper to build than most wind turbines; however, it is not very efficient and are not self-starting which means that a giromill turbine requires a motor to start.

3.3.2.2 Horizontal Axis Wind Turbines

Horizontal axis wind turbines are the most common and widely used wind turbine design. In a horizontal-axis wind turbine the axis of the rotation of the blades is parallel to the wind flow. This wind turbine must be pointed into the wind and the rotor and electrical generator are located in the top of the tower. Typically, in an horizontal-axis wind turbine (HAWT) the ratio of maximum linear speed of the blades to the wind speed is about 5:1 which is much higher than the ratio that could be obtained from a vertical-axis design, with the exception of the Darrieus wind turbine which could deliver a ratio of up to 6:1.

In order to prevent the blades of the wind turbine from being pushed into the tower under high speed wind conditions, the blades are made from rigid materials such as aluminum and fiberglass. Also, to reduce the turbulence produced by the tower, the blades are placed a reasonable distance from the tower and sometimes are tilted up by a small amount.

Up-wind HAWT: Most horizontal-axis wind turbines are designed to operate in an up-wind mode; that is, with the blades upwind of the tower. In this variant, the blades move in the direction from which the wind is blowing. Large wind turbines use a motor-driven mechanism that turns the turbine in response to the wind direction. Small wind turbines, on the other hand, use a tail vane to keep the blades facing into the wind. Up-wind turbines are the most common and widely used horizontal-axis wind turbine design because they produce less turbulence than the Down-wind turbines.

Down-Wind HAWT: A downwind HAWT is a turbine with the blades mounted behind the tower. In this variant, the horizontal-axis wind turbine operates in a downwind mode; that is, the wind passes the tower before striking the blades. The blades move in the same direction that the wind is moving. When this design is used, there is no need for a tail vaine or any other special mechanism for keeping them in line with the wind because the machine rotor naturally tracks the wind in a downwind mode. However, wind turbulence is a problem when using this design, leading to fatigue failures. Figure 7 shows the global average annual wind speed at 80m:

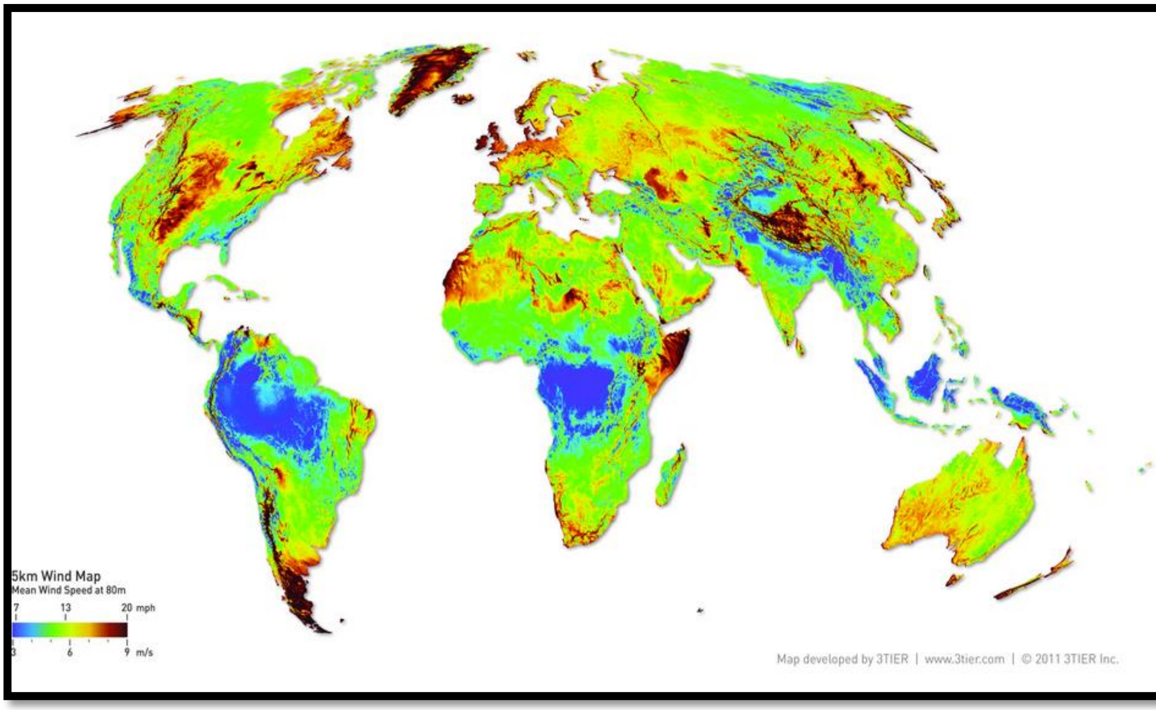

Figure 7 Global average annual wind speed

3.4 MPPT Charge Controller

Converting DC into DC is a feature of power electronic circuits in wind and photovoltaic power systems, this function is basically performed by solid state semiconductor devices that are periodically switched on and off at a desired frequency. No other technology has brought better improvement in power engineering, or holds greater potential of bringing enhancements in the future, than power electronic circuits and devices. In this section the DC to DC converters used in modern wind and solar power systems will be discussed.

3.4.1 Basic Semiconductor Switching Devices

First it is necessary to understand which types of solid states devices are available in the market, and how they function as well. Some of the more commonly used devices are as follows:

- Bipolar junction transistor (BJT).
- Metal-oxide semiconducting field effect transistor (MOSFET).
- Insulated gate bipolar transistor (IGBT).
- Silicon controlled rectifier (SCR), also known as the thyristor.
- Gate turn off thyristor (GTO).

The choice of these semiconductor switching devices solely depends on specific applications; power, voltage, current, and the frequency required for the system. A common feature between these semiconductor devices is that all are three-terminal devices as demonstrated in their regularly used circuit symbols.

The two power terminal 1 and 0 are connected in the main power circuit, and the control terminal G is connected to the controller. In general working operations, power terminal 1 is usually at higher voltage than power terminal 0. This is optional and its selection is arbitrary depending of the user. Terminal G however, is known as the gate terminal and it is connected to the auxiliary control circuit or in other words the controller.

These semiconductor devices are primarily used for switching power on and off as required. In the absence of the control signal at the gate terminal, the semiconductor device resistance between its two power terminal is large thus the semiconductor behaves like an open switch. In the other hand when a control signal is present or applied at the gate terminal then, the device resistance decreases approaching zero thus, making the device behave like a closed switch. The semiconductor device in the closed switch state lets the current flow freely through its body and travel through the circuit.

The voltage and the current ratings of these semiconductor switching devices available for purchase vary a lot. Some specifications and characteristics of each are listed on Table 9.

Table 9 Maximum Voltage and Current Ratings of Power Switching Devices.

Device	**Voltage Rating (Volts)**	**Current Rating (Amps)**	**Remark**
BJT	1500	200	Requires large current signal to turn on
IGBT	1200	100	Combines the advantages of BJT, MOSFET and GTO
MOSFET	1000	100	Higher switching speed
SCR	6000	3000	Once turned on, requires heavy turn-off circuit

The Switch is triggered periodically on and off by a sequence of control signals at the gate terminal of appropriate frequency. This control signal at the gate terminal may be of rectangular or other wave shape, and is generated by a separate firing circuit or triggering circuit. Even though this triggering circuit has a different identity, function, and many different features, it is usually integrated in the main power electronic component assemblage. Stand-alone renewable energy power systems use the DC to DC converter for battery charging and discharging. [59]

3.4.2 DC to DC Converters

DC to DC converters are widely used in power electronics; power supplies, charge controllers, motor drive applications and many others. In stand-alone system the input going to the converter is usually an unregulated DC voltage, and therefore the magnitude of the voltage will fluctuate. This is caused by the varying radiation intensity hitting the photovoltaic panel or by the varying wind speed turning the blades of the wind turbine. Switch-mode DC to DC converters are used to convert the unregulated DC input into a steady DC output at a desired voltage level. Implementation of active switches is a great advantage over passive switches, for example MOSFETs(Active switches) transistors are an efficient and fast way to allow a pulse width modulation (PWM) signal to control the frequency and duty cycle of the ON and OFF time of the switch. The higher the duty cycle the more power is transferred from input to output. One of the advantages of the PWM is that the signal remains digital from the source, in this case from the microcontroller to the gate terminal of the MOSFET, reducing or even eliminating the need for any analog-to-digital signal conversion. Digital signals are not affected as much from outside noise, unless the noise is sufficient to change the signal from 1 to 0(On or Off, depending of selection). Below the following DC-DC basic converters will be discussed;

- Step-Down (Buck) converter.
- Step-Up (Boost) converter.
- Step-Down / Step-Up (Buck-Boost) converter.

3.4.2.1 Step-Down (Buck) Converter.

The Step-Down converter in Figure 8 below is the most widely used DC-DC converter circuit, in other words the buck converter. The semiconductor switching devices used in this type of converter are typically the BJT, MOSFET, or the IGBT. This converter steps down the input voltage to the predetermined battery voltage needed. The transistor switch is turned on and off at high frequency, usually tens of Kilohertz. The duty ratio D of the switch is defined as shown in Equation 1

$$\mathbf{Duty\ ratio\ (D)} = \frac{\mathbf{Time\ on}}{\mathbf{Perios}} = \frac{\mathbf{T(on)}}{\mathbf{T}} = \mathbf{T(on)} * \mathbf{switching\ frequency} \qquad \text{Equation 1}$$

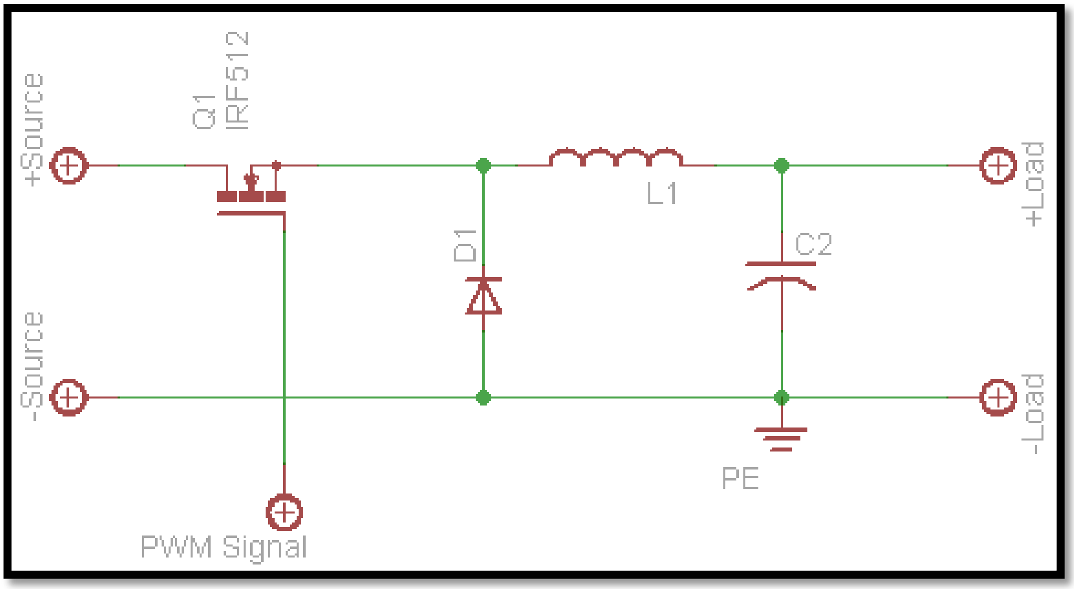

Figure 8 Battery charge converter for PV systems (DC to DC buck converter).

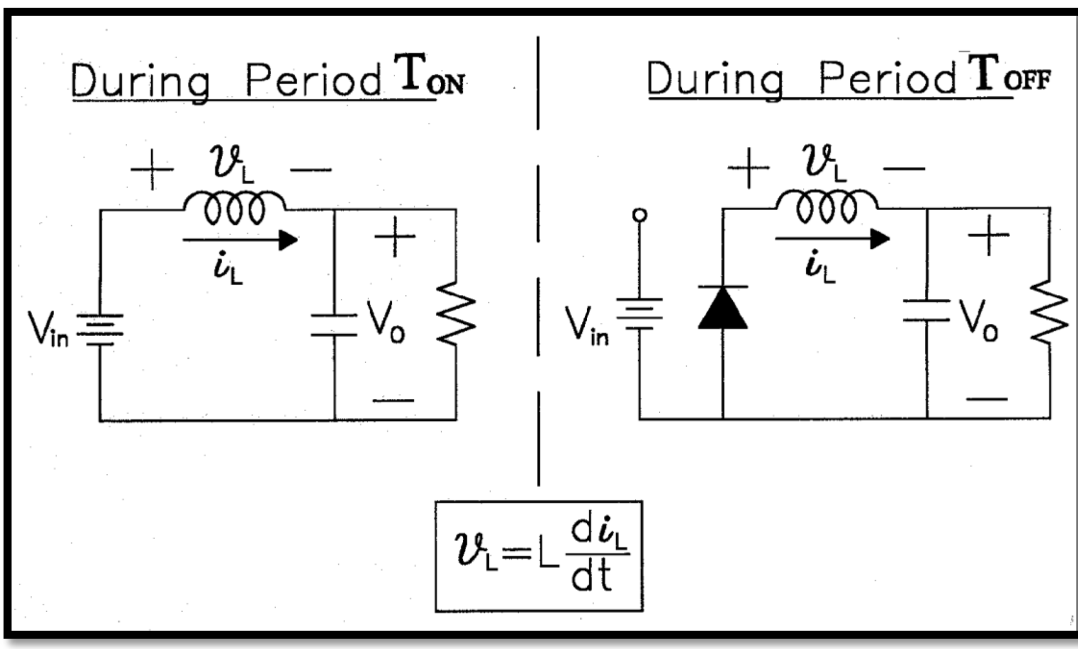

Figure 9 Charge converter operation during switch on-time and off-time. [60]

The converter process during one complete cycle of the triggering signal is demonstrated above in Figure 9. During the on time, the switch is closed and the circuit operates as shown on the left side. The DC source charges the capacitor and supplies power to the load via the inductor. During the off time, the switch is open and the circuit operates as shown on the right side. The power drawn from the DC source is zero. However full load power is supplied by the energy stored in the inductor and the capacitor, with the diode providing the return circuit.

Thus, the inductor and the capacitor provide short-time energy storage to ride through the off period of the switch.

A written description exemplifies the essential method of analyzing all power electronic circuits. The power electronic circuit analysis is based on the energy balance over one period of the switching controlled signal.

• Energy supplied to the load over the total period of repetition must equal the energy drawn from the source during the on-time, and Energy supplied to the load during the off-time must equal the energy drawn from the inductor and the capacitor during off-time.

In addition, the volt-second balance method is used, which in real meaning gives the energy balance. In the steady state condition, the inductor volt-second balance during the on and off periods must be maintained. Since the voltage across the inductor must equal:

$$\mathbf{Vl} = \mathbf{L}\frac{\mathbf{dIl}}{\mathbf{dt}} \qquad \text{Equation 2}$$

Then, During (On-Time): $\mathbf{\Delta Il * L = Vl\,(Ton) \gg Vl = (Vin - Vout)}$ Equation 3

And, During (Off-Time): $\mathbf{\Delta Il * L = Vl\,(Toff) \gg Vl = -\,Vout}$ Equation 4

If the inductor is sufficiently large, which is usually the case in practical circuits, the change in the inductor current is small, and the peak value of the inductor current is given by Equation 5 below:

$$\mathbf{Ipeak = Io + {}^{1}/_{2}\,\Delta Il} \qquad \text{Equation 5}$$

Load current $\mathbf{Io} = \frac{\mathbf{Vout}}{\mathbf{Rload}} = \mathbf{Average\ of\ the\ inductor\ current}$ Equation 6

$$\mathbf{Vout = Vin * D} \qquad \text{Equation 7}$$

It is seen from Equation 6 that the output voltage of the circuit is controlled by varying the duty ratio D. This is done in a feedback control loop with the required battery charge current as the reference. The duty ratio is controlled by (PWM) modulating the pulse width of Time On.

3.4.2.2 Step-Up (Boost) Converter.

The step-up converter circuit is shown below in Figure 10. This also called boost converter, steps up the low sagging input voltage to the required output voltage. When the transistor switch is on, the inductor is directly connected to the DC source. When the switch is off, the inductor current is forced to flow through the diode and the load. The output voltage of the boost converter is derived again from the volt-second balance in the inductor. With duty ratio D of the switch, the output voltage is given by the following Equation 8

$$\mathbf{Vout} = \frac{\mathbf{Vin}}{\mathbf{1-D}} \qquad \text{Equation 8}$$

For all values of D < 1, the output voltage is always greater than the input voltage. Therefore, the boost converter can only step up the voltage. On the other hand, the buck converter described above can only step down the input voltage.

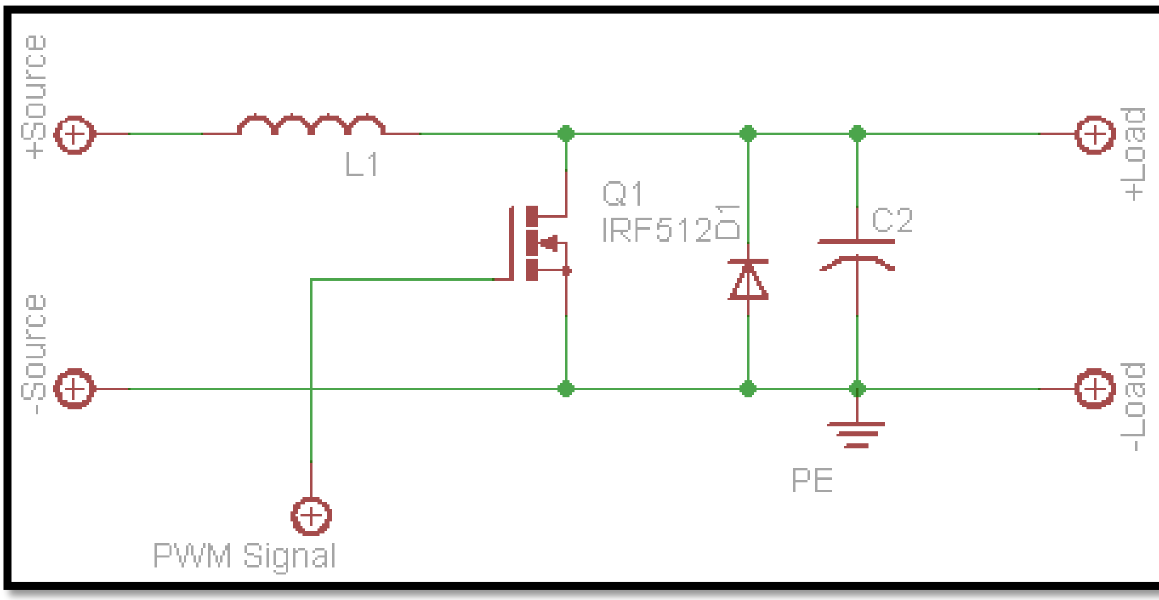

Figure 10 Battery discharge converter circuit for PV systems (DC to DC boost converter)

3.4.2.3 Step-Down/Step-Up (Non-inverting Buck-Boost) Converter

Combining the two converters in cascade, therefore, give a buck-boost converter, which can step down or step up the input voltage. A modified buck-boost converter often used for this purpose is shown in Figure 11 Buck-Boost converter circuit (general DC to DC converter for PV systems).. The voltage relation is obtained by cascading the buck and boost converter voltage relations. Equation 9 illustrates this relation.

$$\mathbf{Vout} = \frac{\mathbf{Vin*D}}{\mathbf{1-D}}$$

Equation 9

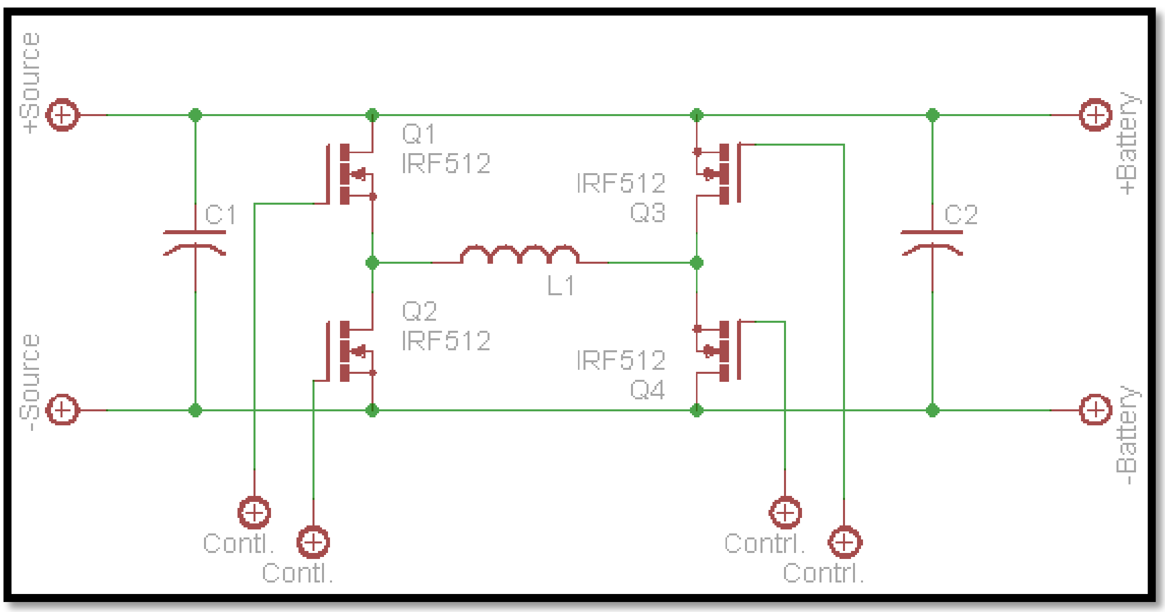

Figure 11 Buck-Boost converter circuit (general DC to DC converter for PV systems).

Equation 9 for the buck-boost converter shows that the output voltage can be higher or lower than the input voltage depending on the duty ratio D shown in Figure 12.

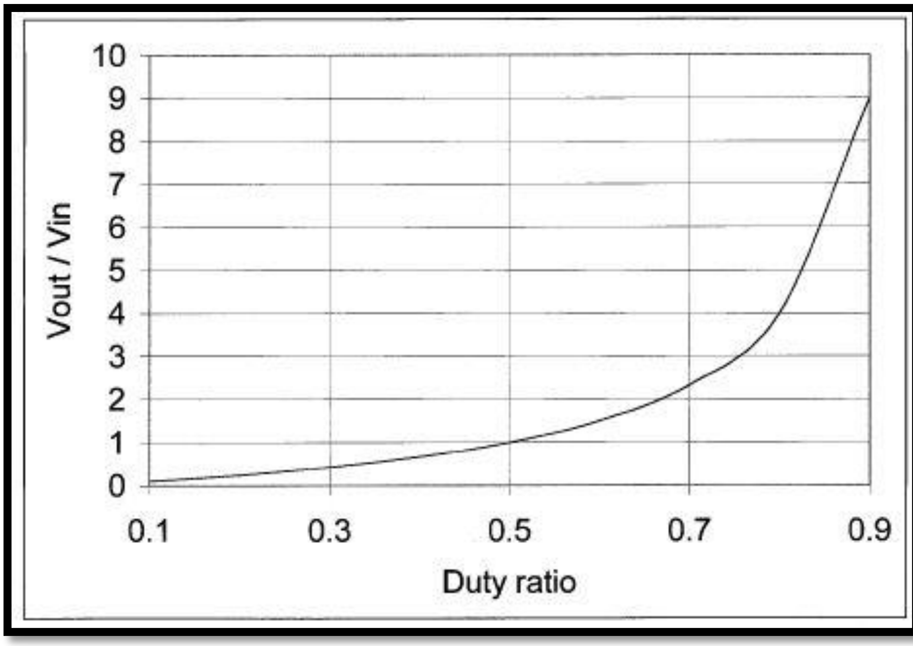

Figure 12 Buck-boost converter output to input ratio versus duty ratio.[60]

As shown in the Figure 12 above Buck-Boost DC to DC converters is the ideal topology for battery charging controllers, since the input can be lower or higher than the desire Output voltage. Another way to make it more efficient is to substitute the rectifier components with actual switches; Bipolar junction transistor (BJT), Metal-oxide semiconducting field effect transistor (MOSFET), Insulated gate bipolar transistor (IGBT), Silicon controlled rectifier (SCR), also known as the thyristor, or Gate turn off thyristor (GTO). MOSFETS always seem more practical for robust designs and for cost considerations.[60]

3.4.3 Half-Bridge and Full Bridge Drivers

Regardless of the DC-DC converter topology used from section 3.4.2 all of the topologies will use either a Bipolar Junction Transistor (BJT), or a Metal Oxide Semiconductor Field Effect Transistor (MOSFET), or Insulated-Gate Bipolar Transistor (IGBT) to achieve the fast switching speeds need for the topology. These devices need to be driven by a separate device other than the microcontroller. The driver will still receive commands from the microcontroller as to which transistor to turn on or off and at what rate but the microcontroller is not designed to work directly with the transistor for the transistor to be at an optimum working condition.

The drivers are attached at the gate of each transistor and optimize the transistor's switching speed. When a transistor is turned on or off it does not instantaneously go to the desired state it ramps up or ramps down to it. Although in most cases this ramp up or down is in the nanoseconds range and can be overlooked for most applications our project cannot over look this time delay. For our application the less time to achieve the desired state the less noise and higher the efficiency of the DC-DC converter will be. Another reason to use drivers is that the gate voltage for the on state could be higher than what our low power microcontroller will be.

Both half-bridge and full bridge drivers do the same thing, which is to drive the transistors. A bridge configuration of four transistors is so common that a specific driver was configured for it. The difference between a full-bridge and the half-bridge is exactly like the name implies. The full-bridge will drive all four transistors at the same time while the half-bridge will only drive two of those transistors. There are applications where one can be better than the other, including cost, performance and speed. However for the purpose of a charge controller a full bridge driver will be used. Just note that when the term driver is used, it is meant to describe the process of the full bridge driver and all four transistors.

To achieve the fastest possible switching speed of the transistor the driver plays with the electrical physics that go behind a transistor. Each transistor regardless of the type (i.e. BJT, MOSFET, or IGBT) there is a change in the material's (silicon in most transistors) doping. This change will create an effective capacitance between the dissimilar doping levels. "Ultimately, the switching performance of the MOSFET transistor is determined by how quickly the voltages can be changed across these capacitors. "[14] Another factor that the driver can help out with is the $R_{G,I}$ resistance, which is not usually specified in the data sheets for transistors. For the purposes of this section a MOSFET will be the only transistor type considered, but the same principles still apply to other transistors.

For MOSFETs there are three main capacitances that need to be considered they are as follows; C_{GD}, C_{GS}, and C_{DS}. They can be calculated from a typical data sheet from the below Equations 10, 11 and 12.

$$\mathbf{C_{GC} = C_{RSS}\ ;\ C_{GS} = C_{ISS} - C_{RSS}\ ;\ C_{DS} = C_{OSS} - C_{RSS}} \qquad \text{Equation 10}$$

"The CGS capacitor is formed by the overlap of the source and channel region by the gate electrode.
Its value is defined by the actual geometry of the regions and stays constant (linear) under different operating conditions." [14] Therefore, there is no changing the capacitance of this effective capacitor and needs to be a part of the selection process when designing. The other two effective capacitances can be controlled and minimized by changing the V_{DS} voltage, see equations below. This is the exact reason why a driver is needed. A driver will be able to increase the speed of the transistor by adjusting the V_{DS} voltage.

$$\mathbf{C_{GD}} \approx \frac{\mathbf{C_{GD,0}}}{\mathbf{1+K_1*\sqrt{V_{DS}}}}$$ Equation 11

$$\mathbf{C_{DS}} \approx \frac{\mathbf{C_{DS,0}}}{\mathbf{1+K_2*\sqrt{V_{DS}}}}$$ Equation 12

For a transistor there are only two transition states which are from off to on and on to off, obviously. The process in which a driver drives their respective transistor is different. Below is a model of a MOSFET and a series of graphs describing the off to on transition for a transistor. "In the first step the input capacitance of the device is charged from 0V to VTH. During this interval most of the gate current is charging the CGS capacitor." [14] "This period is called the turn-on delay" [14] this delay time is so insignificant that it can be ignored for the design of the software for the charge controller.

The second interval is what we care about to reduce the noise and increase the efficiency. "In the second interval the gate is rising from VTH to the Miller plateau level, $V_{GS,Miller}$. This is the linear operation of the device when current is proportional to the gate voltage. "[1] This part of the transition for the transistor is where a driver can be a big help. Entering into the third period of the turn-on procedure the gate is already charged to the sufficient voltage (VGS,Miller) to carry the entire load current and the rectifier diode is turned off. "The last step of the turn-on is to fully enhance the conducting channel of the MOSFET by applying a higher gate drive voltage. "[14] If you look at the diagram in Figure 13 below the on to off procedure is the same thing backwards.

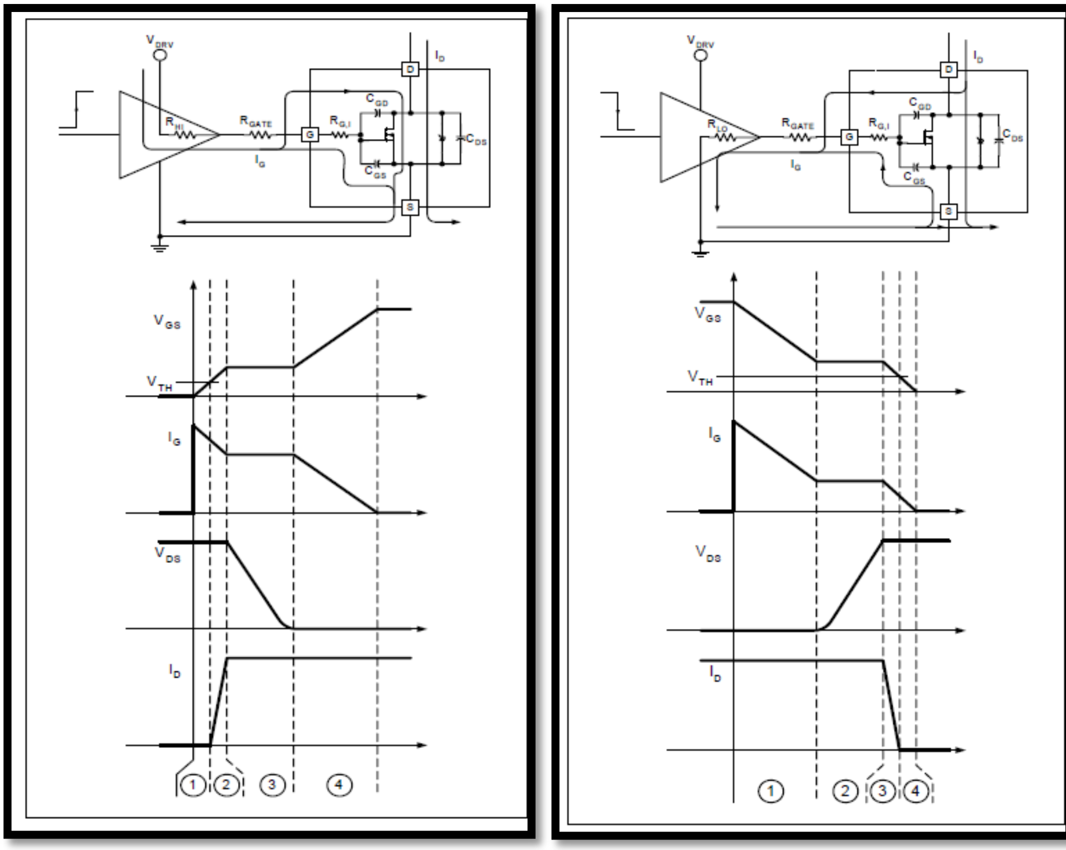

Figure 13 On-Off Procedures for a driven MOSFET

Drivers whether it is a full bridge or half bridge driver help increase the speed of the transition times for a transistor. Although in this section the MOSFET was the main discussion the principle ideas work the same with BJTs and IGBTs. They all have these effective capacitances and resistances. A driver is able to work with these physical problems and increase the overall performance.

3.4.4 Max Power Point Tracking Algorithms

3.4.4.1 Max Power Point

Like all electrical devices there is usually a complicated I-V curve that is associated with that electrical device. PV panels and wind turbines (this also includes hydro and other similar turbines) are no exception to this. However, because PV panels' and wind turbines' I-V curves change as the sun, temperature, or wind changes (unlike diodes for example) finding the maximum power point becomes a challenge.

Below is a typical I-V curve of a PV panel showing the dependence on the temperature or on the irradiance. It is clear from both graphs that as we increase the voltage from 0 our power will continue to increase because current is unchanged. As we draw more power from the PV the current will finally drop of and so will the power. This shows that there is a maximum power point somewhere on this curve.

From Figure 14 a change in temperature will change the voltage point where maximum power point will occur. It does little to change the amount of current we can draw from the PV panel. A change in temperature will increase the sharpness of the I-V curve. Figure 14 also shows that temperature decreases the PV panel will be able to produce, for more information on this go to PV Panels chapter on section 3.2

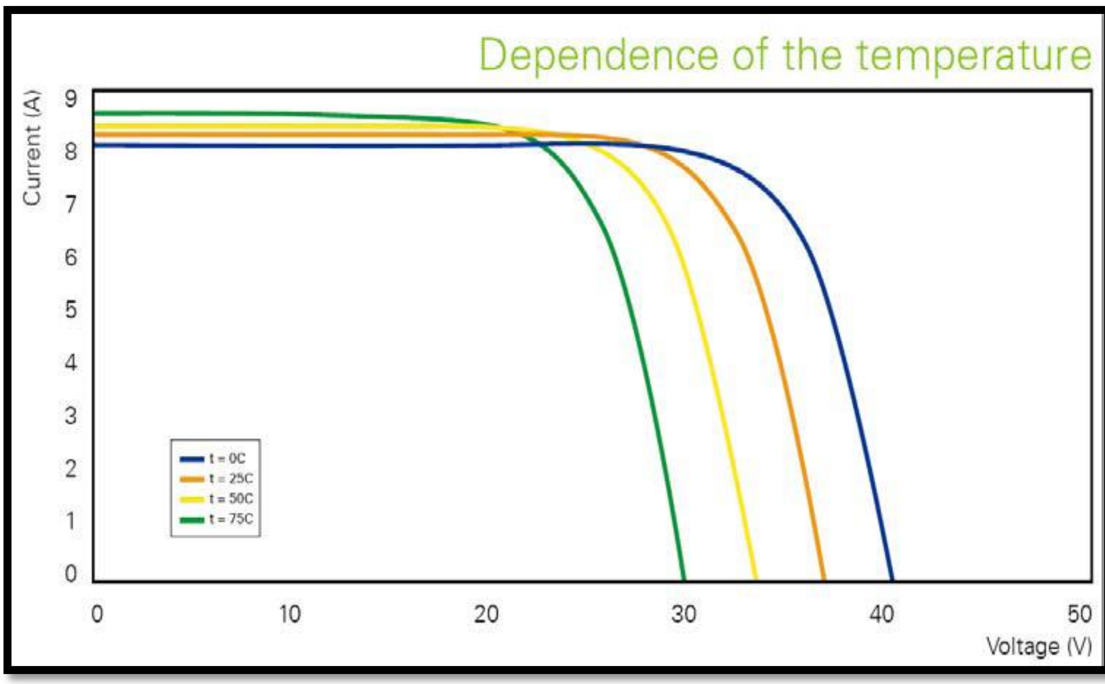

Figure 14 Dependence of the Temperature for PV Panel [14]

Below shows the relationship of irradiance and the I-V curve. Irradiance does change the amount of current we are able to take from the PV panel, unlike temperature. Irradiance as it becomes less intense will flatten out the I-V curve. For more information PV panels and their I-V curves go to PV panel chapter on section 3.2

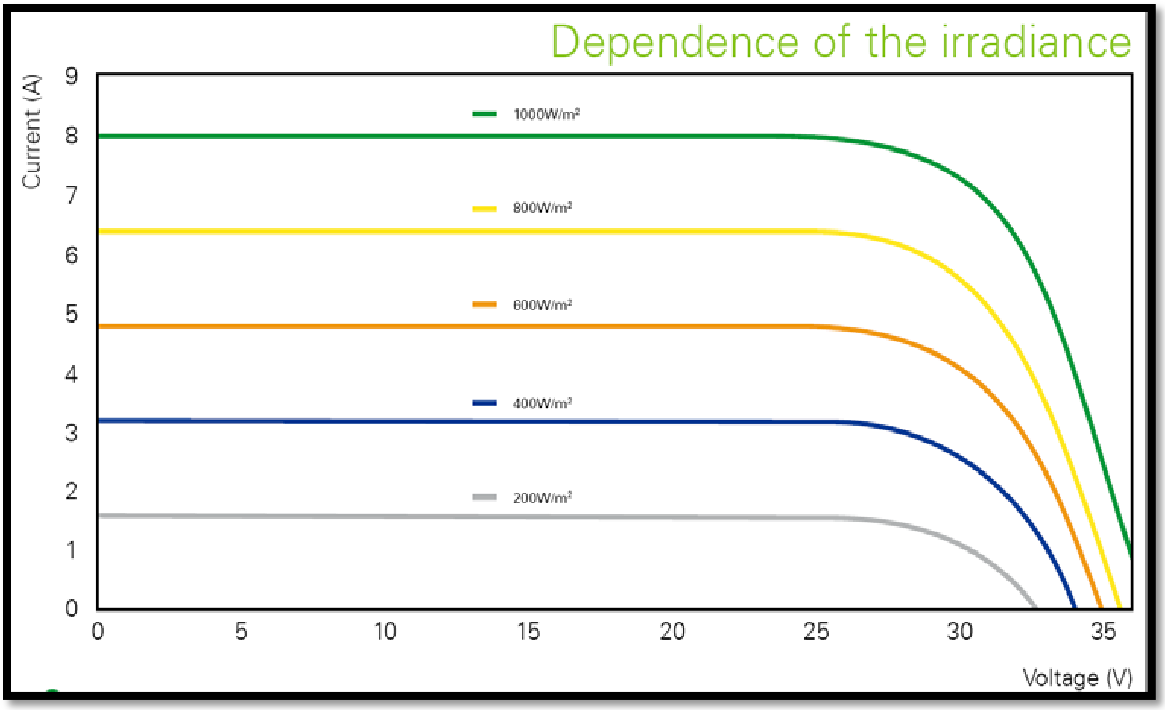

Figure 15 Dependence of the Irradiance for PV Panels [14]

If you could measure and plot every I-V curve for different temperatures and irradiance levels you could simply measure these two variables and select the best voltage to get the maximum power point. Also for wind you could do a similar measure and plotting for wind speeds. The problem becomes having all those points for an unknown PV panel or wind turbine which change slightly from panel to panel and turbine to turbine. Therefore knowing the maximum power point is impossible, but finding it is possible. Finding the maximum power point will require an algorithm, each having advantages and disadvantages. In most cases using a combination of algorithms under varying conditions is implemented into the code to get desired results.

3.4.4.2 Design Factors

Costs: The costs of a system depend on the complexity of the system. The more accurate a system is the more and faster sensors or processors are needed. The sensors themselves need to be more accurate making them more expensive. The processor needs to be faster to find the maximum power point faster, increasing the efficiency, making it more expensive and so on. Another cost may also be the complexity of the system making the amount of time to design it more thus making that system more expensive.

Convergence: This is the speed at which the algorithm can converge to the maximum power point. This is an important factor that both the algorithm and processor used can change the ultimate results. An algorithm that uses less iteration will converge fast or a processor that is fast will have the same effect. It is important to have a fast convergence time because factors like irradiance, temperature and wind change. The changing environmental conditions change the I-V curve and thus the maximum power point. A combination of both a fast processor and an algorithm with few iterations is the ultimate goal of a design without going out of budget.

Oscillation: Oscillations around the maximum power point can occur with some algorithms. If these oscillations become out of control the system may not ever find the maximum power point and try to go to a unrestricted voltage. This will result in lower efficiencies.

Local Maxima: Although the I-V curves look smooth in Figure 14 and Figure 15, on certain PV panels and wind turbines the relationship between current and voltage maybe more complicated resulting in local maxima. If the algorithm becomes fixated on a local maxima it will fail to find the true maximum power point. Algorithms need to be intelligent enough to either avoid local maxima or somehow discover if they are at local maxima. This again can result in lower efficiencies if proper methods are not employed.

3.4.4.3 Algorithms

3.4.4.3.1 Perturb and Disturb

This is a commonly used algorithm that has very good results. It is a simplistic method that can use much iteration to achieve the maximum power point. It uses a 'hill climbing' method that changes the voltage until it sees a decrease in power then starts its way back up the hill from the other side. This method has problem with oscillations and is not a fast method to convergence. Another problem with this method is that at times of rapid environmental changes it can track in the wrong direction and never recover. There is also the question of what voltage do you start at and what would be the sampling rate. This algorithm is usually used with other algorithms alongside it. "For example, if increasing the voltage to a cell increases the power output of a cell, the system increases the operating voltage until the power output begins to decrease. Once this happens, the voltage is decreased to get back to the maximum power output value. This process continues until the maximum power point is reached. Thus, the power output value oscillates around a maximum power value until it stabilizes. Perturb and observe is the most commonly used MPPT method due to its ease of implementation." [17]

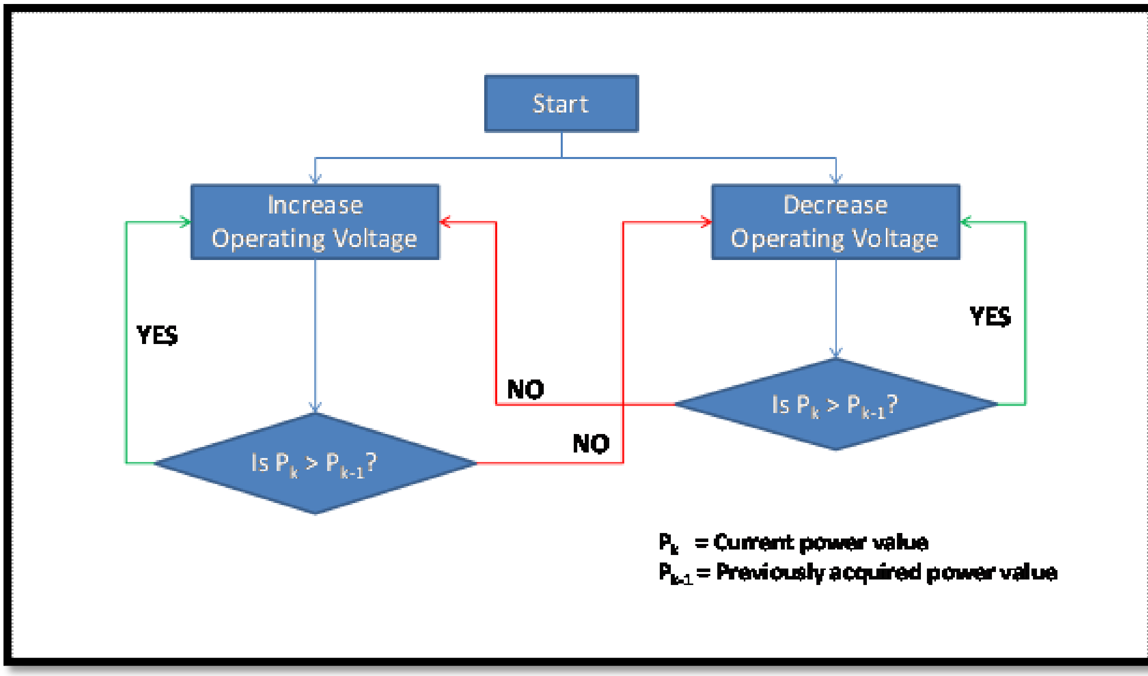

Figure 16 Block Diagram for Perturb and Disturbed Method [18]

3.4.4.3.2 Incremental Conductance

The incremental conductance is similar to the perturb and disturb method in that it measures the values then makes a decision in which way would give it more power. The difference between the two methods is that the incremental conductance method uses the rate of change rather than the value at a point. This then uses a series of equations to decide the next change in voltage, whether that is in the positive direction, negative, or none.

$$\frac{\mathbf{dP}}{\mathbf{dV}} = \mathbf{0} => \boldsymbol{at\ Maximum\ Power\ Point};\ \mathbf{no\ change\ required}$$
Equation 13

$$\frac{\mathbf{dP}}{\mathbf{dV}} > \mathbf{0} => \boldsymbol{to\ the\ left\ of\ the\ Maximum\ Power\ Point};\ \boldsymbol{increase\ voltage}$$
Equation 14

$$\frac{\mathbf{dP}}{\mathbf{dV}} > \mathbf{0} => \boldsymbol{to\ the\ right\ of\ the\ Maximum\ Power\ Point};\ \boldsymbol{decrease\ voltage}$$
Equation 15

$$\mathbf{dP} \equiv \mathbf{change\ in\ power}$$ Equation 16

$$\mathbf{dV} \equiv \mathbf{change\ in\ voltage}$$ Equation 17

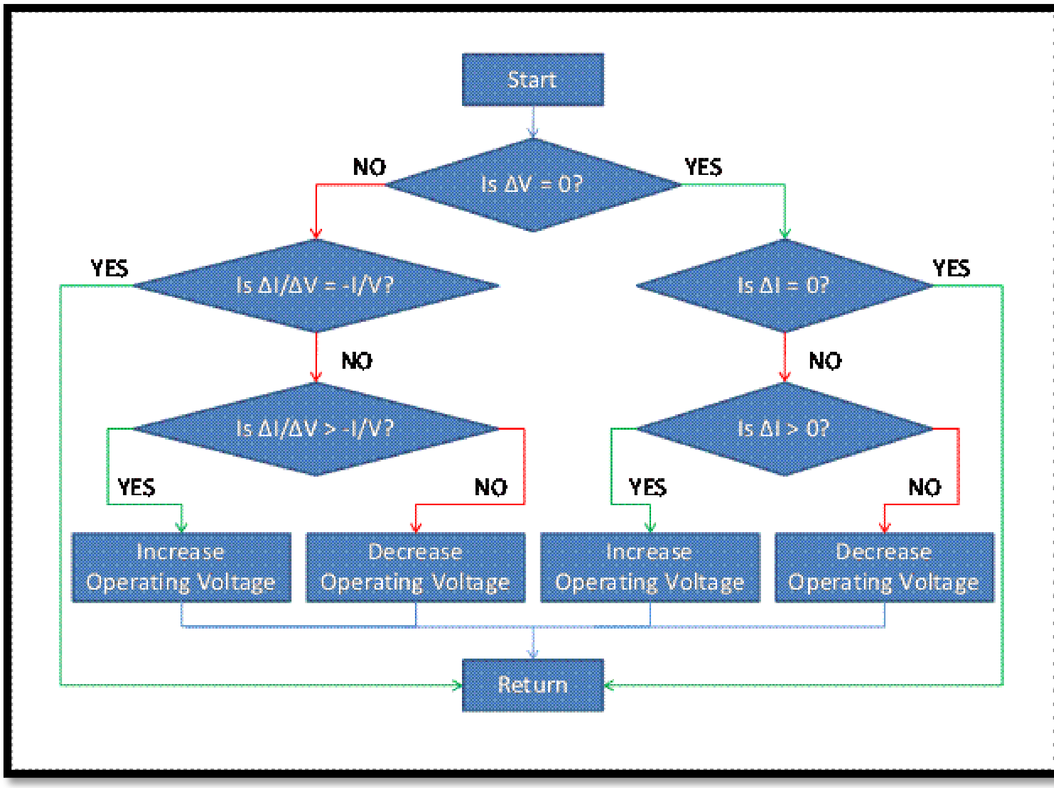

Figure 17Block Diagram for Incremental Conductance Method [19]

3.4.4.3.3 Fractional Open Circuit Voltage

There is a relationship between the maximum power point voltage and the open circuit voltage. This relationship is linear making it is to find the maximum power point voltage once the constant of proportionality is found. The main problems with this method are to finding the proportionality constant and that for a brief moment the power is disturbed.

First you need to find the proportionality constant which is usually between 0.71 and 0.78. This is different for every PV array and it also differs for the same array at different temperature. To compute the proportionality constant you just need to know the open circuit voltage then find the maximum power point voltage. Then divide Vmpp by Voc.

$$\mathbf{V_{mpp} = k_1 V_{oc}} \qquad \text{Equation 18}$$

The second problem with this method is once the proportionality constant is known to find the maximum power point voltage you must open the circuit temporarily cutting off power to the rest of the circuit. This can create bad ripple voltages because of the periodic on off switching of the converter. This method also cannot be used for wind turbines because if a wind turbine is connected to an open circuit the turbine could stall. [20]

Table 10 MPPT Algorithms Conclusion [21]

MPPT technique	Convergence Speed	Implementation Complexity	Periodic Tuning	Sensed Parameters
Perturb & Disturb	Varies	Low	No	Voltage
Incremental Conductance	Varies	Medium	No	Voltage, Current
Fractional Voc	Medium	Low	Yes	Voltage
Fractional Isc	Medium	Medium	Yes	Current
Fuzzy Logic	Fast	High	Yes	Varies
Neural Network	Fast	High	Yes	Varies

3.5 Voltage Sensors

The voltage sensor in our system will help us determine the power coming from the solar or wind power source. The information from the voltage sensor will go to both the MPPT charge controller and the main controller. This sensor will also be isolated on the high power side and then the information will be transferred over to both of the controllers. This is important because if there is a voltage spikes the isolation will protect the microcontrollers which are more sensitive to the large changes in voltage.

The MPPT charge controller will take the information from the voltage sensor both from the input side (the side where the solar or wind source is on) and the output side. It will need to not only find maximum power point but also to control the DC to DC converters output voltage. DC to DC converter need both input voltage and output voltage currently to accurately maintain a particular output voltage. The main controller will use the information from the voltage sensor for safety and display features. If there is a trend of the voltage increasing too much or too fast or some abnormal voltage the main controller will be able to open the circuit connecting the solar or wind power source and save the internal electronics. The circuit will have two resistors R1 and R2 which will be place in parallel with the solar or wind power source or the DC to DC converter that will be used to act as a voltage divider. R1 must be much larger than R2. The difference between R1 and R2 need to be orders of magnitude different to prevent damage. Therefore, the voltage across R2 will be proportional to the voltage of the solar or wind power source and not hurt the isolation device. The isolation device is there just in case of a voltage spike so how, it will be discussed further in isolation devices on section 3.7. The voltage across R2 is fed into an isolation device then a low pass filter then to an analog to digital converter. The information from the digital converter will then be distributed to both the MPPT charge controller and the main controller. [22] A block diagram of the voltage sensor is shown below in Figure 18. The analog to digital converter will be there to "talk" to the microprocessors for MPPT charge controller and the main controller. This is needed because microprocessors only read in digital signals and cannot directly tell the voltage from R2. Therefore, it is necessary to convert that analog signal to a digital one.

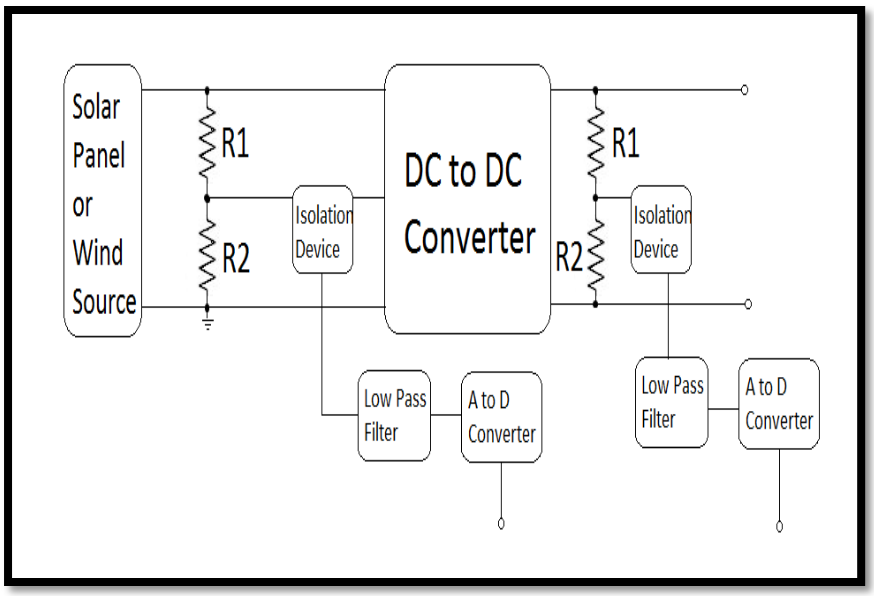

Figure 18 Voltage Sensor Block Diagram

3.6 Current Sensor

The current sensor is just as important as the voltage sensor. Without it the power delivered to the system by the solar or wind power source would be unknown. The maximum power point would also be impossible to find. The current sensor will be isolated as well trying to keep less robust components away from possibly fluctuating currents. By doing this we will slow down the response time but not by a significant amount. The information from the current sensor will go to both the MPPT charge controller and the main controller.

The circuit will have a one resistor called Rshunt which is place in series with the solar or wind power source. The voltage across Rshunt will be measured using a current shunt monitor. The voltage across the voltage Rshunt resistor will be separated by an isolation device to protect the more sensitive electronics. After the current shunt monitor the signal will go through a low pass filter then a analog to digital converter. After the analog to digital converter it will go to both the MPPT charge controller and the main controller. The resistance of Rshunt should be very small to minimize the voltage drop to the DC to DC converter. [23]

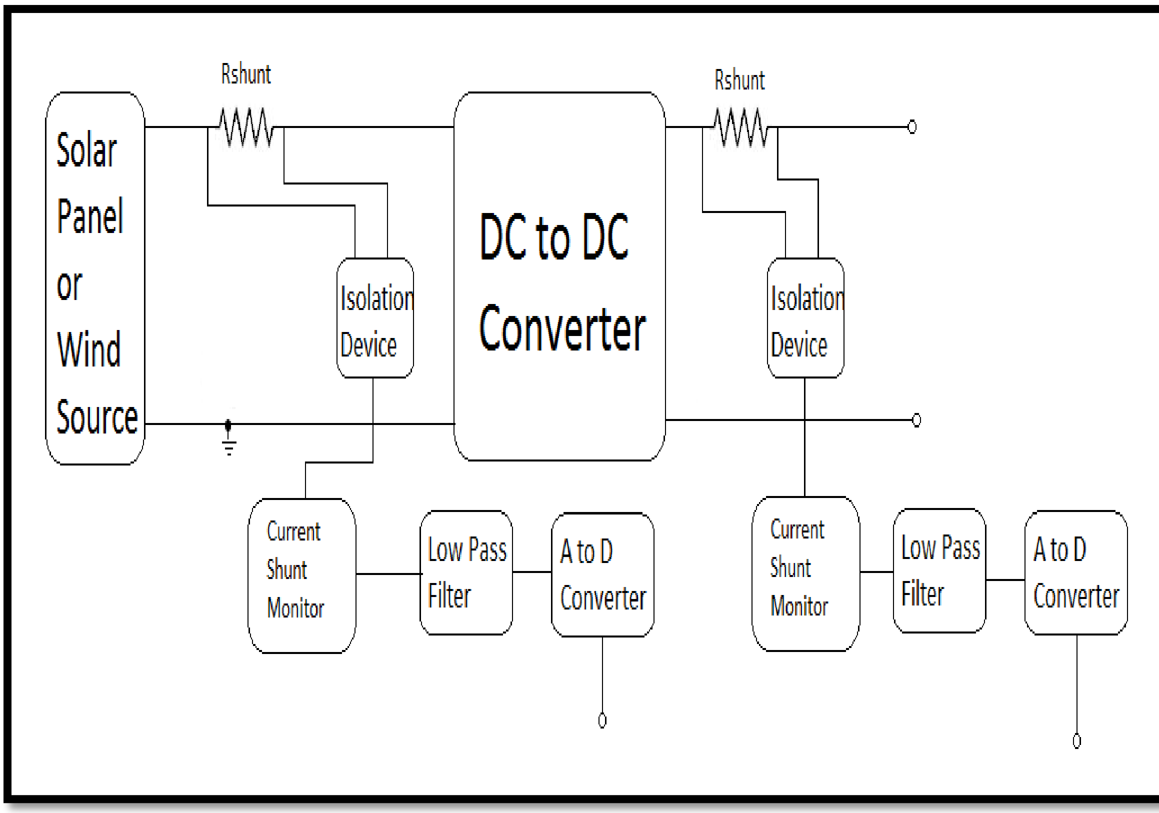

Figure 19 Current Sensor Block Diagram

3.7 Isolation Devices

An isolation device is a method to isolate high power electronics from low power electronics. Microcontrollers are very sensitive to voltage and current. They have very narrow ranges to which the voltage and current cannot go out of without risk of destroying the microcontroller. Because our system is dealing with high power it is necessary to isolate the high powered side from the low power microcontroller side. This could be done with voltage dividers however; to ensure the safety of the microcontrollers we will isolate them from the high powered side. This will decrease the speed and accuracy of the system. These decreases in speed and accuracy are not significant enough to risk the micro controllers.

3.7.1 Optocoupler

Optocoupler are one way of isolating different power level electronics from each other. They use light to transfer the voltage from one source to the next. No electrical power is transferred from the optocoupler so if there is a spike on one side there is no risk to the other side because there can be strict limitations to the maximum power that the other side of the optocoupler can deliver. Optocoupler come in many forms due to the different materials that can make up an optocoupler. Figure 20 shows the basic idea of an optocoupler. [24]

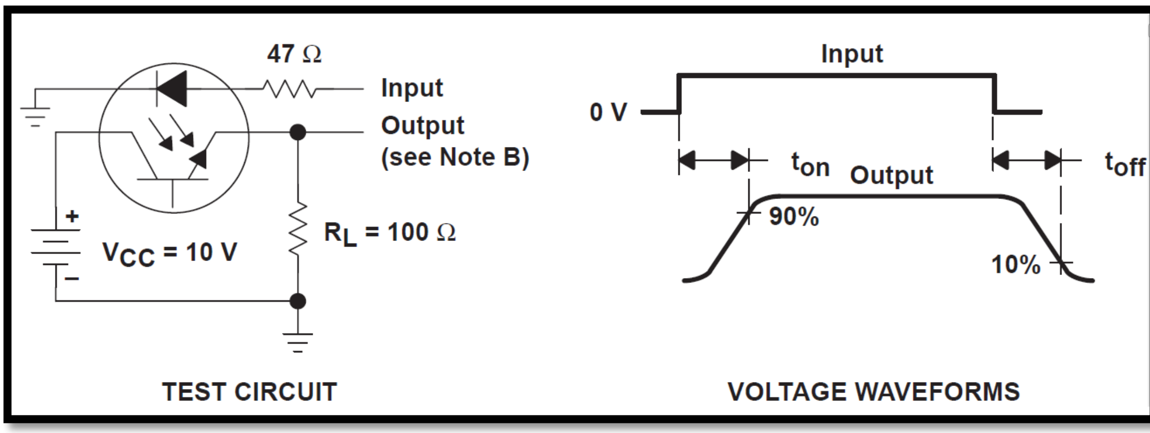

Figure 20 Basic optocoupler [25]

3.7.2 Transformer Based Isolator

Transformer based isolators can be faster and smaller than their optocoupler counter parts. Their main flaw is that they loss accuracy of the information. Transformer based isolators use inductors to separate the two circuits and transfers the information through the magnetic field. They are just as effective as the optocoupler in isolating the high power side from the low power side. The main disadvantage that transformer based isolators face is that they need to be digital instead of analog. The inductors distort the information coming into the isolator and that distortion need to be corrected digitally.

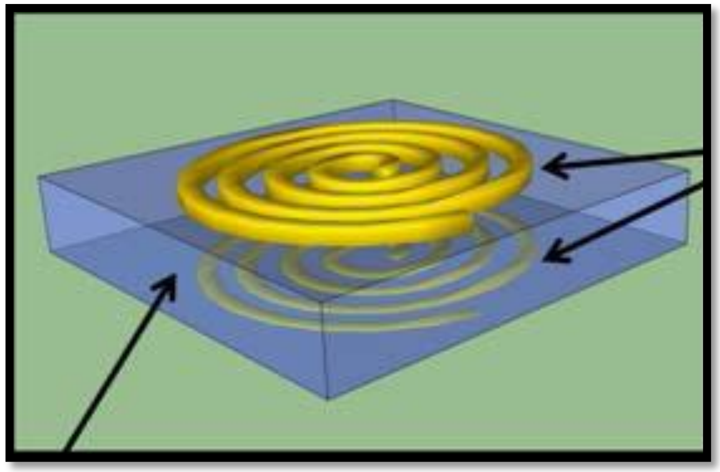

Figure 21 Transformer Base Isolator [26]

3.8 Temperature Sensors

Temperature sensors will be used in our design in order to provide the user with accurately data on the temperature of its surrounding s, which has an effect on the outcome of the solar panel source input, the performance of the batteries, and the overall condition of the component s of our system. Reliable and easy to change sensors will be used, so the readings can be display through the LCD screen and warned the user for any anomaly or failure on the system.

The International Practical Temperature Scale (IPTS) is equipment with calibration standards for making measurements in temperature scales. Since it has only fixed temperature, we must use elements to interpolating between the temperatures that can contain transducers. We will discuss the most common temperature transducers: thermocouples, resistance temperature detectors, thermistors, and IC sensors.

3.8.1 Thermocouple

This temperature transducer uses two wires of dissimilar metals, which are joined together. One end of the junction is the temperature reference, while the other end is where the temperature is measured. When the temperature at the junction of the two metals changes drastically a voltage is produced, and can be display back as temperature. Figure 22, shows the schematic of the thermocouple, the junction of the two wires is the measuring point of the object in contact, the two extension wires represent the two dissimilar metal plates, and the bigger square. As its name suggests, this temperature sensor is actually a junction of two corresponds to the temperature reference point.

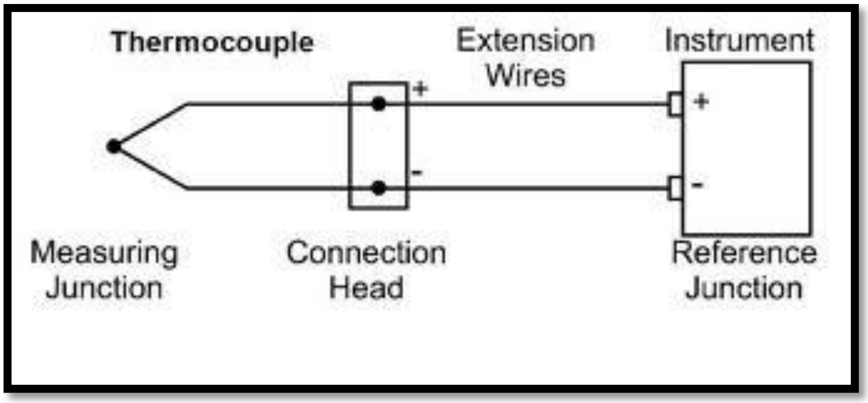

Figure 22 Thermocouple Schematic [27]

There are various combinations calibrations that make up a thermocouple, we will show the four most common which are J, K, T and E, each has a different temperature range and environment conditions which are shown in Table 11. Also, the size of the wire affects the range of the temperature outcome. That is, a very thin thermocouple may not reach the full temperature range.

The criterion has to be analyzed before choosing a thermocouple in a design:

- Temperature range
- Chemical resistance of the material
- vibration resistance
- Installation requirements

Table 11 Temperature Ranges and Accuracy

Calibration	**Temperature Range**	**Standard Limits of Error**	**Spec. Limits of Error**
J	0°C to 750°C	.75%	.4%
K	-200°C to 1250°C	.75%	.4%
E	-200°C to 900°C	.5%	.4%
T	-250°C to 350°C	.75%	.4%

Lastly, we consider the response time thermocouple sensors provide. Generally, five times constants are required for the sensor to approach 100% of the step change value. Depending on the size and type of it can vary the response. [28]

3.8.2 Resistance Temperature Detectors (RTD)

Often called resistance thermometers, this sensors are composed of wire wound and thin film devices that increases the resistance as the temperature increases, and conversely. RTDs are similar to thermocouple, instead of measuring the temperature as voltage, measure it as resistance.

Some of the advantages of using thermometers include linearity of operating range and good stability at high temperature. In the contrary, these devices possess low sensitivity, and the cost is higher compare to the thermocouples. An schematic of this type of temperature sensor is shown in Figure 23

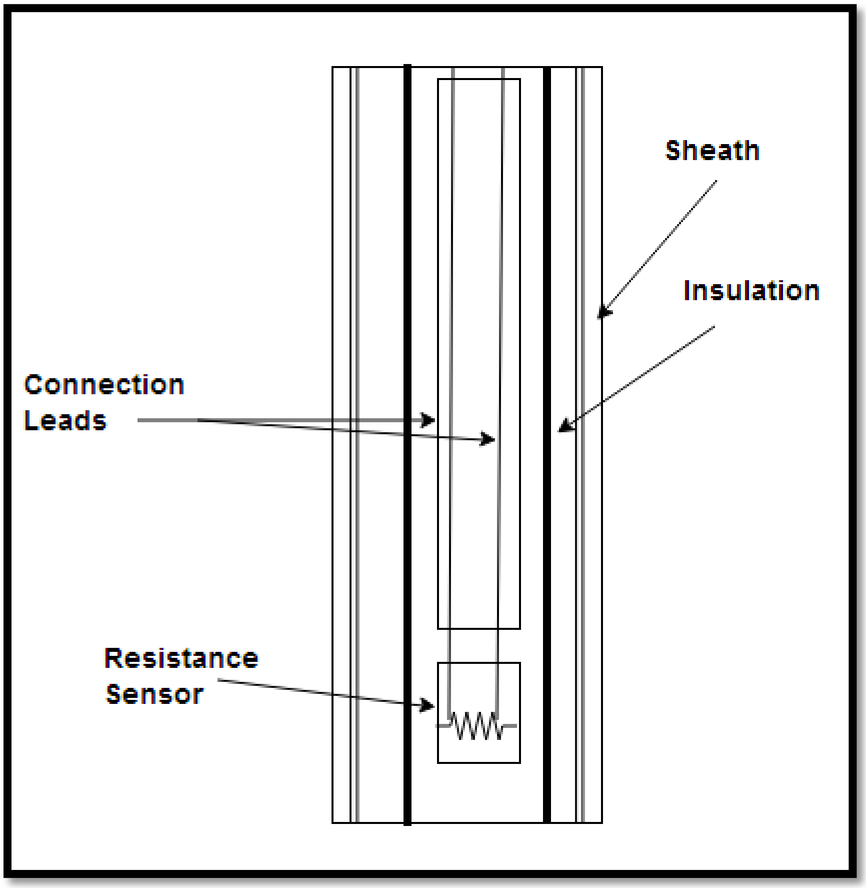

Figure 23 Schematic of Resistance Temperature sensors

One example of a High-Precision digital thermometer is the DS18S20, which is easy to implement in a system that requires temperature readings. This device does not require any external components, and it can derive power directly from the data line, often called parasite power, which reduce the need of power supply.

One unique feature of this thermometer is that has 64-bit serial code, allowing multiple DS18S20s to function at on the same 1-Wire the same time, as its name suggest 1-wire thermometer. Another feature of the DS18S20 is the capability to function without an external power supply, as mention above. The power is supply by the DQ on the 1-Wire communication bus. When the bus is high, it charges the pull-up resistor, and when the bus goes to low it charges the internal capacitor. Having these two alternative ways of charging, it will not need the external power, saving the system outer power for the rest of the components. [31]

3.8.3 Thermistors

As its name suggest, thermistors are temperature sensitive resistors. Similarly to RTDs, thermistors chance resistance when there are temperature changes. The only difference is that thermistors have negative temperature coefficient, meaning its resistance increases when the temperature decreases. The most common form of the thermistors is a bead with a range of about .02” to .2” with two wires attached as shown in Figure 24

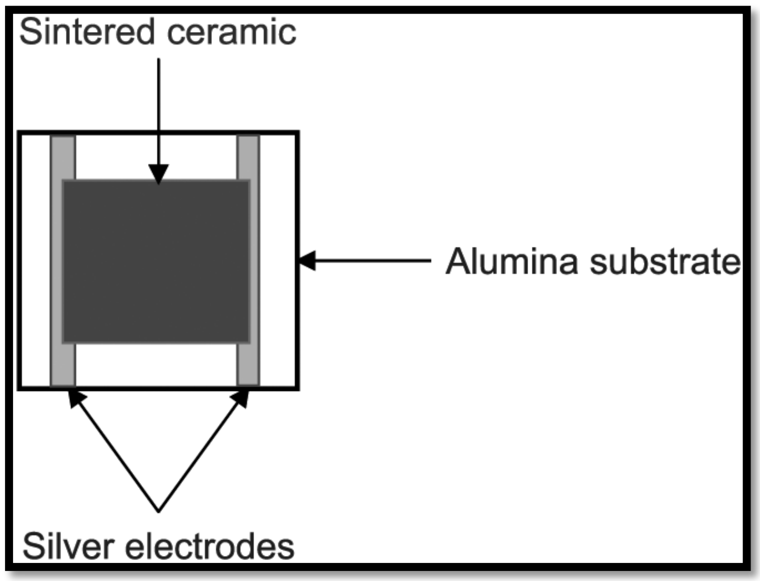

Figure 24 Schematic of a thermistors [29]

Compare to other temperature sensors, thermistors are often mounted in stainless steel tubes, to protect them from the environment in which they will be implemented. Grease is typically used to improve the thermal contact between the sensor and the tube.

These type of sensors are convenient because of they are at low cost and easy to implement. They are manufacture in a wide range of sizes and base resistance values. Most devices use 25°C as the base temperature. One great advantage is that they are very sensitive to small variable changes, when there is a slightly change in temperature, there will be a large change in resistance value. That leads to one disadvantage on the hardware linearization of the thermistors which behaves poorly at higher temperatures.

Even thought, thermistors have a fast response and come in small package; they have limited precision, especially over extensive range of temperatures. Also, the thermistors have an the output as resistance, and the microcontroller we are using takes the reading as an output voltage. These two devices will interfere with each other, and may lead to programming difficulties. Overall, combined accuracy and signal conditioning, it will be considered another device as a temperature reader in the system.

3.8.4 Precision IC Temperature Sensors

This type of temperature sensor is an integrated circuit sensor that measures temperature, and whose output voltage is proportional to the temperature in Celsius (Centigrade). This device it is more accurate then the thermistors are able to provide the following accuracies for temperature range:

- $\pm 1/4^\circ$C at room temperature
- $\pm 3/4^\circ$C over a full -55 to $+150^\circ$C

Possessing low output impedance, and a linear output makes the readout of the temperature very easy. Also, It only draws 60 micro amps from its supply, and hold a low self-heating capability. It functions over a -55° to $+150^\circ$C temperature range, which it follows our design specifications for the temperature readings. Since we are placing the sensors in several places in our systems, we have to take into account the surroundings and the capacity this sensors have.
As shown in Table 12, the LM35 is one type of precision centigrade temperature sensor that has three pins, the Vs which acquire the device voltage, the Vout which will pin to our circuit, so the microcontroller will be able to read the voltage output, and related to its temperature.

Table 12 Precision Centigrade Temperature Sensors [30]

Pin No	Function	Name
1	Supply voltage; 5V (+35V to -2V)	+Vs
2	Output voltage (+6V to -1V)	OUT
3	Ground (0V)	GND

This device generates higher linear output voltage in comparison with thermocouples. When applying it to our system, a simple conversion temperature is used to acquire accurate readings. The general equation is the following:

$$\text{Temperature (°C)} = V_{out} * (100\frac{°C}{V})$$

For example, if the output voltage is 2 volts, the temperature is 200°C. Due that it is a linear variation it ease our design.

3.9 Energy Storage

Electricity is more adaptable in use because it is a more practical form of energy that can be converted efficiently into other forms. For example, it can be converted into mechanical form with very high efficiency, in the high 90 percent range or into thermal energy with 100 percent efficiency. Thermal energy, on the other hand, cannot be converted into electricity with high efficiency; this is confirmed by the laws of physics and more specifically by the 2nd law of thermodynamics which dictates that 100% of the thermal energy cannot be transformed to work. Entropy can be produced but never destroyed. [32]

One of the main problems for society is not to produce the energy but to store it. A disadvantage of electricity is that it cannot be easily stored on large scales; almost all electrical energy used today is consumed as it is generated. The photovoltaic and wind sources of power, cannot meet the load demand all of the time, 24 hours a day, 365 days of the year, therefore a energy storage system is a desired feature to incorporate with renewable power systems, particularly in stand-alone plants. Figure 25 below can better illustrate a stand-alone system.

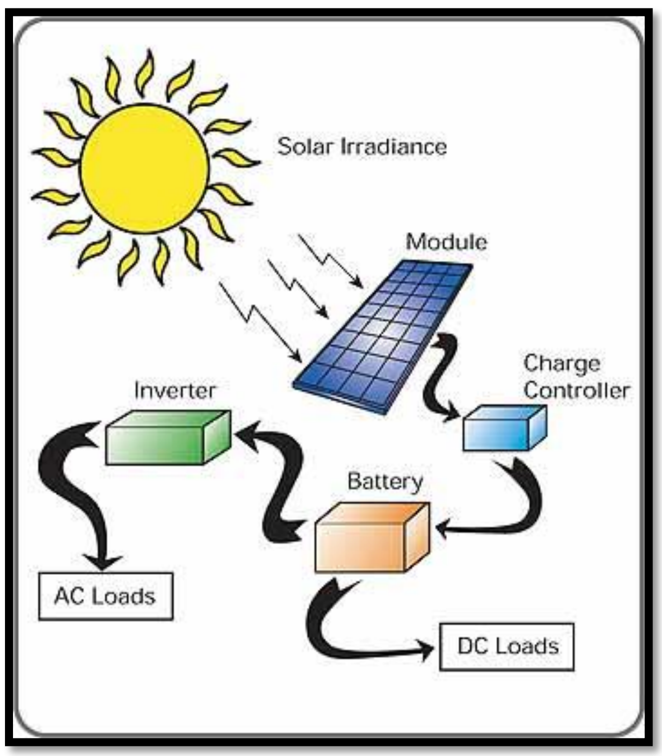

Figure 25 Stand Alone System [35]

It can drastically improve the load availability, a key requirement for any power system. The present and future energy storage technology that may be considered for stand-alone photovoltaic or wind power systems falls in the following broad categories: Battery, flywheel, compressed air and superconducting coil. For our project batteries are the most practical and accessible source, we will focus on its structure and on the different types of batteries only.

3.9.1 The Battery

The battery stores energy in the electrochemical form, and is the most widely used mechanism for energy storage in a wide range of applications. The primary battery converts the chemical energy into the electrical energy. The electrochemical reaction in the primary battery is nonreversible, and the battery after discharge is discarded. For this reason, it finds applications where high energy density for one time use is needed. The secondary battery, which is also known as the rechargeable battery.

The electrochemical reaction in the secondary battery is reversible. After a discharge, it can be recharged by injecting direct current from an external source. This type of battery converts the chemical energy into electrical energy in the discharge mode. In the charge mode, it converts the electrical energy into chemical energy. In both the charge and the discharge modes, a small fraction of energy is converted into heat, which is dissipated to the surrounding medium.

The cell stores electrochemical energy at low electrical potentials, typically a few volts. The cell capacity, denoted by C, is measured in Ampere-hours (Ah), meaning it can deliver C amperes for one hour or C/n amperes for n hours. The battery is made of numerous electrochemical cells connected in a series-parallel combination to obtain the desired operating voltage and current. The higher the battery voltage, the higher the number of cells required in series. The battery rating is stated in terms of the average voltage during discharge and the Ah capacity it can deliver before the voltage drops below the specified limit. The product of the voltage and the Ah forms the Wh energy rating it can deliver to a load from the fully-charged condition. The battery charge and discharge rates are stated in unit of its capacity in Ah. For example, charging a 100 Ah battery at C/10 rate means charging at 10 A rate. Discharging that battery at C/2 rate means draining 50 A, at which rate the battery will be fully discharged in 2 hours.

There are at least three major rechargeable electro-chemistries (Battery's Chemistry) available and most suitable for the project. They are the following: lead-acid (Pb-acid), lithium-ion (Li-ion), and molten salt. In this project these will be researched and compared with the purpose of using the most efficient and economical for the design. Some construction and operating features of the above electrochemistry are presented in the proceeding sections. [33]

3.9.1.1 Lead-Acid Batteries

The Lead-Acid is the most common type of rechargeable battery used today, even though it has the least energy density by weight and volume. it is best because of its maturity and high performance over cost ratio. In the lead-acid battery under discharge, water and lead sulfate are formed, the water dilutes the sulfuric acid electrolyte, and the specific gravity of the electrolyte decreases with the decreasing state of charge. The recharging reverses the reaction in the lead and lead dioxide is formed at the negative and positive plates, respectively, restoring the battery into its originally charged state. There are three types of lead-acid batteries: starting, deep-cycle, and marine. The starting lead-acid is your typical automotive battery used to start a car. This type of battery has many thin plates of lead (high surface area) which allows for a high current output. These batteries are great for applications where a high current is needed for a very short time, but for deep-cycle applications this type of battery has a very short lifespan. The deep-cycle lead-acid battery has thicker lead plates which allow this type of battery to be discharged and recharged many times without degradation. One drawback is the fact that there is lower surface area between the lead plates and the acid electrolyte meaning smaller current. Though the deep-cycle lead-acid is designed to be discharged to 20% capacity, the battery will last longer if the charge never falls below 50%. This is better demonstrated in Figure 26 below.

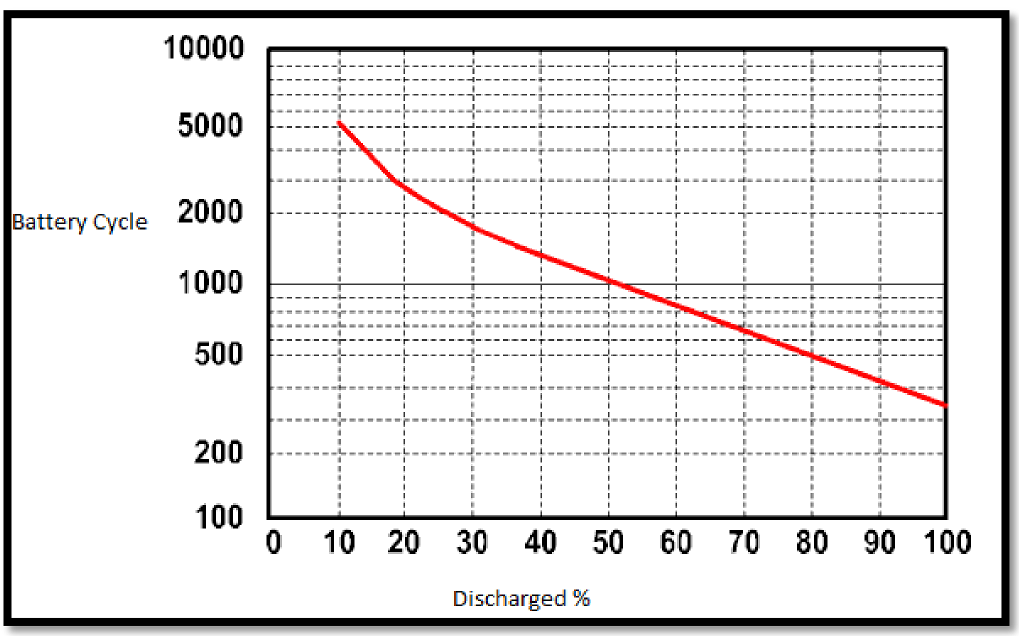

Figure 26 Cycles Vs Discharge % of average deep cycle batteries [36]

A marine lead-acid battery falls somewhere in between the automotive and deep-cycle. The lead plates are thinner than deep-cycle yet thicker than a starting battery which gives it better current output and shorter lifetime when used in deep-cycle applications. In the domain of deep-cycle lead-acid batteries there are three types of battery construction: flooded, gel, and absorbed glass mat (AGM). Flooded lead acids are the cheapest and most common construction type. The electrolyte in this type of battery (30% sulfuric acid, 70% water) is in a liquid form. This allows for spilling and evaporation of the electrolyte, which shortens lifetime and is dangerous. The gel type batteries use a thickening agent to hold the electrolyte in place. This prevents leakage in the event that the case is damaged. This type of battery is sealed, which means that in the event that a significant amount of electrolyte is evaporated, it cannot be re-filled.

Absorbed glass mat lead-acid batteries are by far the most advantageous of the three types of construction. AGMs have Boron-Silicate fibers embedded in the electrolyte which prevents leakage even if the case is breached. In addition, the fact that this type of battery is sealed and pressurized forces Hydrogen and Oxygen to recombine into water while charging, thus greatly reducing water lost due to evaporation. They have a very slow self-discharge rate and are resistant to shock and vibration damage. The main disadvantage to AGMs is that they usually cost two to three times that of a flooded lead-acid of the same capacity. For this reason (Budget Limitation) We will be using flooded Lead-Acid Batteries. [36]

3.9.1.2 Lithium-Ion Batteries

Lithium-ion technology is a relative late development, which offers three times the energy density over that of lead-acid. Such large improvement in the energy density comes from lithium's low atomic weight of 6.9 versus 207 for lead. Moreover, the lithium-ion has higher cell voltage of 3.5 versus 2.0 for lead-acid and 1.2 for other electrochemistry. This requires fewer cells in series for a given battery voltage, thus reducing the manufacturing cost. On the negative side, the lithium electrode reacts with any liquid electrolyte. Every time when the cell is discharged and then charged, the lithium is stripped away, a free metal surface is exposed to the electrolyte and a new film is formed. To compensate, the cell uses thick electrodes, adding into the cost. Or else, the life would be shortened. For this reason, it is more expensive.

Li-ion batteries tend to have one of the highest cost per-watt ratios, much higher than lead-acid chemistries in operation, the lithium-ion electrochemistry is susceptible to damage from overcharging or other faults in the battery charge control. Therefore, it requires a more sophisticated charging technique with mandatory protection against overcharging. In addition, it is essential to build protection circuitry into the battery pack so that thermal dissipation does not cause the battery to light on fire and/or explode. Lithium is also highly reactive with water so care must always be taken to not overexpose these batteries to water.

Rechargeable lithium batteries all use lithium ions to store the energy by the migration of these ions from the cathode to the anode. During discharge the anode undergoes an oxidation reaction which frees electrons to conduct current (do work) in an external circuit while the cathode undergoes a reduction reaction (gaining of electrons). The cathode is made up of a lithium-metal-oxide and the anode is made of graphite (porous carbon). Some common cathodes used in Li-ion batteries are: lithium-cobalt, lithium manganese, lithium phosphate, and lithium-nickel manganese-cobalt. The different cathodes offer differing levels of safety, specific energy, lifetime, and cost. Most of these Li-ion batteries use a liquid electrolyte to carry charge between the anode and cathode, but some use a polymer with a gelled electrolyte. These lithium-polymer batteries offer a slight advantage to liquid electrolyte types by the fact that there is no need for a rigid case, and thus can be made smaller, lighter, and more flexible. Lithium Polymer is simply a lithium battery with solid polymer electrolytes. Its structure consists of a film of metallic lithium bonded to a thin layer of solid polymer electrolyte. Which is a negative aspect since Metallic lithium is highly reactive and flammable, thus very unsafe. It is usually put on mineral oil for that reason, but that would just be too unpractical for the project. in addition the solid polymer enhances the cell’s specific energy by acting as both the electrolyte and the separator. Moreover, the metal in solid electrolyte reacts less than it does with liquid electrolyte. [36]

3.9.1.3 Molten Salt Batteries

There are two main types of batteries which use molten salt electrolytes: thermal batteries and high temperature rechargeable batteries. In both cases, the advantages of molten salt electrolytes are their high conductivity which leads to very high energy density in comparison with the substitute ambient temperature batteries; lead-acid batteries. The high energy density and the extremely long storage life without maintenance of the thermal batteries makes them preferably appropriate to providing electrical power storage for power systems. Nevertheless their high cost and limited energy density due to the heavy weight of the steel case and the weight of the insulators excludes them from most applications.

This battery uses sodium-containing substances melted at a high temperature. The technology has been around for decades, but existing molten-salt batteries require keeping the electrolyte in a liquid state at a temperature higher than 300 C. Now researchers developed a sodium material that melts at around 57 C. Having approximately double the energy density of a typical lithium ion battery, this molten salt battery would let an electric vehicle travel twice as far as a lithium ion battery of the same size. Sodium is cheaper than lithium because it is in abundant supply. But in contrast an ambient temperature lithium ion battery, the most sophisticated molten salt battery must be kept at a temperature around 80 C to output power. This is the main disadvantage of these batteries; they need to be set to high temperatures for these batteries to function.

3.9.1.4 Other Types of Batteries

In addition to Lead-Acid, Lithium-Ion and Molten Salt batteries; There are at least 4 other major rechargeable electrochemistry available today; even though they are not extensively researched on the report. Due to their disadvantages and limitations in relation to the project, they are mentioned below. Table 13 demonstrates some of the main characteristics of these batteries and Figure 27 below illustrates the different energy densities of the electro-chemistries. They are as follows;

- nickel-cadmium (NiCd).
- nickel-metal hydride (NiMH).
- lithium-polymer (Li-poly).
- zinc-air.

Table 13 Average Cell Voltage During Discharge in Various Rechargeable Batteries

Electrochemistry	**Cell Voltage**	**Remark**
Lead-acid	2.0	Least cost technology
Nickel-cadmium	1.2	Exhibits memory effect
Nickel-metal hybride	1.2	Temperature sensitive
Lithium-ion	3.4	Safe, contains no metallic lithium
Lithium-polymer	3.0	Contains metallic lithium
Zinc-air	1.2	Requires good air management to limit self-discharge rate

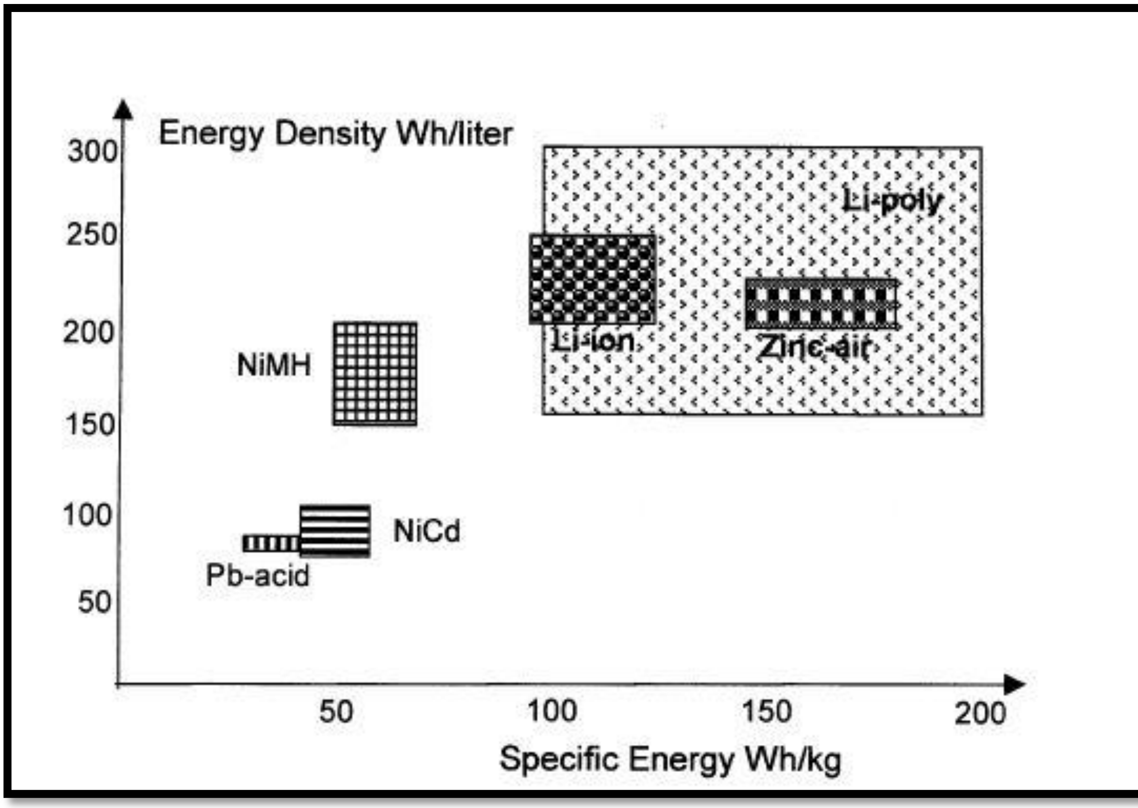

Figure 27 Specific energy and energy density of various electrochemistry. [33]

Nickel Cadmium: The NiCd is a well researched electrochemistry. The NiCd cell has positive electrodes made of cadmium and the negative electrodes of nickel hydroxide. Two electrodes are separated by Nylon separators and potassium hydroxide electrolyte in stainless steel casing; with sealed cell and half the weight of conventional lead-acid. They have a longer deep cycle life, and are more temperature tolerant than the lead-acid batteries. However, this electrochemistry has a memory effect, which degrades the capacity if not used for a long time. In addition, cadmium has recently come under environmental regulatory scrutiny. For these reasons, the NiCd is being replaced by NiMH and Li-ion batteries.

Nickel-Metal Hydride: The NiMH is an addition of NiCd technology, and offers an improvement in energy density over that in NiCd. The major construction difference is that the anode is made of a metal hydride. This eliminates the environmental concerns of cadmium. Another performance enhancement is that it has negligible memory effect. The NiMH, however, is less capable of delivering high peak power, has high self-discharge rate, and is vulnerable to damage due to overcharging.

Lithium-Polymer: This is a lithium battery with solid polymer electrolytes. It is constructed with a film of metallic lithium bonded to a thin layer of solid polymer electrolyte. The solid polymer enhances the cell's specific energy by acting as both the electrolyte and the separator. In addition, the metal in solid electrolyte reacts less than it does with liquid electrolyte.

Zinc-Air: The zinc-air battery has a zinc negative electrode, a potassium hydroxide electrolyte, and a carbon positive electrode, which is exposed to the air. During discharge, oxygen from the air is reduced at the carbon electrode and the zinc electrode is oxidized. During discharge, it absorbs oxygen from the air and converts into oxygen ions for transport to the zinc anode. During charge, it evolves oxygen. A good air management is essential for the performance of the zinc-air battery. [33]

3.9.2 Temperature Effects

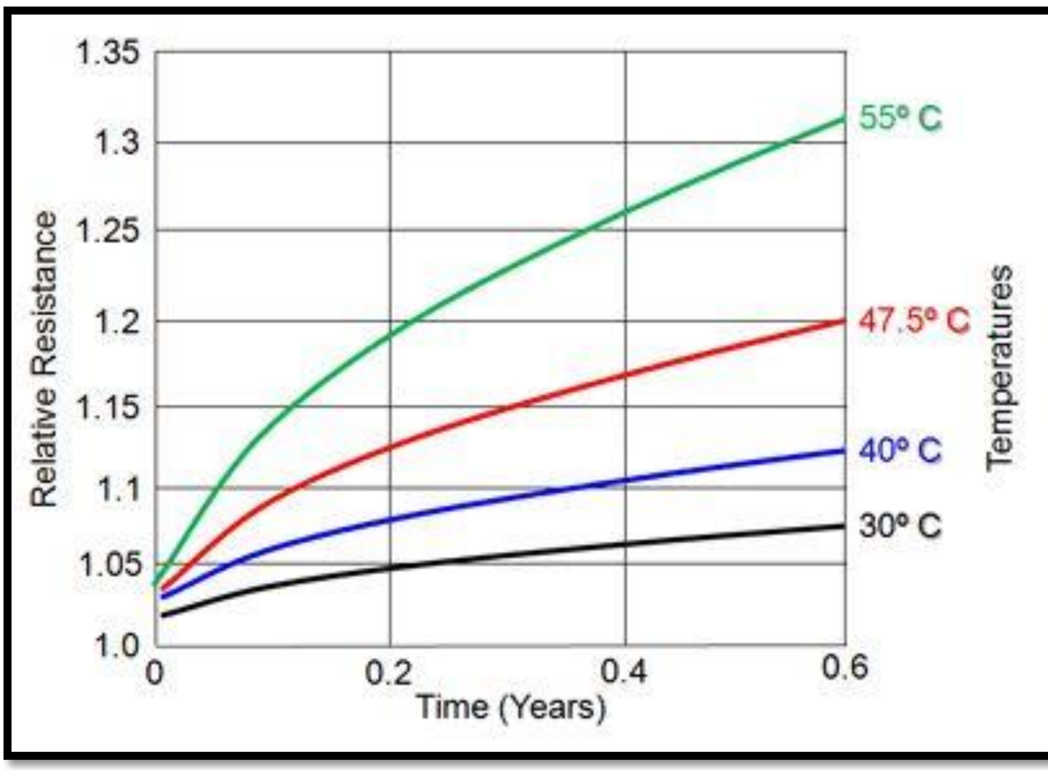

Figure 28 Increasing Internal Resistance with time and temperature. [37]

Batteries are affected by temperature and or humidity. If batteries are too hot or too cold, batteries will exhibit performance that would be irregular with their normal and designed operating specifications. Figure 28 above better illustrates this relation. This is not a manufacturer fault but a direct consequence of using a battery in an environment that the battery was never designed to be used in. If a battery is exposed to a extreme weather it may stop working, bulge, bubble, melt, damage the device, smoke, create sparks, create flames, expand, contract, and or even blow-up in very extreme cases. High current and environmental factors can cause battery temperature to rise and voltage decreases with increased battery temperature. The algorithms executed by the microcontroller will factor in battery temperature when calculating current and voltage values to both maximize efficiency and provide emergency cutoff in the event that the temperature reaches an hazardous level. Temperature reading compensation is a must have in the charge controller for the safety and efficiency of the project.

3.9.3 Battery Charging Algorithms

Charging Algorithms are different for each battery's chemistry; although they all have similar charging stages. The charging stages of the batteries are described below.

The *Bulk* is the first stage and in this stage the voltage can range from 11V to 15V for a 12V battery, the only requirement being that the charging voltage must be set higher than the present battery voltage. This stage takes presence when the charge percentage of the battery is 0 to 80-90 percent of full capacity. The voltage of the battery at complete discharge will give a reading of about 10.5 volts. At this point little power can be extracted from the batteries but it can permanently damage the battery if discharged below this point. The MPPT (Maximum Power Point Tracking) will be better used in this stage the "Bulk" stage. The Maximum power point tracking (MPPT) device will make great difference in relation to the efficiency of the system. [33]

The *Absorption* stage is the second phase of the process and it begins immediately after bulk charging stage (when the voltage reaches the determined value). In this stage the charging voltage is held at a constant value but the current decrements as the internal resistance of the battery increases. As the battery reaches full capacity, the current diminishes due to the internal resistance. For example when the current drops below a certain level, typically 0.5% of the battery's rated capacity, it is considered fully charged.

The *Float* stage is the final phase of the battery charging process. In this stage the charging voltage is set to a constant value but at a lower level than the absorption stage. The float stage balances for the battery's discharge or small steady loss of voltage over time, which is the main setback of all battery chemistries. In this stage the objective is to maintain the battery charged at full capacity. [33]

3.9.3.1 Lead-Acid Battery Charging Algorithms

Battery charging takes place in 3 basic stages: Bulk, Absorption, and Float. the figure below better illustrates this process.

Bulk Charge: This is the first of the three-stage battery charging process. In this stage current travels to the batteries at the maximum possible safe rate until the voltage rises, this will happen when the charge of the battery is near 80 to 90 percent. Voltage at this stage can typically range from 10.5 volts to 15 volts. There is no specific voltage at this stage but there might be some limitations such as the maximum current the wire or battery can withstand. [4]

Absorption Charge: This is the second stage of the battery charging process, where the voltage must remain constant and the current slowly decreases since the internal resistance of the battery increases during charging. During this stage maximum voltage output is present, 14V to 15.5V usually. Internal resistance is increased with the charging cycles. Meaning the battery will always take less charge, due to this resistance taking some of the space. Figure 29 and Table 14 best illustrates why the battery's voltage is higher during this state (voltage in each cell increases thus giving a higher battery voltage) [35].

Float Charge: This is the third and final stage of the battery charging process. in this stage battery reaches full charge. And its charge voltage is reduced to a lower voltage, around 12.8 to 13.3 volts. This is typically done to extend battery's life and to reduce gassing. in this stage the objective is to keep an already charged battery from discharging, this is why this stage is also referred to as the trickle or maintenance stage. This is similar to what PWM (Pulse Width Modulation) accomplishes. PWM simply senses small voltage drops in the battery and sends very short charging pulses to the battery. This may occur as many times as necessary to keep the battery charged, maybe thousands of times per minute. The width of these pulses may vary from a few microseconds to possibly several seconds depending on the amount of discharge of the battery. The float charge voltage should be around 13.02 to 13.20 volts [35]

Table 14 Effects of Charge Voltage on a Small Lead Acid Battery (SLA) [33]

	2.3V to 2.35V/cell	**2.4V to 2.45V/cell**
Advantages	Maximum service life; battery stays cool; charge temperature can exceed 30°C (86°F)	Faster charge times higher and more consistent capacity readings; less sulfation.
Disadvantages	Slow charge time; capacity readings, may be inconsistent and declining with each cycle. Sulfation may occur without equalizing charge	Subject to corrosion and gassing. Needs constant water. Not suitable for charging at high room temperatures, causing severe overcharge.

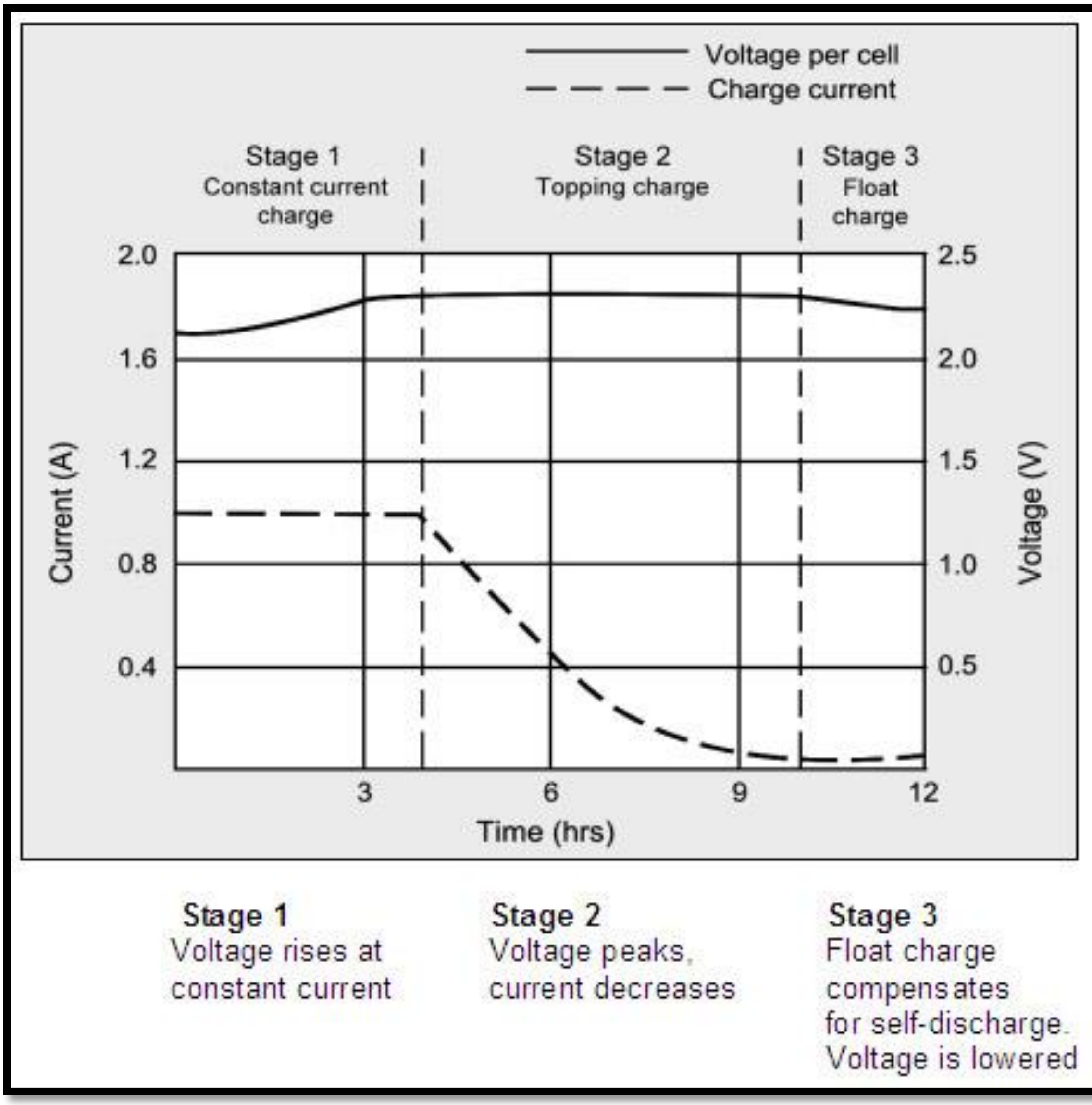

Figure 29 Lead-Acid Charging stages [33]

Lead-acid batteries are sluggish to charge, usually taking between 12 and 16 hours to reach full capacity. This is a advantage for solar cell applications. The sun usually shines for many hours during a given day, delivering power at a rate that is slow enough to allow efficient charging of lead-acid batteries. Lead-acid batteries also have a high overcharge tolerance compared to lithium-ion. For instance, a lead-acid left at an absorption level voltage (~14.3V) for extended periods of time after reaching full charge will not destroy the battery like it would in Li-ion chemistry.

3.9.3.2 Lithium-Ion Battery Charging Algorithms

Lithium-ion charging is similar to the lead-acid charging system, except for the higher voltage per cell in lithium-ions and the float charge stage which is a very delicate charging phase for lithium-ions since they cannot accept overcharge unlike lead-acid which offer some flexibility.

The first stage in the process is a constant current stage. Here the voltage rises to a pre-determined level and then a constant charging voltage of about 4.4V is applied to the battery. A lithium-ion cell (nominal cell voltage 3.7V) has about 4.2V when fully charged with a tolerance of +/– 50mV per cell. Higher voltages could increase the capacity, but the resulting cell oxidation would reduce service life. In addition it would be unsafe if charged beyond 4.20V per cell. When this level is reached, charging should terminate, because Li-ion batteries only take what it can absorb, any extra charge causes stress. If not used for a while, the Li-ion will self-discharge and will need to be topped off often to keep the battery at full capacity. Figure 30 and Figure 31 shown below best illustrate this process.

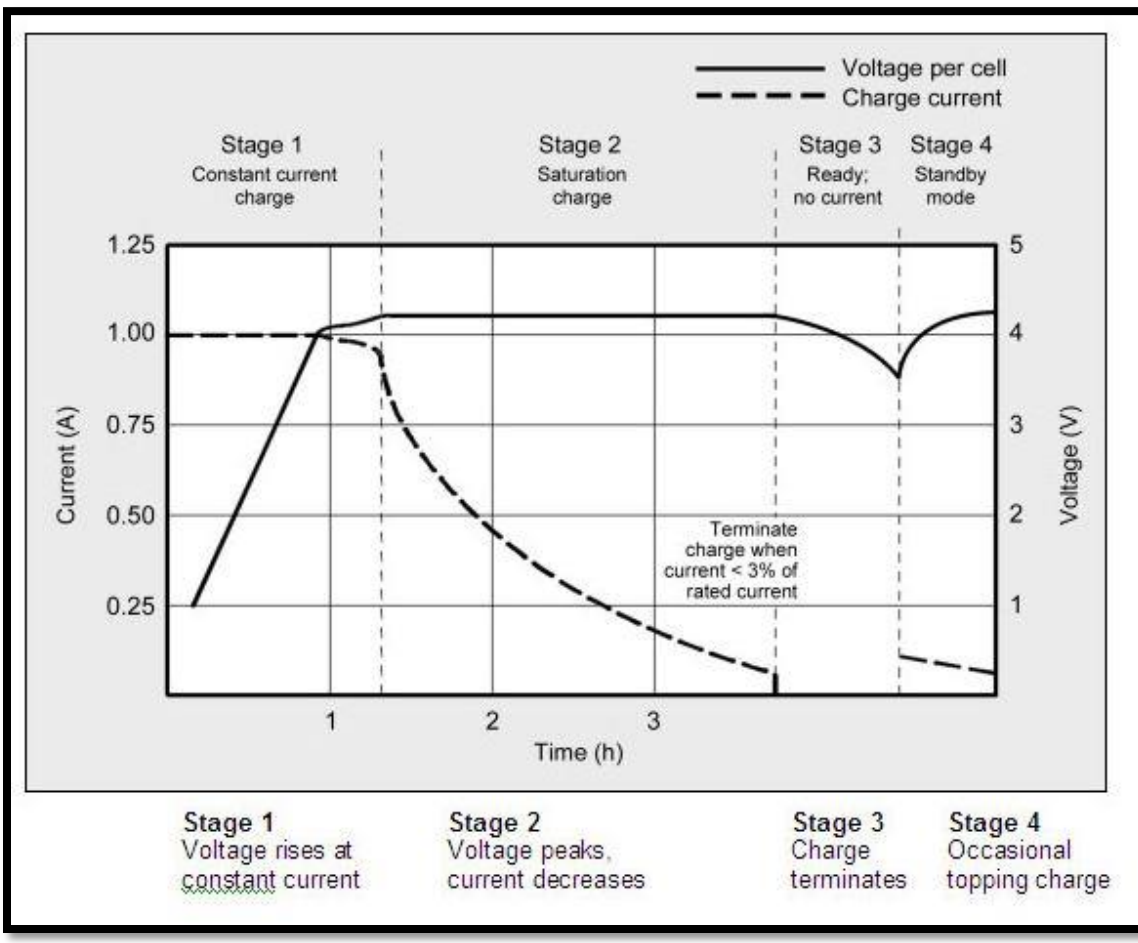

Figure 30 Charge stages of lithium-ion. [33]

Li-ion is fully charged when the current drops to a predetermined level or levels out at the end of Stage 2. In lieu of trickle charge, some chargers apply a topping charge when the voltage drops to 4.05V/cell (Stage 4). [33]

Lithium-ion batteries can be charged much faster than can lead-acid batteries. This means that a Li-ion can be charged in about one or two hours. Lithium-ion batteries are about 97 to 99% efficient in charging and stay relatively cool during the charge process. If a Li-ion battery is overcharged, then the production of CO2 will begin and raise the pressure in the cell. If this pressure gets high enough, the cell will burst and vent out a flame and/or explode. Over discharging lithium-ion batteries is also not advised. If the cell voltage falls much below 3.0 V then the battery might become permanently dead so protection circuitry tries to shut off all current output when the cell voltage reaches around 3 V. [33]

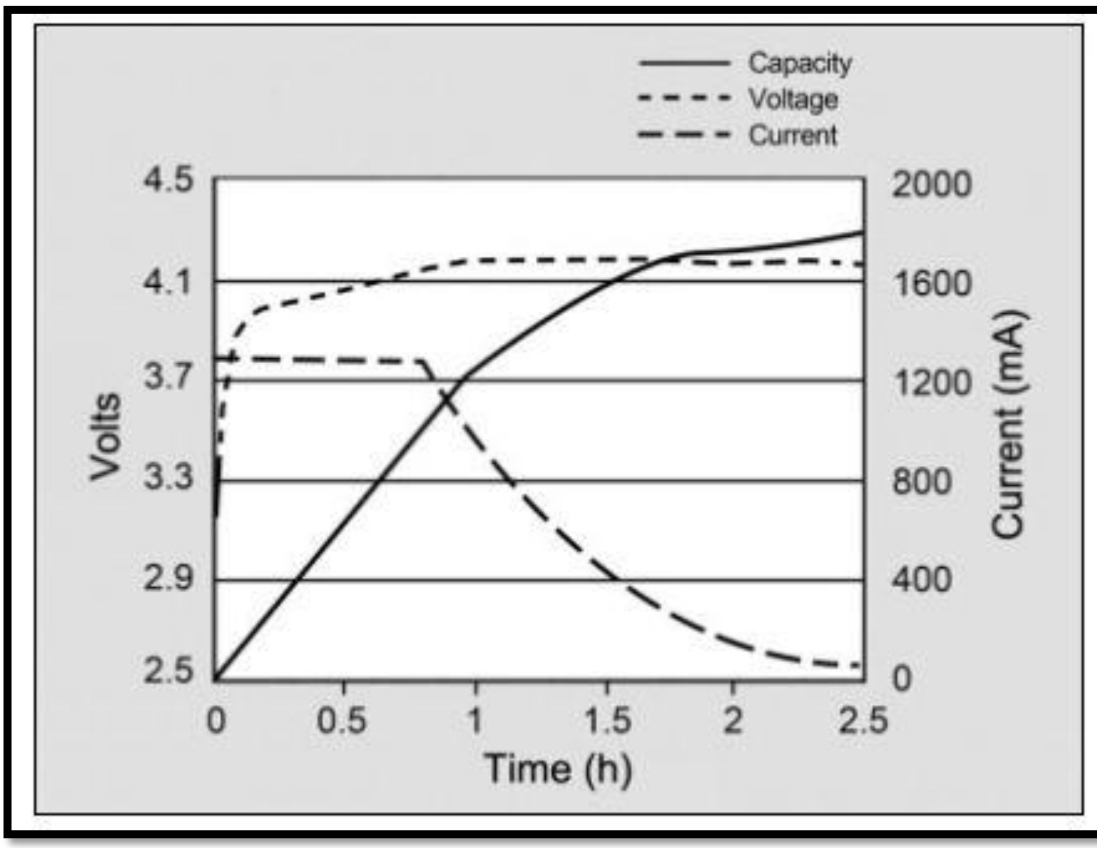

Figure 31 Capacity as a function of charge voltage on a lithium-ion battery [33]

Keeping away from full charge has benefits, and some manufacturers set the charge threshold lower on purpose to extend battery life and prevent hazardous response from the battery. Table 15 below best illustrates the estimated capacities when charged to different voltage thresholds with and without saturation charge.

Table 15 Typical Charge Characteristics of Lithium-Ion [33]

Charge V/cell	Capacity at cut-off voltage	Charge time	Capacity with full saturation
3.8	60%	120min	65%
3.90	70%	135min	76%
4.00	75%	150min	85%
4.10	80%	165min	87%
4.20	85%	180min	100%

Adding full saturation at the set voltage boosts the capacity by about 10 percent but it adds stress due to high voltage. Table 15 above better illustrates this relation.

3.10 Battery Desulfator

Lead acid batteries lose their ability to hold or accept a charge when discharged for long periods of time due to sulfation. Sulfation is one of the most common causes of early battery failures. Sulfation interferes with the ability of the battery to accept, hold, and deliver a charge. A lead acid battery consists of a series of oppositely charged lead and oxide plates (cell dividers). Battery cell are composed with a mixture of 65% distilled water and 35% sulfuric acid. Sulfation in a battery occurs when the battery sits unused for long period of time and the sulfuric acid begins to break down. Sulfation (PbSO4) is a combination of the battery's lead (Pb) in the plates and sulfuric acid (SO4) from the electrolyte. If the battery is completely recharged to 100% in a short period of time the newly formed sulfation is chemically reversed leaving no appreciable sulfation residue on the plates. The sulfur stars to stick to the negative lead plates and this process leads to the crystallization of lead sulfate which reduces the battery capacity and low resistance. Sulfation also lowers charge acceptance; meaning that charging will take longer due to the increase of internal resistance in the battery.

3.10.1 Stages of Sulfation

The first stage of sulfation is completely reversible once the battery is fully charged again. However, if the battery is left unused for more time stage one progresses into stage two sulftaion. At this point small crystals begin to form on the plates of the battery, reducing considerably the capacity of the battery to hold and deliver charge. If the battery sits unused for even longer periods of time, stage two of sulfation could advance into stage three sulftation. In stage three sulfation the battery will become nonfunctional**.** If the battery sits unused for even longer periods of time the sulfur crystals could become so large that would cause the battery to deform. At this point sulfation is considered to be permanent (hard sulfation).

3.10.2 Sulfation Treatment

Solar cells and wind turbines do not always provide enough energy to fully charge a battery bank and this leads to sulfation in systems designed with lead acid batteries. Best results are achieved when desulfation methods are applied at the earliest stages of sultation. One way to combat a reversible stage of sulfation is to apply an overcharge to the affected battery using a regulated current which typically is about 0.2amps. In this process, the battery voltage is increased to 16V for a period of 24 hours. Moreover, this technique will increase the internal temperature of the battery which subsequently will also help in dissolving the sulfur crystals formed in the cell of the battery.

Another way to attack sulfation in a lead acid battery is to use an anti-sulfation device. Basically what this device does is to apply pulsed radiofrequencies. As more and more crystallization occurs, the voltage required to dissolve the crystals and bring them back into the electrolyte also increases. However, if a constant high voltage is put through the battery it would overheat and could potentially damage it. Pulse conditioning is therefore used to ensure that only the sulfate crystals are affected and the battery does not overheat.

First, a battery conditioner sends small resonate electronic pulses through the battery to break down the sulfuric crystals. In this way, not only the plates of the battery are cleaned but also the lost sulfur returns to the electrolyte solution. Every lead acid battery has a resonant frequency at around 2 to 6 megahertz. The pulses that are sent into the battery are pulses of electricity with high frequency, high voltage, but low power. Then, the battery conditioner fully charges the battery and keeps it at peak voltage levels. This process usually takes weeks in order for the battery to be fully reconditioned.

To break a bond, any bond, energy needs to be introduced. In the case of lead acid battery sulfation, sulfation, $PbSO_4$ is a bond of PB and SO_4. Once allowed to stay together the bond hardens or crystallizes. Replacing the energy given up to make the original bond is not sufficient any longer to break the hardened bond and recharge the battery without a little extra help.

3.11 Earth Grounding

The safety and environment are main concerns when designing and implementing a system that will be positioned outdoors and managed directly by the user. First topic that we will make emphasis is proper earth grounding, which plays one of the most important roles in protecting the solar panel array, wind turbine, inverter and other components from lightning strike damage during a thunderstorm. Proper size of copper (grounding) wire will be needed to connect the system with an earth grounding electrode.

Electrical system grounding has three individual purposes: to provide protection for over current on devices; to offer zero reference for the electrical system; and to balance out potential differences in the system.

There are various ways to ground our whole system, different techniques to prevent the damage of each component and most importantly the inverter.

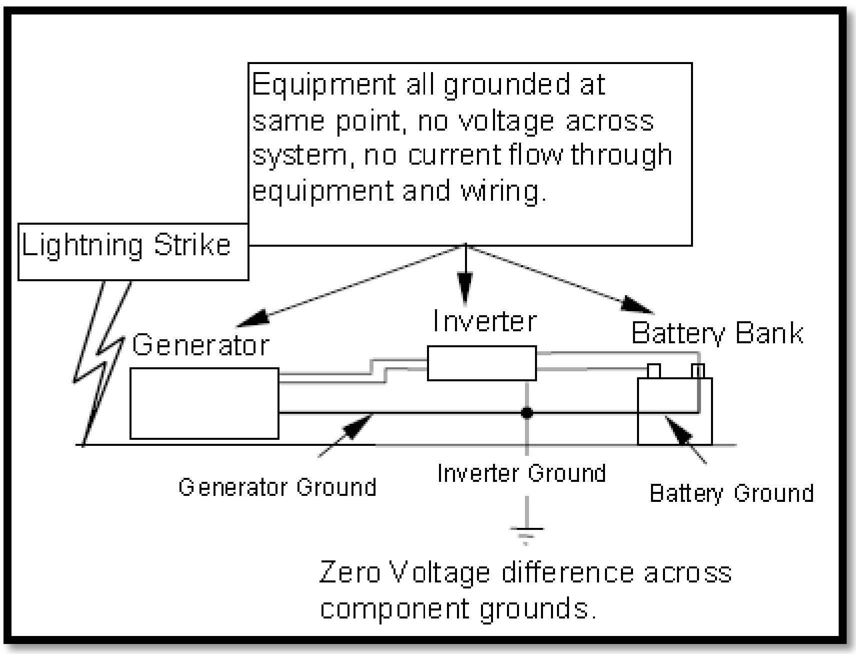

Figure 32 Single-Point Ground System [38]

Figure 32 demonstrates a typical single-point grounding system connected using a grounding rod. There are several advantages, for example, if a phase-to-ground fault occurs at one component of the system, a relatively controlled low-impedance path is provided back to the source. The fault current has limited routes back to the source and does not have the opportunity to diverge to multiple paths; otherwise the current would divide itself among the multiple paths with the possibility of damaging the entire system.

Another advantage of single-point grounding is how effective handles the changes in grounding potential, which evolves during a thunderstorm causing electrical disruption. A lightning strike can trigger instantaneous changes in potential at the grounding system. When electrical components are grounded at different points in a system, each point can have different potentials from each other; in this situation, a common ground reference is essential, and a single-point system provides a predictable grounding method. The overall potential will rise due to the lightning strike, but each component will have the same potential because they are electrically tied at the same point using a grounding rod. The components' potential will uniformly rise and fall, therefore will protect our equipment in case of a thunderstorm. However, one concern with single-point grounding is future testing and maintenance of equipment, but after researching the area where our system will be located, the risk of lightning strikes are very low. Single-point grounding should be employed as the baseline of a building grounding system. Provide a main ground bar to act as a common distribution point for ground risers and connections.

In Contrast with the single-point, the multi-point system does not trace a singular path back to equipment. Figure 33 represents a multi-point grounding system, with primary goal is to provide multiple paths for ground currents to flow and to equalize potentials throughout the grounding system.

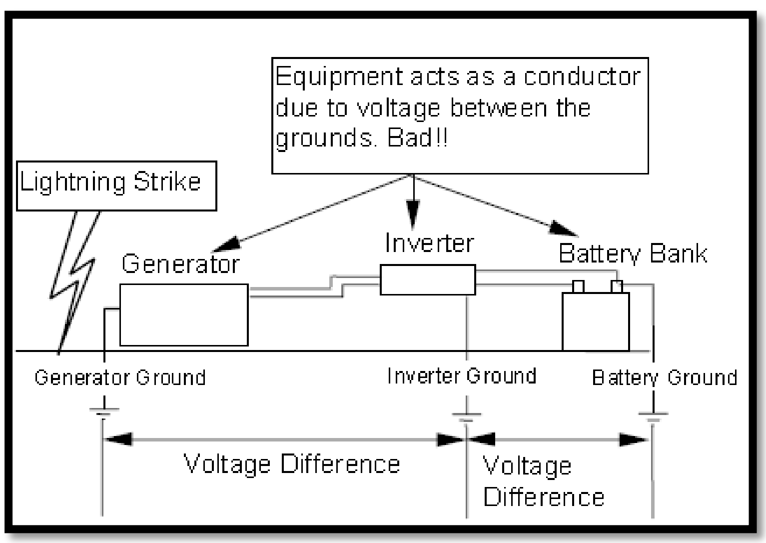

Figure 33 Multi-Point Ground System [38]

Due of its multiple paths and numerous connections provides opportunities for stray currents to wreak havoc on electrical and IT systems. When it comes in choosing between the multi-points vs. single-point, both grounding are able to offer significant facts to support their cause, and it depends on the design specifications. Multi-point grounding should be utilized as a grounding subsystem for data centers and computer rooms filled with high-frequency electronic equipment.

Nevertheless, it is crucial when using a multi-point subsystem it must be tied to the single-point grounding system. This type of hybrid system will work in most applications. After comparing both grounding systems, we have come to a clear conclusion that the best design is to utilize the single-point system. And mostly because our system is design at a small scale and we do not have to worry about large frequencies or big communication power room.

3.12 Ground Loop Interference

In class and in theory ground loop interference doesn't exist. This is because in most of our theoretical circuits that have been designed have had perfect grounds. This implies a ground that is a zero volts a wire that could handle an infinite amount of current and dissipate that current at and infinite rate. This of course is all theory. Real world grounds have resistance that can induce a voltage or have magnetic inductance. Ground loop interference needs to be studied whenever there is a situation of low power, high power, or large amounts of conductive metal in the system. The power systems use both low power and high power. "A ground loop is formed when there is more than one conductive path between the 'ground' terminals on two or more pieces of equipment."[39] This is exactly how the design for the entire system will be once each component of the power system is added. Each part of the entire system will be grounded and have more than one conductive path to that ground. Ground loop interference, if not taken into account, could be a major problem and destroy circuitry.

The main reason to take ground loop interference into account is safety and safety. The safety of the equipment and the safety of personnel working on or around the power control box. If ground loop interference was not taken into account there could be unaccounted currents or voltages in the system that might find its way to a ground other than predicted, such as another circuit or worse case a person.

The only ground loop interference that is of concern is ground imbalance. Ground loop interference due to magnetic inductance is much less of a factor because there will not be that much metal in the entire system to worry about in currents getting generated from magnetic inductance. An example of ground loop interference from ground imbalance is discussed below.

"If a large current is flowing in the ground system, and a sensor is placed in a circuit with a ground that also has a ground loop, then the voltage difference between the two ground points will be added to the signal. "[39] From the circuit shown in Figure 34 below, it is clear to see that if there is a 'Ground System Resistance' then there will be a potential difference that needs to be added on when making an equivalent circuit shown to the left. The higher the 'Ground System Resistance' and the larger the current the more caution and planning that will need to go into ground loop interference. This effect also needs to be considered for the high power side of the system, as well as the low power sensors as shown below. The danger from the high power side will not be from offset data like the sensor will have, but larger current than expected trying to find another ground. Improper grounding could result in electrocution to any person trying to work on the system. This is why fuses and proper grounding will be taken into account for the design.

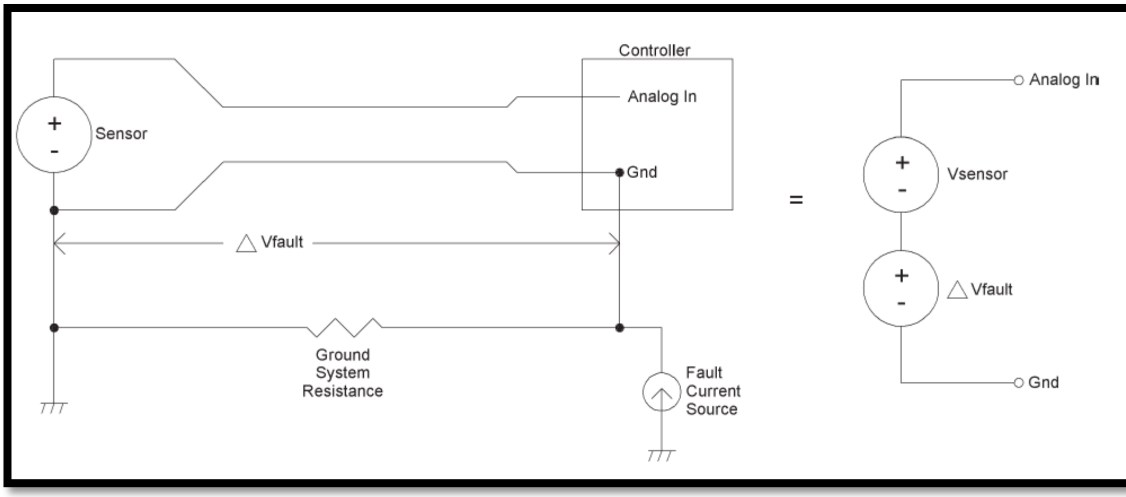

Figure 34 Ground Loop Circuit [39]

3.13 Heat Sinks

Internal temperature of power electronics components is one of the most important factors that need to be taken into consideration when designing the system. Since excessive internal temperatures are detrimental to all power electronic components, especially power semiconductors devices, which is the foundation for high and efficient performance. The understanding of heat transfer mechanism including conduction, radiation, and convection is fundamental not only for design and specifications of heat sinks but it is also needed in the design of inductors and transformers where thermal considerations are a major part of the design. In addition, attention to detail when selecting passive components such as; resistors, capacitors, and heat sinks must be present. Figure 35 below shows an illustration of heat flow through a heat sink.

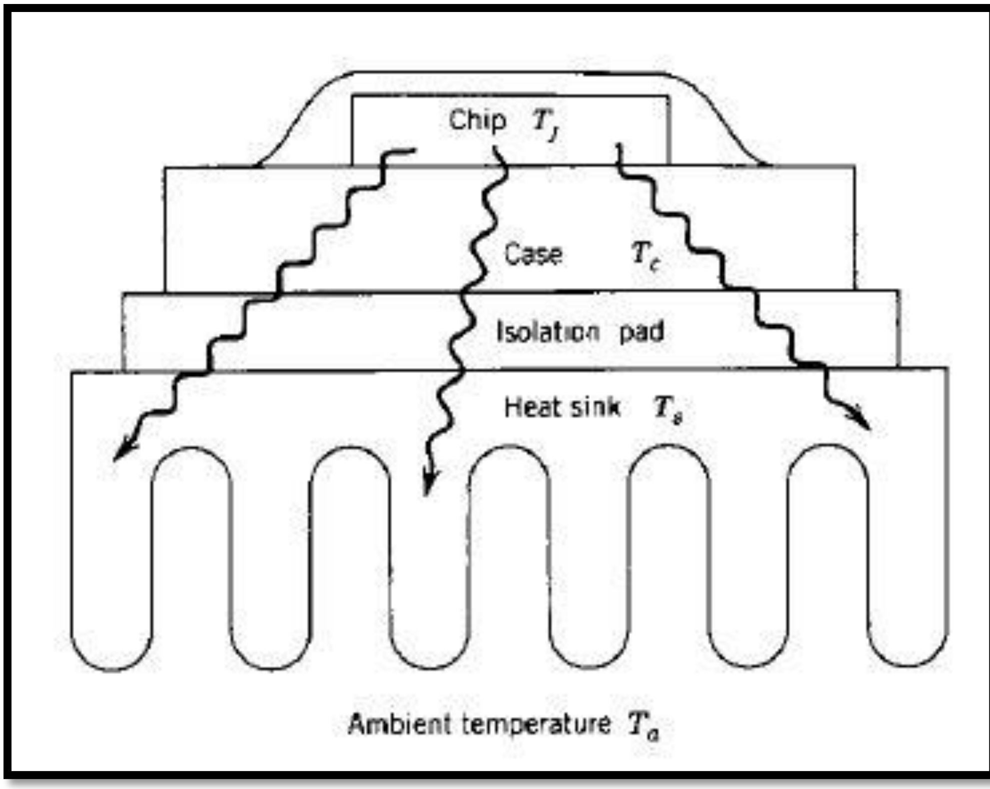

Figure 35 Steady-state heat flow and thermal resistance in a multiple layer structure including a heat sink. [12]

In power electronic systems, a heat sink is a passive heat exchanger component that cools a device by dissipating heat into the surrounding air. A heat sink is an essential component for cooling high power integrated circuits. Heat sinks are used with high power semiconductor devices such as power transistors; MOSFETs, BJTs, LEDs, and others where the heat dissipation of the device is insufficient to control its temperature. A heat sink is designed to increase the surface area in contact with the cooling medium surrounding it, such as the air. Approach of air speed, choice of material, fin design and surface treatment are some of the factors that affect the thermal performance of a heat sink. Heat sink attachment methods and thermal interface materials also affect the eventual die temperature of the integrated circuit. Thermal adhesive or thermal grease fills the air gap between the heat sink and device to improve its thermal performance. Theoretical, experimental and numerical methods can be used to determine a heat sink's thermal performance. [40]

The user's responsibility is made easier by the wide availability of aluminum heat sinks of various shapes that are used for cooling of the power semiconductor devices. If the heat sinks are cooled by natural convection, the distance between each fin should be at least 10-15 mm. A coating of black oxide results in a reduction of the thermal resistance by 25% but the cost may be higher by almost the same factor.

Thermal time constants of natural convection cooled heat sinks are in the range of 4-15 minutes. If a fan is added, the thermal resistance decreases, and the heat sink can be made smaller and lighter, which will also reduced the heat capacity. Thermal time constants for force cooled heat sinks are much smaller than for natural convection cooled heat sinks. Sometimes even as low as 1 minute. Heat sinks that utilize forced cooling should have spacing between in the cooling fins of not more than a few millimeters. In higher power ratings, water or oil cooling is used to further improve the thermal conduction.

The choice of the proper heat sink depends on the allowable junction temperature the device can tolerate. The junction to case thermal resistance can be obtained from the semiconductor device data sheets, and the case to sink thermal resistance depends on the thermal compound and the insulator used, if any. It is important to understand that the thermal grease or heat sink compound is only to be used to remove the air from the between microscopic high points of the mating surfaces (mica-heat and mica-transistor) and thus effectively utilize the entire surface area for heat conduction. If too much thermal compound is used, the layer will be excessively thick and will increase the thermal resistance. A proper heat sink can be selected based on the information provided by the heat sink manufacture's data sheets such as shown in table16 below.

Table 16 A Selection of Available of Heat Sinks. [12]

Heat sink no.	1	2	3	4	5	6	7	8	9	10	11	12
R (°C/W)	3.2	2.3	2.2	0	2.1	1.7	1.3	1.3	1.25	1.2	.8	.65
Vol. (cm^3)	76	99	181	0	198	298	435	675	608	634	695	1311

It is very important that when using a heat sink instructions from manufacturer's data sheet are followed closely. Improper mounting of the power device on the heat sink could result in thermal resistance from case of transistor to heat sink being much larger than anticipated and thus intolerably high values of junction temperature of the device during normal operations. a small amount of thermal grease or heat compound should be used to increase the contact area between the device and the heat sink. Application of the proper torque to the mounting bolts and nuts will also help ensure good contact between the device and the heat sink. [12]

3.14 Inverter

The inverter is the last major electrical device in the chain of our design. The inverters purpose is to convert the stored energy from the batteries or the delivered energy from either the wind or solar source from direct current (DC) to alternating current (AC). This is important to our project because AC is the standard way of transmitting power to residential areas. Our purpose and reason for adding the inverter is to mimic the grid system as best we can, so that the typical electrical device used in a home setting can be used without any other additional components outside of our project that would have to be purchased by the African township.

3.14.1 Design Factors

The different factors that are involved with an inverter are:

- The input voltages from the batter or wind or solar source.
- The amount of power the inverter will be able to control continuously.
- The amount of surge power will be able to safely handle.
- The in the output voltage and frequency.
- Over temperature protection.

3.14.1.1 Input voltages

We have really only two choices for the input voltage. The battery limits our selection of voltages because heavy duty batteries are typically 12V. This means the input voltage has to be a multiple of 12. The typical values to use would be 12V or 24V. Anything more would have dangerous consequence for both the safety of the equipment or any person attempting to work on the system. A 24V input is typically more efficient than the 12V input because the 24V input will draw less current. Less current is directly related to more efficient components that'll be used in the topology of the inverter. The reason that 24V is more efficient is because of Ohm's law and the basic power equation for electrical power shown below in

$$V = IR;\ P = VI \Rightarrow P_{consumed} = \frac{I^2}{R}\text{, since R is constant decreasing I decreases P consumed} \qquad \text{Equation 19}$$

The input to the inverter may also be variable within a given range. The batteries or power source will deliver different voltages over a period of time. So an important specification for an inverter would be its input range. For example a typical inverts range for a nominal input of 12VDC would be between 10VDC and

14VDC. If our volt goes anywhere outside of that range the inverter's safety features will trip the inverter.

For the expected batteries that we will use in our system a +/- 2VDC range is acceptable and controllable on our side. A battery should not diverge more than this as long as the battery is still healthy. Also because of the MPPT charge controller the controller will be programmed to not go above these limitations. However, if we do need to exceed these limitations a voltage regulator will be needed before the regulator.

Another variable concerning input voltage is the rate of change of the input voltage. How well the inverter will handle a change in voltage will depend on the rate of change and the response time of the voltage regulator used. The only part we can control, to a limited amount, is the rate of change. This is because the voltage regulator is part of the inverters design. We can control the rate of change at the MPPT charge control. When changing the voltage to find the maximum power output of the solar or wind source we need to keep in mind to not change the voltage too quickly. If we do we could see distortions in the output of the inverter.

3.14.1.2 Continuous Power

The maximum amount of power the inverter will be able to handle is 2000 Watts for our system design. This amount of continuous power is for both the amount of power received and drawn from the inverter. The inverter should also be able to handle this amount of power for any amount of time. Therefore, if the user decides to draw 2000 Watts for a minute or a few hours the inverter needs to continue to function. This will mean good design for heat transfer.

For the design in this paper, we have only one single input source from either solar or a wind generation at 500 Watts. However, as we study and learn more about MPPT charge controllers we want to be able to parallel four sources each at 500 Watts which would total to 2000 Watts. This will give our project the ability to be expanded upon as further research is conducted.

Another reason we are opting for the inverter to be 2000 Watts is so that the township as it grows and develops will be able to use this inverter if their power needs change with less cost to them. It is important to our design that there is room to expand because the township needs room to expand.

*Surge power: B*ecause it is unknown what power surges might occur, the inverter needs to be able to survive a power surge for a brief moment. This is very different than the continuous power and will be a high power than the continuous power. A power surge can only occur for a short amount of time. The inverter needs to be able to survive this surge of power long enough for the main controller to realize the increase in power and throw the switch to the inverter.

Output voltage and frequency: There are a few output voltages and frequency choice that could be made which is talked about in detail on section 4.6. The choice of output voltage for the inverter will be 120 volts at 60 hertz. We are choosing the American standard of AC electrical power for a few reasons.
The first reason, which will not be discussed in detail in this chapter (see section 3.15 for further detail), is it is easier to find converters from the American power standard to other AC power standards across the world.

The second reason is that if we buy an inverter it will be easier to buy an inverter that delivers this output. Although there is a big market for the European standard at 230 volts at 50 hertz, there would be a greater shipping cost to deliver that inverter from a factory in Europe because it is rare to find a European standardized inverter while here in the United States. Also, in during research on prices for inverter it is more difficult to find an inverter at the European standard and it is more expensive without out the cost of shipping included. As an example the Cobra CPI 1575 is rated at 1575 Watts has an output of 120 volts at 60 hertz and is priced on their website as $189.95. [42] Whereas the AIMS Power's inverter model number PWRI15002422050 is rated at 1500 Watts for 220 volts at 50 hertz and is priced at $469.00 on their website. [43] that is around two and a half times more expensive to go with the European standard inverter. This is an unacceptable difference in the price.

3.14.1.3 Over Temperature Protection

The inverter also needs to include an over temperature protection. An inverter generates a lot of heat, because it is not 100% efficient. The more power going through the inverter and the less efficient that inverter is the more heat it will generate. That heat needs to be dissipated from the inverter. If there is no heat dissipation the inverter will continue to heat up and finally melt the electronics inside. Most inverters come with a fan to help with heat dissipation. For our design the inverter will not be in an open air situation making it more likely to overheat. The inverter need to have an over temperature sensor so that if the temperature inside the enclosure increases too much it will shut off, saving itself. Once the power stops flowing the enclosure can cool down and restart.
In conclusion: If the inverter's specifications will be as follow:

- Input needs to be a multiple of 12VDC because of the batteries
- Input needs to have a range of +/- 2VDC
- Input needs to have a acceptable response time to handle a change in voltage

- Handle a total of 2000 Watts minimum
- Use the American standard of power as an output at 120VAC at 60Hz
- Must mimic the grid as best as possible, meaning <5% harmonic distortion
- A reasonable price that will be determined based on budget
- High efficiency to reduce the demand for heat distribution, >80%
- Very robust and possibly a warranty
- Will not be grid tie compatible

All of the above specifications for the inverter are to enhance the efficiency of our project, to be able to expand for future addition either by ourselves or the township where this will be delivered to, and have the convenience for adaptability for multiple power standards across the world at the lowest price.

3.14.2 Topologies

3.14.2.1 Square Wave/Modified Sine Wave Inverter

Square wave inverters are the simplest and cheapest AC inverters that we could design. Low amounts of parts and the design test and build time estimated would be only a two to three week process and would give us an AC power output. The discussion below describes a possible design for the square wave inverter, and the advantages and disadvantages of the design.

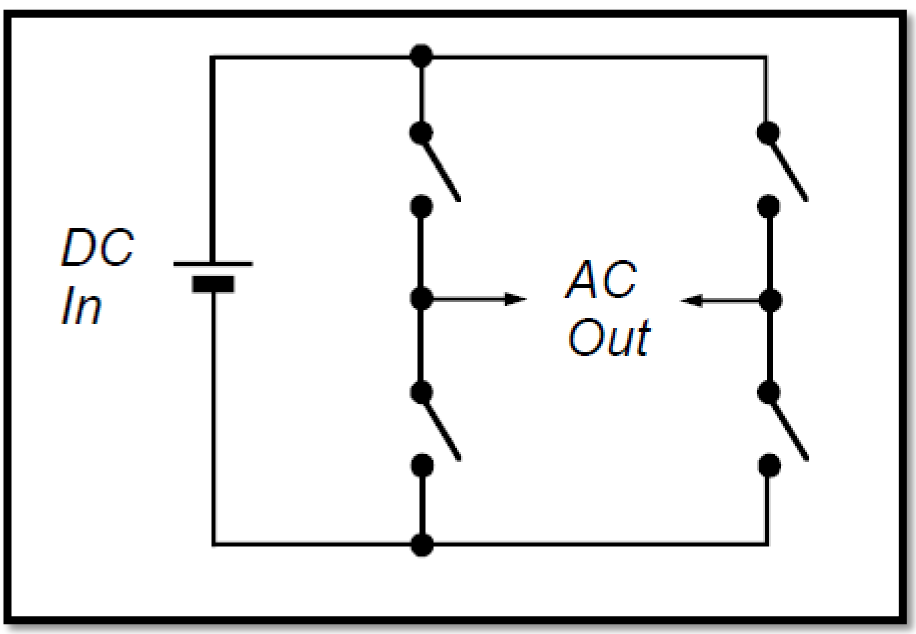

Figure 36 Topology of a square wave [44]

The Figure 36 diagram is the simple topology of the design for a square wave. In short all we need to be able to do is close the left highest and right lowest switches, to get the positive portion of the square wave (assuming the left side of AC out is positive voltage). Both the right highest and left lowest are left open during this time. To obtain the negative portion of the square wave you would do the opposite. Doing this back and forth rapidly would give an AC power output. In addition to an AC output we could also control the duty cycle. If all switches were in the open position no current would follow allowing use to change the duty cycle. This would allow us to change the output power.

A non-detailed part list:

- Microcontroller able to send Pulse Width Modulated (PWM) signals out to control the frequency and duty cycle of the inverter.
- Four MOSFET transistors able to handle 85+ Amps from the DC source
- Four opto-isolators to isolate the high power from the microcontroller

A possible design would be to use the PWM signal from whatever microcontroller chosen. The PWM signal would be split. One split would go to two of the opto-isolators to control the left highest and right lowest MOSFET transistors. The other split would go to an inverter and then to the other two opto-isolators controlling the remaining two MOSFET transistors. This would produce a square wave with a 100% duty cycle. (Please assume that a step-up converter is before this circuit stepping-up the voltage to 120VDC) The output and possible schematic of the circuit are below in Figure 37 and Figure 38.

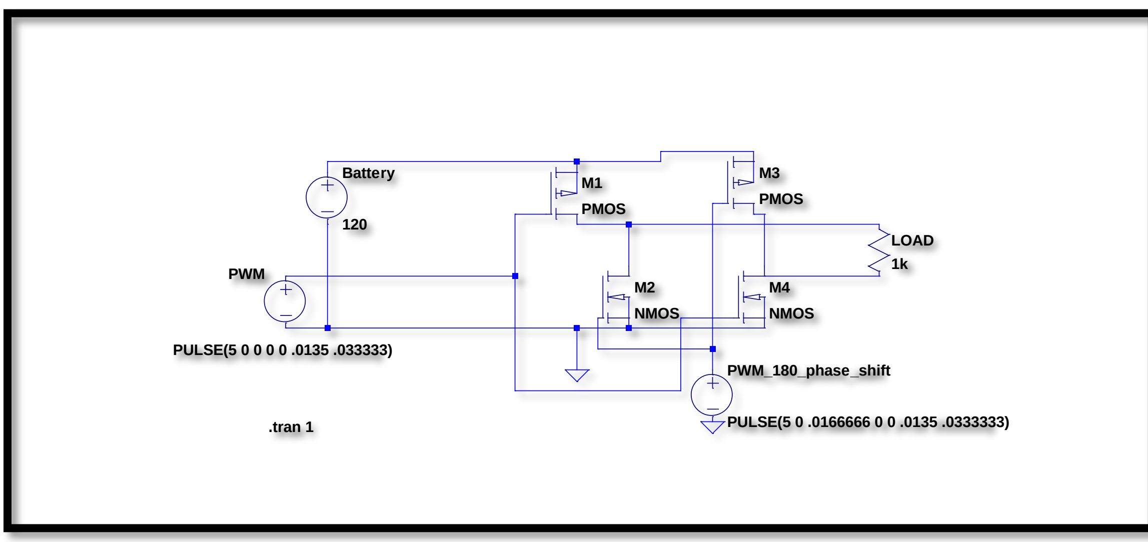

Figure 37 120V @ 60 Hz Output

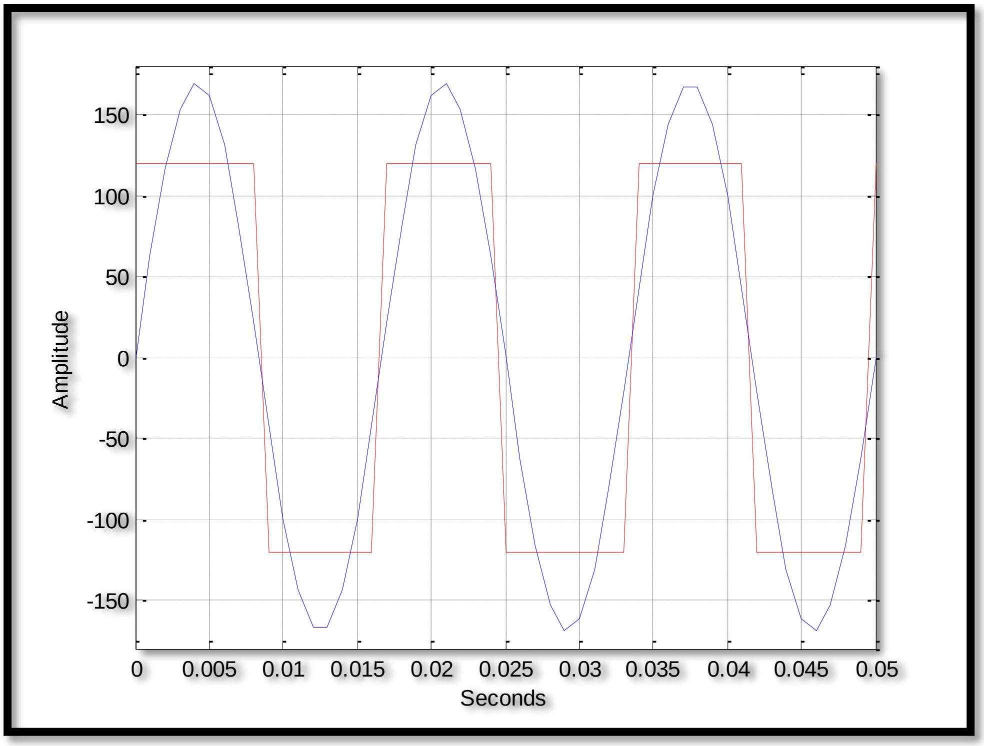

Figure 38 120V @ 60 Hz Output

Although the square wave is both very easy to implement and design it will not meet a major specification. The square wave output from the inverter is not compatible with electronic devices that are designed for on-grid power which of course is a pure sine wave. Devices that would use on-grid power would have to have a specially designed converter that is not on the market and would be very difficult to design. "This generates a square output waveform whose peak amplitude (NB: peak and RMS are same for square wave) is equal to the DC source voltage. This is very easy to implement, but a square wave will not satisfy the requirement for low distortion. (The total harmonic distortion of a square wave is around 55%)". [44] This is one other reason this design will not work. Thus a new idea must be explored.

3.14.2.2 Modified Sine Wave Inverter

Another idea that might be explored is the modified sine wave. This is the same design as the square wave inverter. The difference is that the output of the inverter goes to zero volts for a time ($t < T/2$) then will switch to the opposite sign. By going to zero volts for some time less than half the period we can reduce the power to the harmonic frequencies increasing the overall efficiency.
"Motors, such as refrigerator motor, pumps, fans etc will use more power from the inverter due to lower efficiency. Most motors will use about 20% more power. This is because a fair percentage of a modified sine wave is higher

frequencies - that is, not 60 Hz - so the motors cannot use it. Some fluorescent lights will not operate quite as bright, and some may buzz or make annoying humming noises. Appliances with electronic timers and/or digital clocks will often not operate correctly. Many appliances get their timing from the line power - basically, they take the 60 Hz (cycles per second) and divide it down to 1 per second or whatever is needed. Because the modified sine wave is noisier and rougher than a pure sine wave, clocks and timers may run faster or not work at all. They also have some parts of the wave that are not 60 Hz, which can make clocks run fast. Items such as bread makers and light dimmers may not work at all - in many cases appliances that use electronic temperature controls will not control. The most common is on such things as variable speed drills will only have two speeds - on and off." [41]

However, "The harmonic distortion of this 'modified sine' wave is also less than a square wave (at around 25%) but this is still too high to meet the specification." [44] This is a better method than the square wave and would work for many electrical devices that require on-grid power. However, since we do not know the devices that might be used in the future for the community center, this is also unacceptable for our design specifications.

3.14.2.3 Pure Sine Wave Inverter

This type of inverter will meet our design specification of mimicking the grid. As we research a pure sine wave inverter it became obvious that the level of complexity and time would significantly go up. There are a large number of parts that are involved and because of our power requirements all of the parts that are directly manipulating the current need to be able to work with large amounts of current. This will also mean lots of heat distribution.

The majority of other designs we research, done by other students and hobbyists, were all designing their inverters to handle about 500 Watts of power. This is far less than we what we require. This would imply a major re-design of any topology that we found of a pure sine wave inverter. The designs were not easily scalable to the levels that we needed because of limitations of the solid-state device that they used. This adds an uncertainty that it would be able to work for our final project.

The following is an example that we might be able to use after we re-engineer some of the parts to be able to handle the large amount of current that would go through our inverter. We would also have to consider the increase in heat from our design to protect the electrical components used. However, this does hold some promising results.

The figures below show close to pure sine wave oscillation (See Figure 39) with less than 6% harmonic distortion. This low percentage of harmonic distortion is within the tolerances of home appliances meeting one of our specifications. We must note that 0% harmonic distortion is impossible because of noise introduced by the electrical components used. Thus less than 6% harmonic distortion will decrease the efficiency of certain devices such as electric motors which are very sensitive to harmonic distortion. But again, these losses are expectable because the device would still function. There are also very good results coming from the efficiency of this inverter with a peak of 90% at 260 Watts. (See Figure 40)

But again the major problem with this design is that its maximum output was 550 Watts. This is still a lot of power but not what our system requires. [44]

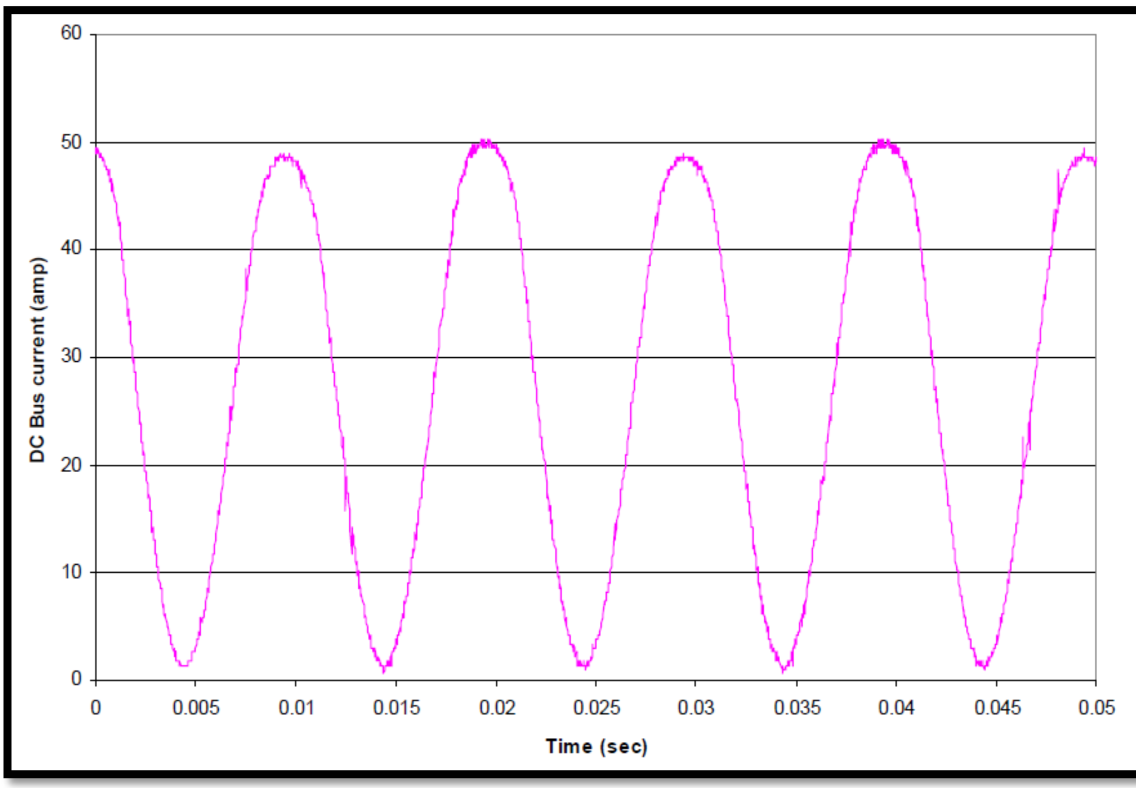

Figure 39 Pure Sine Wave Output [44]

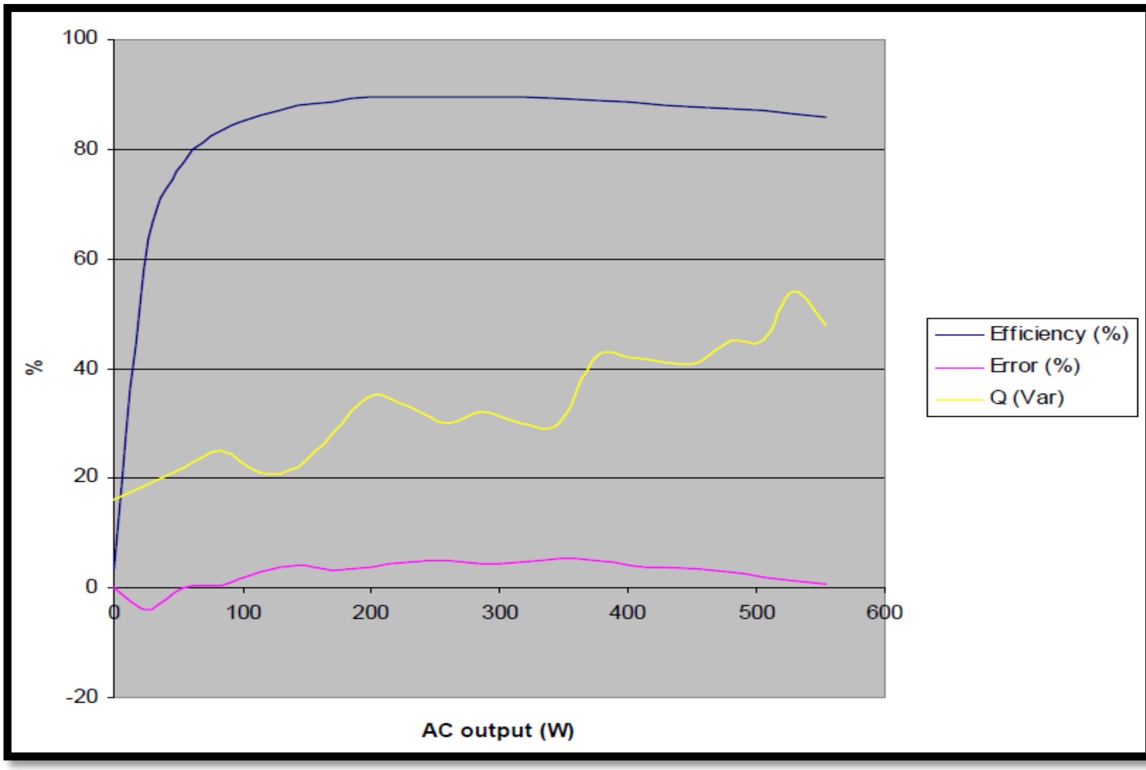

Figure 40 AC Output Efficiency [44]

3.15 AC/AC Converters

An AC-AC converter translates an AC waveform to another AC waveform where the output voltage and frequency can be set arbitrarily. As mentioned in above sections, this system will be placed in small town in South Africa, where the outlet specifications differ from American standards. Besides the voltage and frequency output, the design of the outlet socket is different from each country. American standard voltage and frequency output is 120 volts and 60 hertz, where African standard is 220 volts 50 hertz. Due that there is a different between two countries, appliances differ as well. Therefore, this system will have to incorporate both standards, American and African, that way there is more freedom when using the system, knowing that any appliance can be plugged in without the fear of burning it up.

An adapter is to be known as an AC to AC converter due that it is plugged into a outlet socket that have a set voltage and frequency depending which location it is, and converts it to a different depending on the appliance's specification. Figure 41 shows the AC to AC topologies that have to be taking into account when designing the converter or adapter.

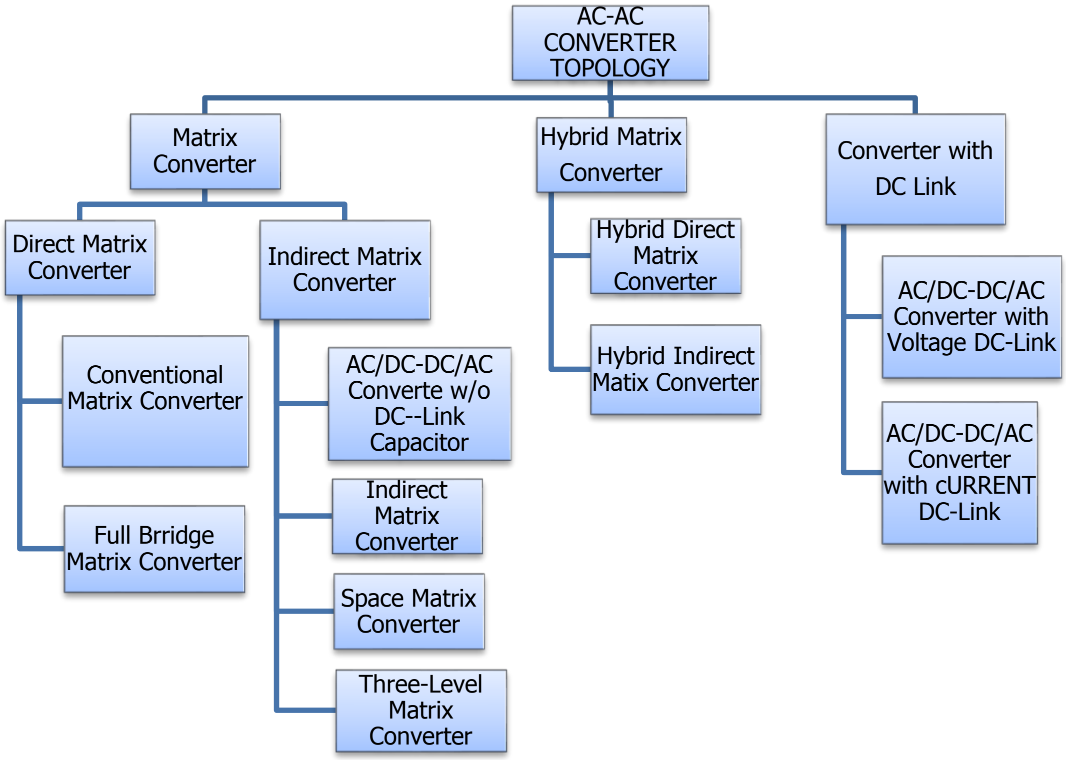

Figure 41 AC/AC Converter Alternatives

3.15.1 Topologies

There are two main categories that can be used to separate the types of converters, whether the frequency of the waveform is changed or unchanged, in this case, our project will change both the voltage and frequency. The first one is an AC to AC converter that does not allow the user to modify the frequencies are known as AC Voltage Controllers or Regulators. In the other hand, the AC converters that allow the user to change the frequency are simply referred to as frequency converters for AC to AC conversion.

The purpose of an AC Voltage Controller or Regulator is to vary the root mean square voltage across the load while maintaining a constant frequency as shown in Figure 42. These controllers are employed utilizing Thyristors between the load and a constant voltage AC source. The ac voltage is controlled by adjusting the angle of the Thyristors in the circuit. It is also know as a type of Thyristors power converter which is used to convert a fixed voltage and frequency to obtain a variable voltage AC output. [47]

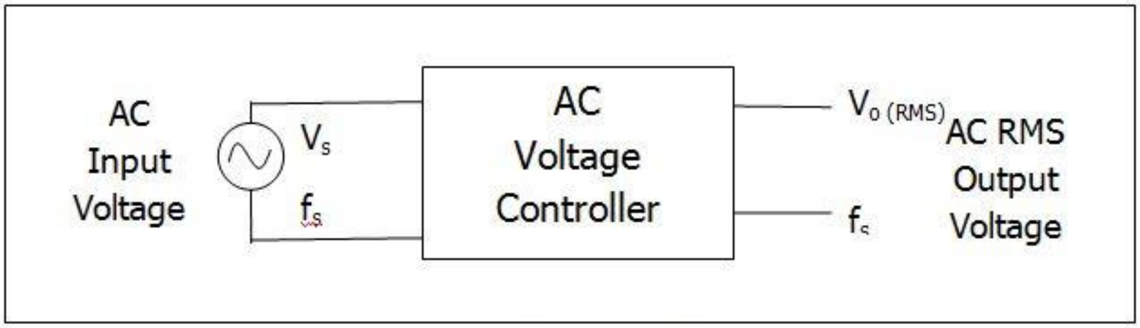

Figure 42 AC Voltage Controller

The following are two control methods that are used as AC voltage controllers:
ON/OFF Control: in this method Thyristors are used as switches to connect and disconnect the load circuit to the AC source, in the project will be the power coming from the inverter, for few cycles in order to acquire the desirable output voltage.

Phase-Angle Control: Various circuits exist to implement a phase-angle control on different waveforms, such as half-wave or full-wave voltage control. Likewise ON/OFF control, in phase control the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle, depending if is a half or full wave. By controlling the phase or delay angle, the output RMS voltage can be controlled.

Some of the applications of an AC voltage controllers are in lighting ac power circuits, industrial & domestic heating and transformer tap changing along others. This project will aim to obtain a constant output voltage and constant frequency for the two different standards.
Another technique used as a ac to ac converter is the frequency converter, which is what the project will center its focus on. The following classifications are deep analyzed for further understanding and applications:

- DC-Link Converter (AC-DC-AC converters)
- Cycloconverter
- Hybrid Matrix Converters

3.15.1.1 DC-Link Converter

This technique, also known as AC/DC/AC converters, converts an AC input to an AC output with the use of a DC link in the middle. Meaning the first stage is using a rectifier method to change the power from AC to DC, and then it is converted back from DC to AC using of an inverter methodology. The end result is an output with a lower or higher voltage and different variable frequency. Nowadays many systems used this technique because is the most common and

easy to implement. Other advantages to AC-DC-AC converters are that they do not overload and make a stable voltage and frequency conversion. For the DC link there are two different techniques, the pulse width modulation and the resonant each using hard and soft switching respectively. Figure 43 illustrates DC-link topologies. Hard switching known as Pulse Width Modulator consists of a dc capacitor for a voltage source inverter (VSI) or the inductor for a current source inverter (CSI). The resonant has a dc bias circuit that will not the system cross zero, even if the voltage and current pulse becomes zero. [45]
This converter receives sinusoidal input currents that can be recognized by coupling a pulse-width modulation rectifier and inverter to the DC-link. Once the energy is taken by the DC-link is impressed by an energy storage element known as a capacitor C for the voltage DC-link or an inductor L for the current DC-link.

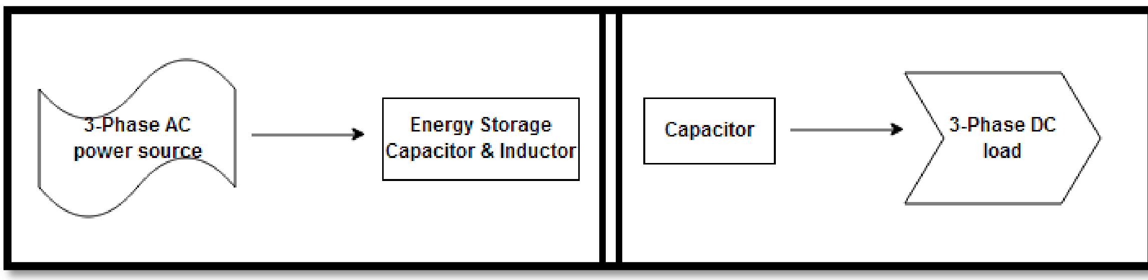

Figure 43 DC link AC to AC converter topology

In order to attain higher power density and reliability in our system, research has been conducted and found the consideration to implement the Matrix Converters that achieve three-phase AC-AC conversion without any intermediate energy storage element like capacitor or inductor.

3.15.1.2 Cycloconverter

The cycloconverter technique is widely used in industry for AC to AC conversion due to the ability of functioning for high power applications. A cycloconverter (CCV) translate a constant AC voltage and frequency waveform to another AC waveform of a lower frequency. There are two main types of cycloconverter, circulating current or blocking mode type.

Generally, the combinations of CCVs are 1-phase/1-phase, 3-phase/1-phase and 3-phase/3-phase input/output configurations respectively. The power rating of a cycloconverter ranges in the megawatts. It is applicable in large machinery and systems that need a conversion of power because location difference standards.
This type of converter connects the alternating output voltage waveforms with high order harmonics. Unlike other converters, cycloconverter design does not include any inductor or capacitor; therefore the instantaneous input and output power are equal.

With recent device advances, newer forms of cycloconverter are being developed, such as matrix converters. Matrix converters, shown in Figure 44 function that each switch input is connected to each output, or one phase to one phase connection, without connecting any two switches from the same phase at the same time; otherwise this will cause a short circuit of the input phases. As a result matrix converters are lighter, more compact and versatile than other converter solutions.

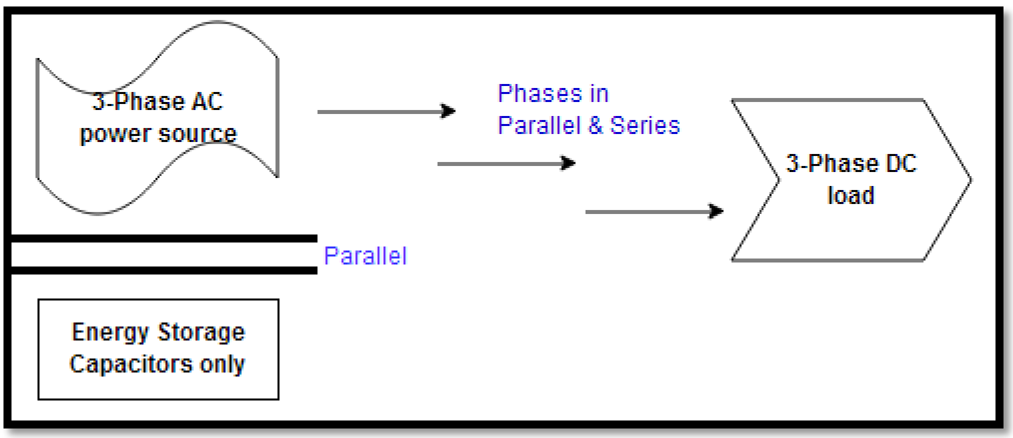

Figure 44 Matrix Converter [45]

There are two types of matrix converters, direct and indirect. Direct matrix converter works when the direction of the current is bi-directional, blocking voltages, and letting current passed on either direction. This switching approach permits the highest possible output voltage and reduces current that flows in either direction.

Unlike the direct matrix converters, the indirect matrix converters has the same functionality, but is connected through a DC link without storage elements, inductor or capacitor. The topology design includes a current source rectifier and a voltage source inverter.

3.15.1.3 Hybrid Matrix Converters

This technique is relatively new for AC/AC converters. It is called hybrid because is a combination of the AC/DC/AC design with the matrix converter design. There have been several types of hybrid converters that have been developed in the recent year, as an example is a converter that uses uni-directional switches and two converter stages without the dc-link. Without the capacitors or inductors, the weight and size of the converter is reduced, and the power converted is relatively the same as the matrix converter. Like Matrix converter, Hybrid has two sub-categories named hybrid direct matrix converter (HDMC) and hybrid indirect matrix converter (HIMC). Direct converts the voltage and current in one stage, while the indirect utilizes separate stages, like the AC/DC/AC converter, but without the use of an intermediate storage element. The following Table 17 shows a summary of specs of the different types of topologies we discussed earlier. There are more topologies, but we have recompiled the main ones and the ones that we will be analyzing in our design section of the project.

Table 17 Excerpt AC/AC Converter Comparison

<table>
<tr><th>Converter Topology</th><th>Input Stage</th><th>Output Stage</th><th>Passive Component Count</th><th>Method of Switching</th></tr>
<tr><td rowspan="2">Sinosoidal PWM VSI</td><td>passive</td><td>PWM</td><td>1C</td><td rowspan="2">hard</td></tr>
<tr><td>active</td><td>PWM</td><td>1C</td></tr>
<tr><td rowspan="2">Six-step VSI</td><td>passive</td><td>6-step</td><td>1C</td><td rowspan="2">hard</td></tr>
<tr><td>active</td><td>6-step</td><td>1C</td></tr>
<tr><td>Cyclo-converter</td><td colspan="2">single-stage</td><td>0</td><td>natural commutation</td></tr>
<tr><td>Resonant Commutated</td><td>PWM</td><td>PWM</td><td>2C</td><td>primary switch ZVS</td></tr>
<tr><td>SR AC Link</td><td>DPM</td><td>DPM</td><td>1L, 1C</td><td>Soft ZCS</td></tr>
<tr><td>Matrix</td><td colspan="2">single-stage</td><td>0</td><td>hard</td></tr>
</table>

3.16 LCD

A LCD screen will be incorporated in this design in order to improve the user interactivity with the system and keep the user updated with the current status of the overall system. The LCD will display the valuable information to the end user such as the temperature at the different points where the sensors are located, the current and voltage that the solar and wind sources are producing, and the overall charge of the battery bank used.

A liquid crystal display is the most common display type among battery-powered electronics because of its low power consumption and good image quality. They are generally easy to read, even under direct sunlight. The smallest element of an image displayed on a LCD is the pixel. Each pixel normally consists of a layer of molecules aligned between two transparent electrodes, and two polarizing filters. There are several different types of LCD technologies to choose from. Choices range from minimal character displays to rich full color displays with touch screen capability. The type of LCD screen that will be chosen will be based on the screen that best balance the ability to show the information that needs to be displayed, the amount of power consumption and the cost.

3.16.1 Segmented LCD (Alphanumeric)

Segmented LCD screens can display Arabic numbers represented by 7 segments or Arabic numbers and Roman letters represented by 14 segments. Symbols, such as plus or minus signs, measurement units and any custom icons, can also be displayed. Each symbol is treated as one segment. Segment LCD screens are widely used on the displays of scientific instruments. This type of LCD screen is easy to program and is the most cost-effective screen to develop. However, a segment LCD is limited to displaying numbers, roman letters and fixed symbols. Therefore, in case is needed to display anything else, another type of LCD display such as dot matrix or graphic display needs to be used.

3.16.2 Character LCD (Dot Matrix)

A Dot matrix LCD is used to display a number of lines of characters. The most commonly used dot matrix LCD shows 1 to 4 lines of 16 to 40 characters. Each character is represented by 5x7 dots plus cursor. Each character block is addressed separately and can form numbers, roman letters, character in other languages and a limited number of symbols.

Dot matrix LCD is used when is needed to display more characters than those in the English alphabet. A character LCD is relatively simple to control and program, inexpensive, and also require low power to operate when compared to other LCD screen types such as graphics and touch screen models.

3.16.3 Graphical LCD

A Graphical LCD provides users with a greater degree of flexibility. This type of LCD is composed of pixels arranged in rows and columns. Each pixel can be addressed individually for text, graphics or any combination of the two.
Graphic LCD is used in applications when the user needs to have total control of the whole viewing area. However, flexibility also comes with the difficulty in designing the control circuitry. One key advantage of incorporating a graphical LCD screens is that it allows for more text, pictures and logos, as well as a larger interface increasing the flexibility in the design. However, because of the increase in size, the LCD will also consume more power. In addition, the programming required is also more complex.

3.16.4 Backlighting

One key factor when choosing an LCD screen is if the system requires a screen that has backlighting or if internal illumination is not necessary for the specific application. Backlighting is needed in applications where the screen will be exposed to low lighting conditions. However, a screen that incorporates backlighting will consume more power than a screen that do not require lighting. For the purpose of this project a backlighting display will be used because this will allow to make the design much more versatile and able to operate in a wider range of situations.

3.16.5 Color and Monochrome

Another important option to consider when choosing an LCD is whether to incorporate a color or monochrome screen. Monochrome LCDs are typically passive-matrix. Monochrome LCD images usually appear as blue or dark gray images on top of a grayish-white background. Color LCD displays use two basic techniques for producing color: Passive matrix is the less expensive of the two technologies. The other technology, called thin film transistor (TFT) or active-matrix, produces color images that are as sharper, but they are usually more expensive. Technologies, Color and Monochrome screens are relatively low power.

3.16.6 Touch screen

The main advantage of using a touch screen is the infinite ways the user interface can be designed compared to a set of fixed physical buttons. In essence, a touch screen display would eliminate the need for any buttons or control devices. The design can be programmed to accept hand printing, handwriting, graphics and finger gestures such as multitouch. Touch screens can also be made resistant to harsh environments. All touch screens place the point of contact on screen into an X-Y coordinate. However, touch screen displays would increase the cost in the design because of their relatively high price when compared to other types of display technologies. Also, the incorporation of a touch screen display will incur extra programming complexity.

3.17 OSHA Law & Regulations

One of the purposes of this project is to provide a safe and healthful power generation system for the Harrismith community in South Africa. In order to accomplish this, the project will comply and follow the safety regulations and standards of the Occupational Safety & Health Administration (OSHA). By following OSHA's electrical standards this project will protect the habitants of Harrismith that could be exposed to dangers such as electrocution, electric shock, explosions, and fires. In other words, this project will comply with OSHA's standards in order to address these concerns.

3.17.1 Green Job Hazards

Some hazards on mounting a PV panel to a roof or any facility that is higher than 6 feet, has to follow regulations to ensure the safety of the person mounting the system and the people around them. Before starting the installation, make sure the following criteria is met:

- *Safety nets:* is the facility where the PV panel will be installed is sufficiently high; it must have a safe net to protect the person. The safe nets must be installed with enough clearance to prevent contact with the surface or any other structure under it.
- *Fall arrest systems*: Providing personal fall arrest systems for each person such as body hardness, anchorages. Some of this can be purchase and tested before it actually goes on the structure and person. Also, make sure there are not objects that can be subject to fall impact.

Another exposure to potential electric hazards can include electrocution and arc flash vulnerability. As a design group, we will be working on connecting components together, testing the system, and finally installing it at the location. Therefore, OSHA rules must take place to prevent any hazard to occur. Some resources on the standards and practices are listed below.

- *Wiring design and protection:* by the regulatory section 1910.304 that specifies the polarity of connections, "no grounded conductor may be attached to any terminal or lead so as to reverse polarity"
- *Wiring methods, components, and equipment for general use:* by the regulatory section 1910.305 specifies that "metal raceways, cable trays, cable armor, cable sheath, enclosures, frames, fittings, and other metal noncurrent-carrying parts shall be effectively bonded where necessary to ensure electrical continuity and the capacity to conduct safely any fault current likely to be imposed on them."
- *Specific purpose equipment and installations:* regulatory section 1910.303 specifies the proper lighting, sign and outline system needs to be controlled by an external circuit system, this is because the system that the person is working on should be off and grounded. Also they should be located at least 5.0 ft away from any water structure.

Lastly, here we just focus in a couple of regulations that pertain to the design, test and installation of the system. It is beneficial to have all the regulations and procedures to prevent any hazard during the process. There are other precautions that will be undertaken to safely proceed with every component of our systems. There are procedures that are not listed anywhere but are important to act before something can happen. Always read the specifications of every single component and devices used, to know exactly maximum current and voltage that can each undertake.

4. Design

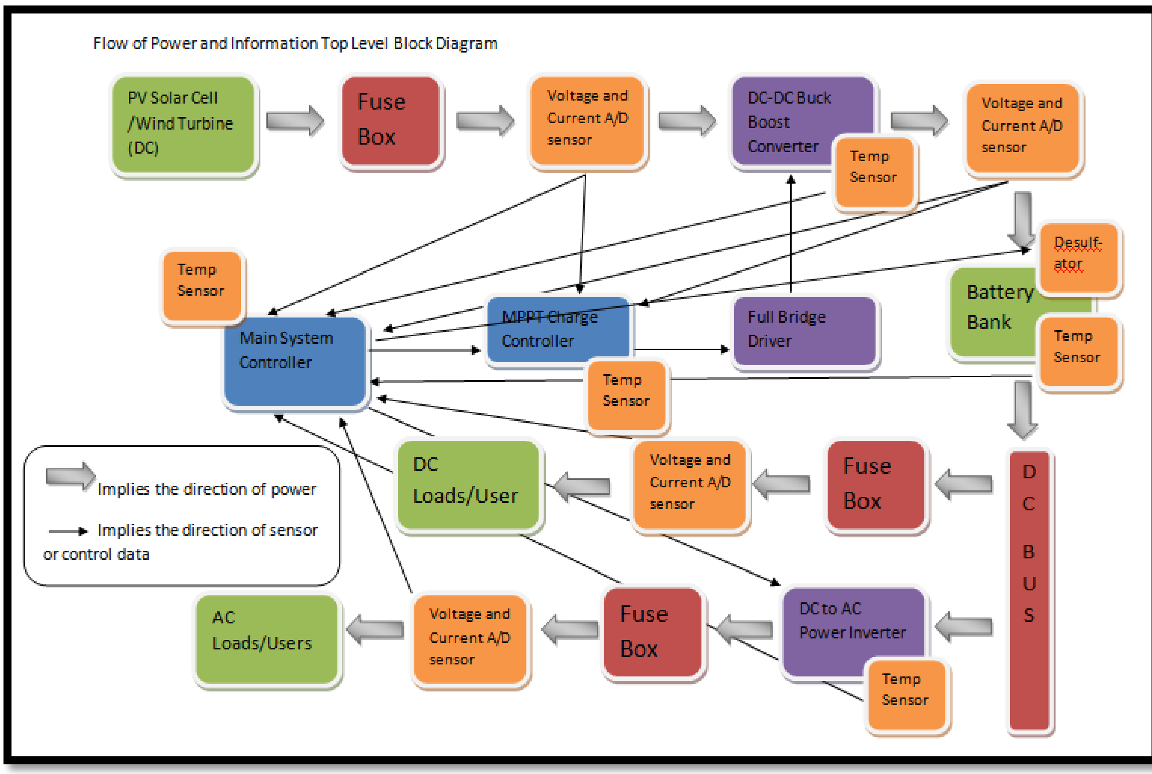

Figure 45 Flow of Information and Energy Top Level Block Diagram

4.1 Main Controller

The main controller is the brains of the operation. The processes that are involved with the main controller are slower and more maintenance based. The main controller's main function is to communicate with the other devices around it and report to the user. In despite the multiple input and output pins, it does not compute in a great amount. It does not require speed because none of the information sent from the main controller is time sensitive to the point where the information from the main controller is needed within microseconds. The speed of the delivered information is closer to the millisecond to second range depending on the device. The functions of the main controller are as follows:

- Determine the charge level and health of the battery
- Control of other internal systems
- Maintain temperature and components of the system
- Report system conditions to the user
- Protect the system from out of bound trending conditions

4.1.1 Requirement Details

4.1.1.1 Determine Charge Level and Health of Battery

The batteries are the central focus of the system. It is important to check on them often, especially when charging. The batteries can be damaged if there is any overcharging. The batteries also need to be check when the system is not charging. This is because the batteries can discharge further than what is recommended, which is about 50% for most batteries, and over multiple deep discharges causes shortening of the batteries life span. The rate of discharge is also another factor. To fast of a discharge rate will damage the batteries.

To prevent overcharging the system has a series of relays and kill switches that will be turned off and disconnected from the battery when necessary. This will give us an accurate reading of the battery that is not interfered with DC-DC buck boost. This reading inform the main controller at what stage of charging and an estimate of the level of charge on the battery. Once the battery is almost charged or fully charged the system needs to stop supplying the battery with power. This will put the battery at the float stage and not over charge it.

The opposite of overcharging would be to do a deep discharge of the battery. The level of power the battery can deliverer is more than the recommended level of power delivered. If the battery was not to be recharge this would not matter but the battery can discharge too far where the health of the battery can to diminish. If there is no power coming from the solar or wind power source then the level of charge on the battery can be easily read, and then checked whether or not it has reached the recommended discharge level. If there is power coming from the solar or wind power source, it needs to be disconnected to get an accurate reading on the level of charge on the battery. If the battery has reached the recommended level of discharge and then a little more to keep the main controller running and some small sensors on, then a shutdown procedure will begin in the main controller. The main controller and a few voltage sensors will need to be on for a few days of the battery has reached its limit to make sure is can maintain the system until there is enough power from either the solar or wind source to recharge the battery. The system will not start to deliver power to the user until the batter is mostly charged. This is to prevent the system doing main starts and shutdowns when there is only partial energy for the solar or wind source.

The main controller will also be in charge of storing data about the battery to see trends the battery might be taking. It is important to store previous data on the battery to see if the battery is acting nominally. Storing data will also allow the main controller be able to calculate a battery that is trending toward failure and alert the user.

4.1.1.2 Control Other Internal Systems

The main controller has the control over all other system within the enclosure. The main controller is the first device to turn on during start-up, and then the main controller will go through a start up sequence to power up other devices. The main controller does not have enough pins to control all other devices and read in the necessary input from sensors. To achieve the number of outputs need an I/O expander will be needed. This will slow the output signals from the main controller but the speed is not as important as the number of pins. The output signals do not need to be change that often.

4.1.1.2.1 Control Over Charge Controller

Due that the main controller has the information on the battery's level of charge and the charge stage of the battery; it reports this to the charge controller. Although the charge controller could do the operation by itself, the main controller needs to have control over the charge controller because there could be future expansions. This way if there is more than one charge controller the main controller can select one as the master charge controller and the others as slaves that follow the master's output voltage. Also by dividing the tasks for the charge controller and the main controller more can be done at the same time. The main controller will also have control over the charge controller's power.

4.1.1.2.2 Control Over Inverter

The inverter has a remote control to it which can turn it on or off. This remote control will be dismantled and used so that the main controller can interface directly with it rather than the user having to. Again the main controller also has the ability to turn off the inverter in an energy saving mode.

4.1.1.3 Maintain Temperature And Components of The System

Because the system has high amounts of energy passing through it there will be a fair amount of heat generated within the enclosure. Certain parts and spots need to be carefully looked at for over-temperature. Again the main controller looks at trending patterns and is able to shut down or protect the system before any damage occurs. The main components that need special attention and a thermal device near them are the main charge controller, the inverter, and the batteries. With all the input signals from thermal reading devices an analog to digital converter with a serial interface will be used to save pins on the micro-controller. Again because the temperature of any device will not change faster than a few millisecond or a few seconds at a time, time is not crucial factor and an analog to digital converter with a serial interface can be used even though it will not be as fast as parallel inputs.

The main charge controller has the ability to turn on fans to help cool the system. There are individual fan on the main charge controller, the inverter, and one ejecting air out of the enclosure.

4.1.1.4 Report System Conditions To The User

A major task to the main controller is to report system conditions to the user. This will include the use of an LCD screen. More details on the LCD can be found in the design section 4.8.

4.1.2 Main Controller Software

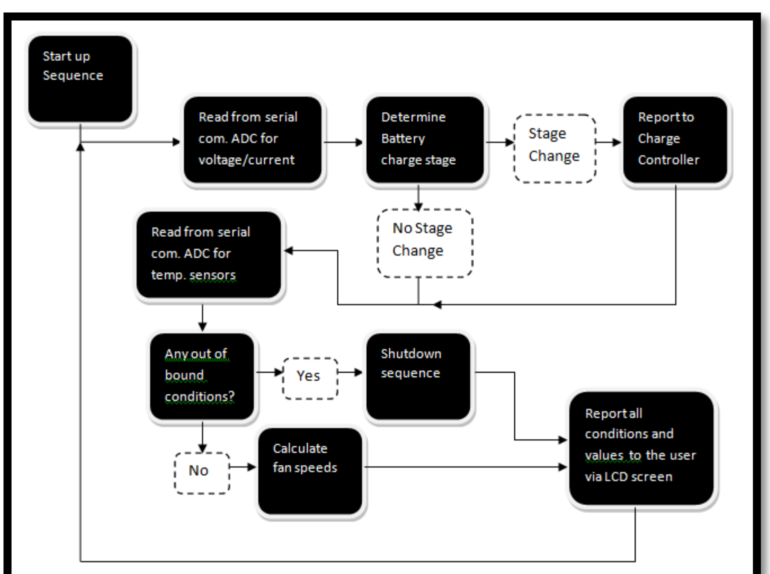

Figure 46 Main Software Flow Diagram of the Main Charge Controller

4.1.3 Microcontroller

The microcontroller chosen was the MSP430G2553, this microcontroller provides all hardware functionality required in the charge controller; all the analog and digital pins required by the sensors and other peripherals are satisfied by this microcontroller. In addition, the 16 MHz clock speed, I2C communication, and robust programming language were also deciding factors in this decision. Protecting the inside from excess dust and water, it adds thermal complications, in great need to be well ventilated and cooled by fans to prevent any overheating.

The enclosure made out of wood and covered with Plexiglas has three different compartments where the components are placed securely inside. The batteries are housed in a separate compartment with its own ventilation, due that are capable of leaking fumes and spilling. The outside user interaction

The front panel is design to include: LCD display, power outlet sockets, American and European standard, USB socket, fans and a switch for emergency shut-down the system.

All electrical components are electrically isolated from the enclosure, in order to prevent any problems with static electricity and accidental electrocution with human interaction.

The speed of the microcontroller needs to be sufficient to run the code without any harmful delays, however is not of main concern. Temperatures will not rise and shift in the orders of microseconds and the peripheral devices will not need to communicate with the main controller constantly, this allows the processing speed to be in the medium range of around 25MHz. At this speed the charge controller can perform its entire task without noticeable changes.

Base on the initial design, one goal was to choose a low power microcontroller. This will be essential in the case of no energy collected from the solar or wind source; the batteries will then supply power to the microcontroller to keep its normal operation.

RISC architecture over CISC architecture will be preferred. The main controller will not perform any complex instructions or calculations. The more RISC the microcontroller's architecture, the faster the number of clock cycles per instruction. This will allow the microcontroller to quickly move from instruction to instruction and taking care of the system.

The MSP430 by Texas Instruments is a processor that falls into all of the criteria above. It has RISC architecture, is low power, and has a moderate processing speed. The microcontroller can then be taken from the Launchpad and place into a designed PCB board after all the code is completed.

The MSP430 is also very inexpensive giving room for the budget in other areas of the project. The MSP430 is priced at $0.25. The development board Launchpad and two MSP430s are $4.30. It meets all of the criteria that the main controller demands.

4.1.4 Analog to Digital Converter

The analog to digital converter with serial interface will be used for the thermocouples taking temperature measurements throughout the enclosure. An analog to digital converter is implemented to read the measurements onf the thermocouples. This device has multiple inputs and few outputs so that there will be remaining pins on the MSP430. There are four thermocouples taking in temperature measurements, one for the each major component; the main controller, inverter, charge controller, batteries. The ADS from Texas Instruments is a great integrated circuit that is designed for thermocouples. The cost for the ADS1246 will be free, this is again because Texas Instruments has free samples and only one will be used in the project.
Even though the MSP430 has an analog to digital converter that could do the readings it is more practical to take the information from a second IC that will send the data through serial communication. This way there will be enough pins for the main controller to continue to monitor and communicate with the rest in the system.
The multiple readings includes, temperature from battery, input and output current through a shunt resistor, and input and output voltage calculated through a voltage divider, placed at the first and end point of the charge controller.
The ADS7830 is a single-supply, low-power, 8-bit data acquisition device that features a serial I2C. With the advantage of an 8 channel analog input module, it can intake several analog devices and values. Also, its nominal voltage supply matches the MSP430 voltage supply of 3.3V, making this device low power consumption.

4.1.5 PCB board

According to the initial design includes two separate boards one for high power and one for the data transmission were designed with the following dimensions 10 x 6. The largest trace widths are .5 inch allowing them to handle a maximum of 20A at a rise temperature of 10°C. The bottom layer of the two-layer board are a ground plain which helps reduce external noise to the electronics and help keep all grounds well connected. In the power electronics circuitry, top copper plains where added in place of traces to assure high current capacities could be handled without overheating. Due to several errors on the design, a last circuit board was purchase including the final design. This board combined high power and data transmission traces and included approximately similar dimensions as the first two.

4.1.6 Hardware Schematic

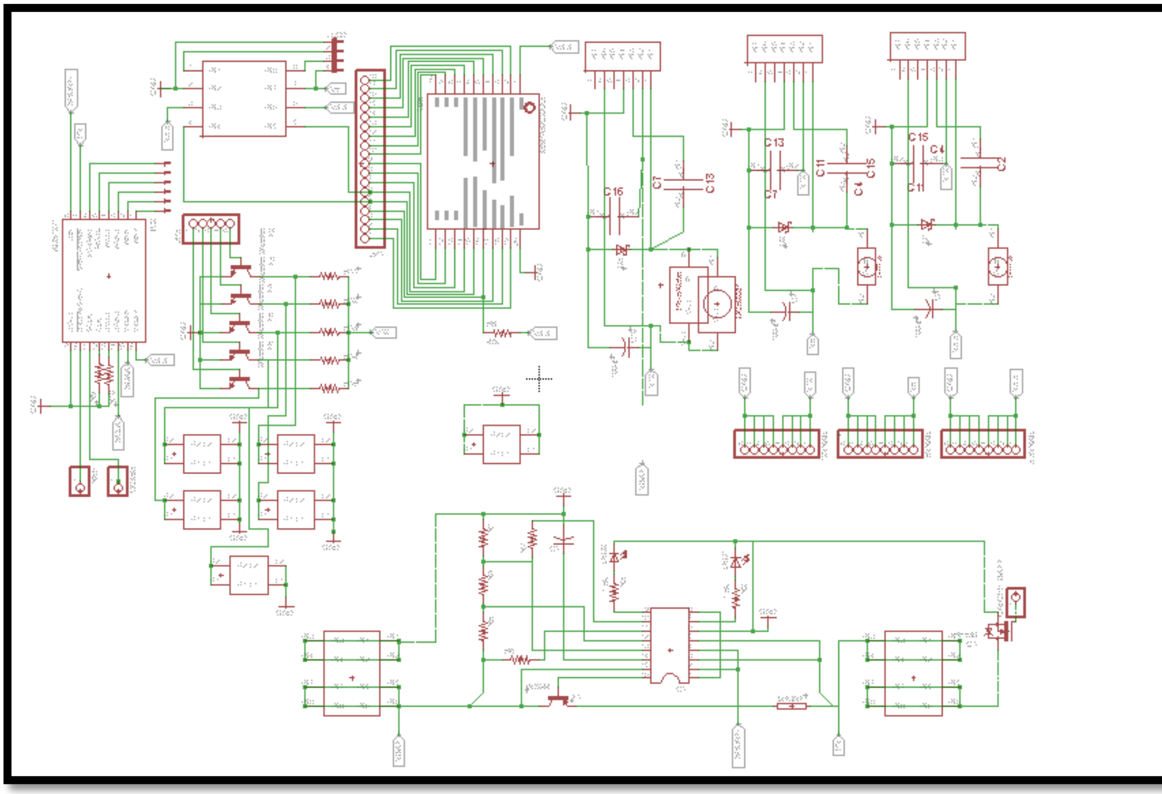

Figure 47 Main Controller Schematic

4.2 MPPT Charge Controller

The charge controller is the most design intensive part of the entire system. The charge controller needs to be faster and have slimmer code than the main controller. Voltages and condition can change much quicker on the charge controller's side of operation. This requires getting into loops doing what is necessary then rechecking for changes. The charge controller communicates with the main controller to get necessary information about the system and charge stages of the battery. By letting the main controller work and monitor the entire system this allows the code in the charge controller to be more streamlined and do its main task. The charge controller's other information comes from the output voltage and current from the solar or wind power sources and the output of the voltage and current of the DC-DC buck boost converter. Figure 48 represents the flow of power and information maximum power point tracker charge controller.

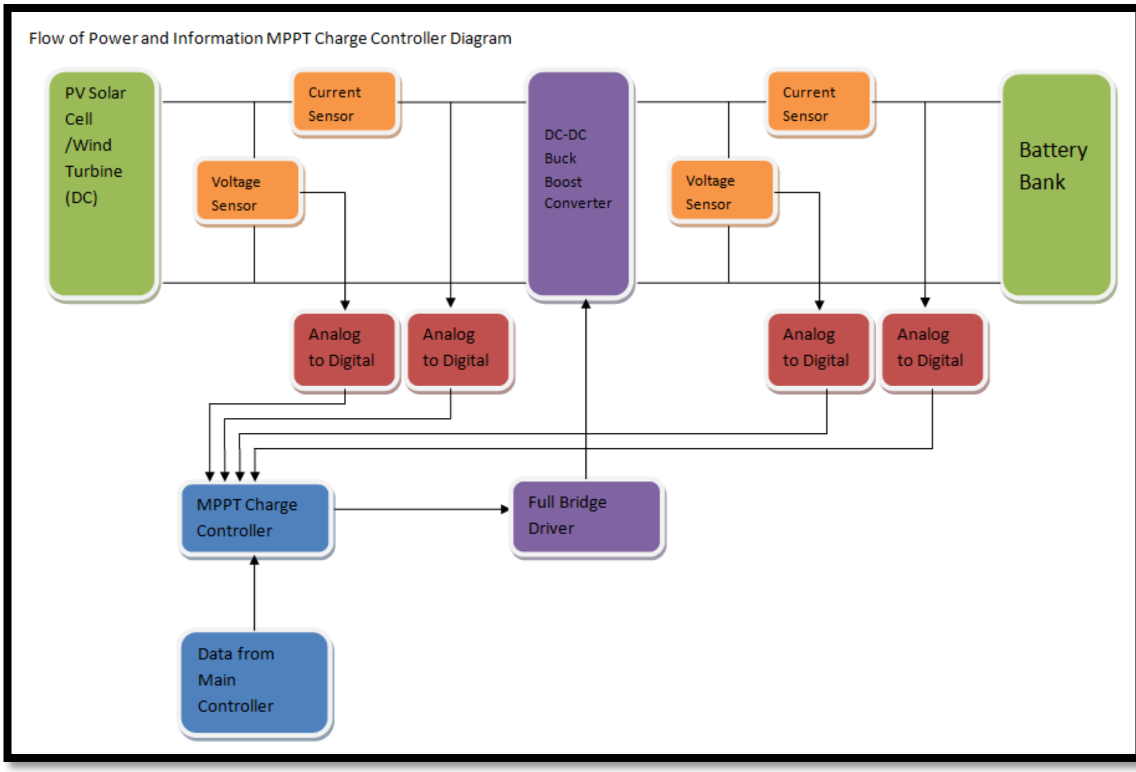

Figure 48 MPPT Charge Controller Diagram

4.2.1 Requirement Details

4.2.1.1 Controller Output Voltage

The first task for the charge controller is to find a desired output voltage of the DC-DC buck boost converter. Because the DC-DC converter is not a linear converter but a buck boost converter there is an equation that relates both the input voltage and the output voltage. The charge controller calculates the output voltage that is needed from this equation. The charge controller then uses a PI algorithm to quickly converge on the difference from the actual output voltage to the needed output voltage to +/- 1%. This first task needs to happen very quickly in the order of only a few clock cycles of the microcontroller to increase efficiency and to move to the next part of the program since the PI algorithm is to be a loop and was called on many times during the whole program. This algorithm to find the desired or needed output voltage should happen as quickly as possible to avoid unstable results.

4.2.1.2 Maximum Power Point Tracking

During the absorption stage of the battery the maximum power point tracking needs to be found to quickly charge the battery. This again needs to be found as quickly as possible to increase efficiency and to avoid missing the maximum power point before it moves causing lots of oscillations. The charge controller uses the perturb and disturb algorithm to find the maximum power point. This method is not the fastest algorithm but it is the simplest to utilize and the maximum power point fast enough if the code used is very slim.

4.2.2 Overview Charge Controller Software

The power to the charge controller is controlled by the main controller. Once power has been given to the charge controller a startup sequence will begin. This startup sequence will be quick and not have much code to it. The first task the charge controller will do is to enter in a loop that begins with checking with the main controller. The charge controller will get information on what stage of charging the battery is in which will determine what task the charge controller will take. The other task the main controller may give the charge controller is to do nothing and have an output voltage of zero. This is done so that the main controller can determine what stage of charging the battery is in. This again is for future expansion and to help streamline the charge controller's code.

If main controller tells the charge controller to go into the absorption mode the charge controller will begin a loop that delivers a constant voltage to the battery. This voltage will be higher than the nominal voltage of the battery. For more information on the absorption stage of the battery see section 3.9.3. To obtain the voltage that the battery wants during the absorption stage the charge controller will first read in all four voltage and current sensors. More on how the charge controller gets those values on 4.1.10. The charge controller then calculate what duty cycle needs to be sent to the H-Bridge driver. Then the charge controller sends that PWM signal to the H-Bridge driver. It then checks what the actual voltage is and adjusts the actual voltage to the desired voltage using a PI algorithm. Once the actual voltage is within +/-1% of the desired voltage the charge controller stores that value in memory. It then rechecks with the main controller to see if any conditions have changed. If a condition has changed it then goes into another charging algorithm or pause until the main controller tells the charge controller to continue. If no conditions changed or the charge controller is returning from a paused condition then the charge controller returns to the absorption stage code. The difference now is that if the input voltage of the DC-DC buck boost converter has not changed within +/-1% then the charge controller uses the previous duty cycle and rechecks to see if it falls within +/-1% of the desired output voltage. This is to increase conversion speed for the output voltage. It then repeats the process until the charge stage changes.

If the main controller reports to the charge controller that the batteries are in float stage then the charge controller starts the code for the float stage. The float stage is a constant voltage with a voltage at or slightly higher than the batteries nominal voltage. The float stage is very similar to the Absorption stage but with one modification. There is no continuous power to the batteries. Instead a trickle charge is used. A PWM signal is sent to the batteries at a rate that allows the batteries to stay charged but does not overcharge them. Before a PWM signal is sent to the batteries the charge controller will disconnect the DC-DC buck boost converter and measure the charge level on the battery then determine the duty cycle for the PWM to the battery. When the charge controller is in the float stage processes and code can be slower than in other processes because it is more important that the battery gets a proper float charge rather than burning up the battery.

If the main controller reports to the charge controller that the batteries are in bulk stage of charging then the charge controller uses the MPPT algorithm. For more information on the Algorithm used go to the next section.

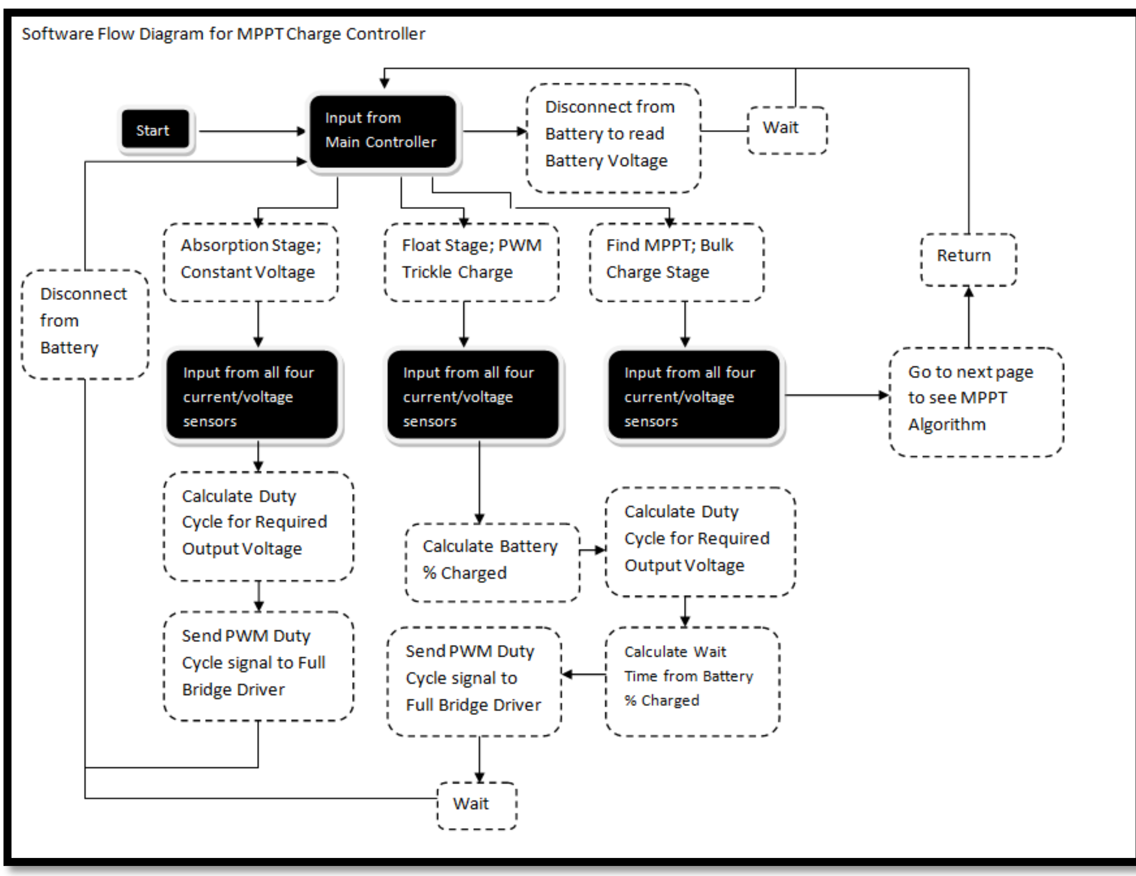

Figure 49 Software Flow Diagram for MPPT Controller

4.2.3 Maximum Power Point Tracking Software

The maximum power point tracking algorithm starts after the values for the input and outputs voltage and current are taken. The first check that happens is for the program to check if there has been a previous value recorded for the power. If there has not it will then record the value at the current moment. The next check is to see if a direction for the next voltage selected has been chosen. If there is not increasing the voltage is the direction chosen. The program increases or decreases the voltage according to the direction chosen. It then calculates the duty cycle needed to get to that voltage then converges to the increased or decreased voltage. Next it calculates the new power and compares it with the old value. If the power is greater than it changes the direction, otherwise it does not. Then it returns to the main program.

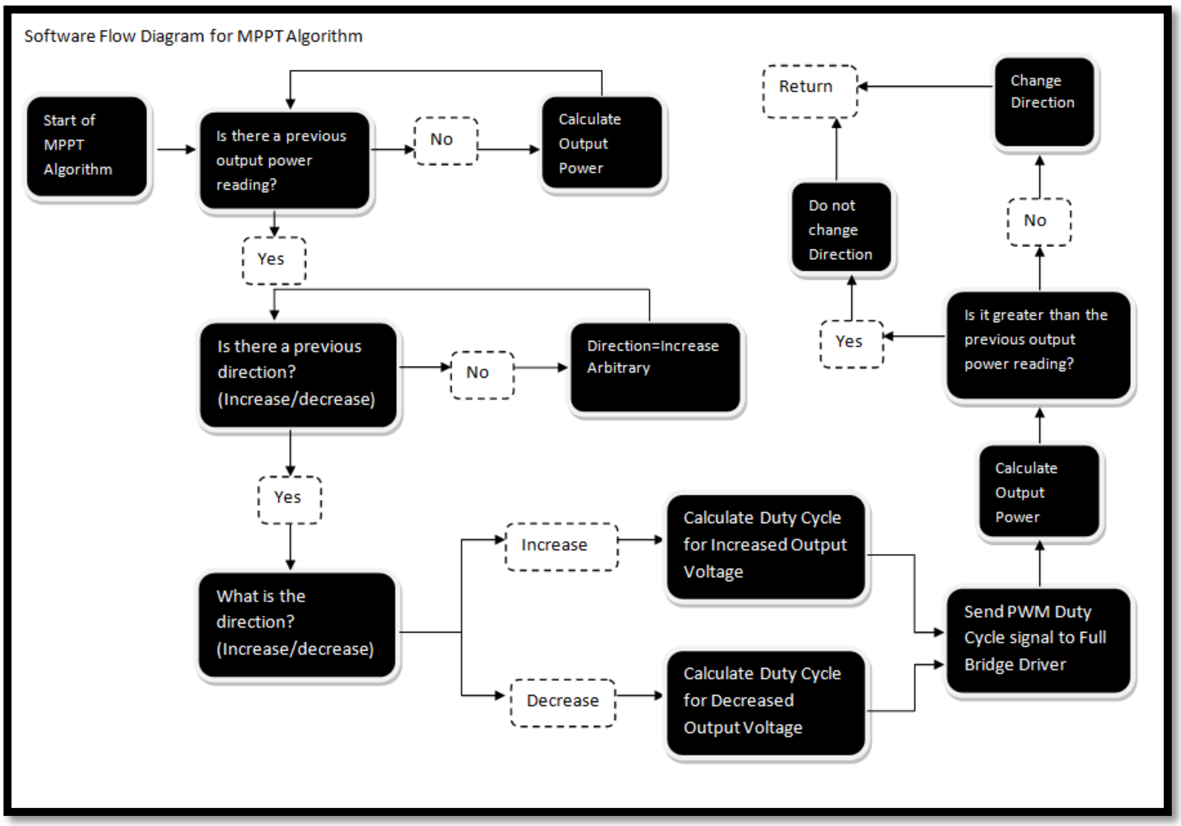

Figure 50 Software Flow Diagram for MPPT Algorithm

4.2.4 Microcontroller

The microcontroller that is needed for this application needs to be fast. The faster the processing speeds the faster the algorithms can converge to the output voltage or maximum power point. If the processor is not fast enough the point on which the MPPT algorithm or the PI controller are converging to might

change and bad oscillations might occur in the system. All the code is programmed in assembly to increase the speed of the code. The architecture that the processor has is a RISC type architecture. There are no instructions that need to be complex. The most complex and time consuming instruction is the multiplying instruction. Other than that, RICC type architecture can be used and will increase the efficiency of the microcontroller.
Again, the microcontroller needs to use as little power as possible. When there is a situation where there has been very little energy collected be the solar or wind power sources the majority of the power will go to the batteries. The lower the amount of power the microcontroller uses shorter the amount of time the system will have to take to charge.

The MSP430 by Texas Instruments is a processor that falls into all of the criteria above. It has RISC architecture, is low power, and has a moderate processing speed. The MSP430 also has a development board called Launchpad that will quickly allow testing and debugging of circuitry or code. The microcontroller can then be taken from the Launchpad and place into a designed PCB board. The MSP430 is also very cheap giving room for the budget in other areas of the project. The MSP430 is priced at $0.25. The development board Launchpad and two MSP430s are $4.30, however only one development board needs to be bought. The MSP430 meets all of the criteria that the main controller demands.

4.2.5 PCB Board

The microcontroller and the buck boost converter are placed on to a single board. The board was designed with EagleCad software and purchased through 4pcb.com. The entire board costs $500.00 with 4pcb.com's student special.

4.2.6 Non-Inverting Buck-Boost

In the design of this project a Buck Boost DC to DC converter is used. Figure 51 below better illustrates the circuitry of this converter. Main reason for this topology, is because a Buck-Boost DC to DC converter allows the user to control the input and desired output voltage. So for example if the input voltage is higher than the desired battery terminal voltage in this case also called output voltage, Buck-mode is implemented to lower the voltage. If the input voltage is lower than the desired battery terminal voltage, then Boost-mode is implemented. This is possible due to high speed switching transistors and active elements in the circuit. The semiconductor device used for switching in this circuit is the MOSFET (N-channel metal oxide). A more specific descriptions of the model used is below in Table 18 and a description of the thermal resistance to help select the heat sink is listed on Table 19.

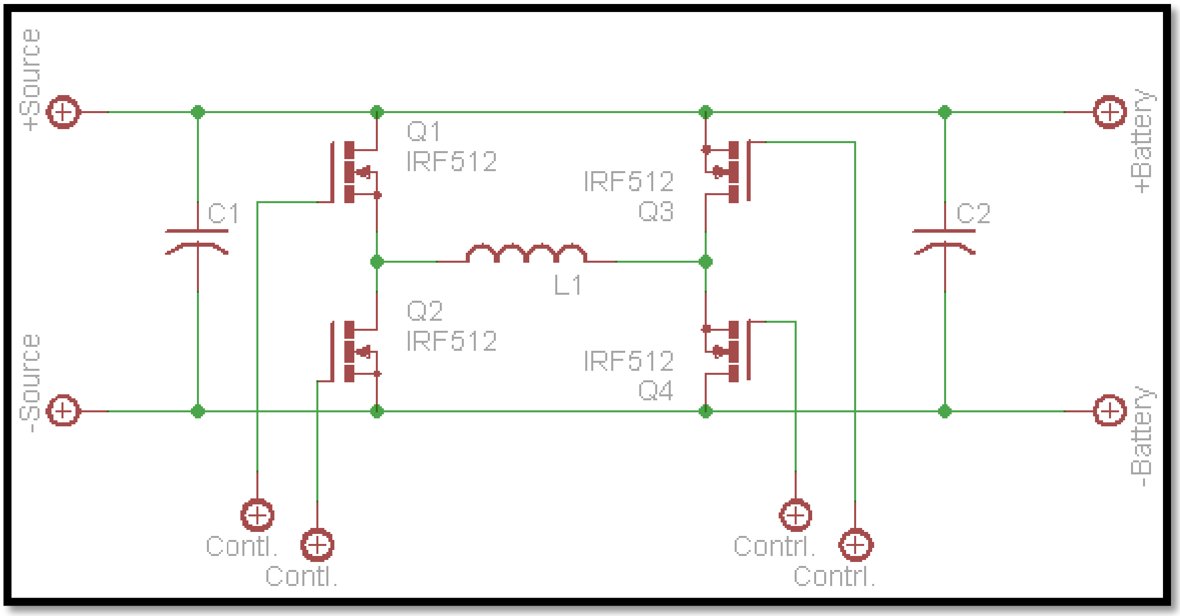

Figure 51 Buck-Boost DC to DC Converter.

Table 18 Absolute Maximum Ratings.[49]

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V (Silicon Limited)	110	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	78	
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V (Package Limited)	75	
I_{DM}	Pulsed Drain Current ①	440	
P_D @T_C = 25°C	Power Dissipation	170	W
	Linear Derating Factor	1.1	W/°C
V_{GS}	Gate-to-Source Voltage	± 20	V
E_{AS} (Thermally limited)	Single Pulse Avalanche Energy②	180	mJ
E_{AS} (Tested)	Single Pulse Avalanche Energy Tested Value ⑥	250	
I_{AR}	Avalanche Current ①	See Fig.12a, 12b, 15, 16	A
E_{AR}	Repetitive Avalanche Energy ⑤		mJ
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 175	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting Torque, 6-32 or M3 screw ⑦	10 lbf•in (1.1N•m)	

Table 19 Thermal Resistance. [49]

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	0.90	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat Greased Surface ⑦	0.50	—	
$R_{\theta JA}$	Junction-to-Ambient ⑦	—	62	
$R_{\theta JA}$	Junction-to-Ambient (PCB Mount) ⑧	—	40	

4.2.10 Hardware Schematic

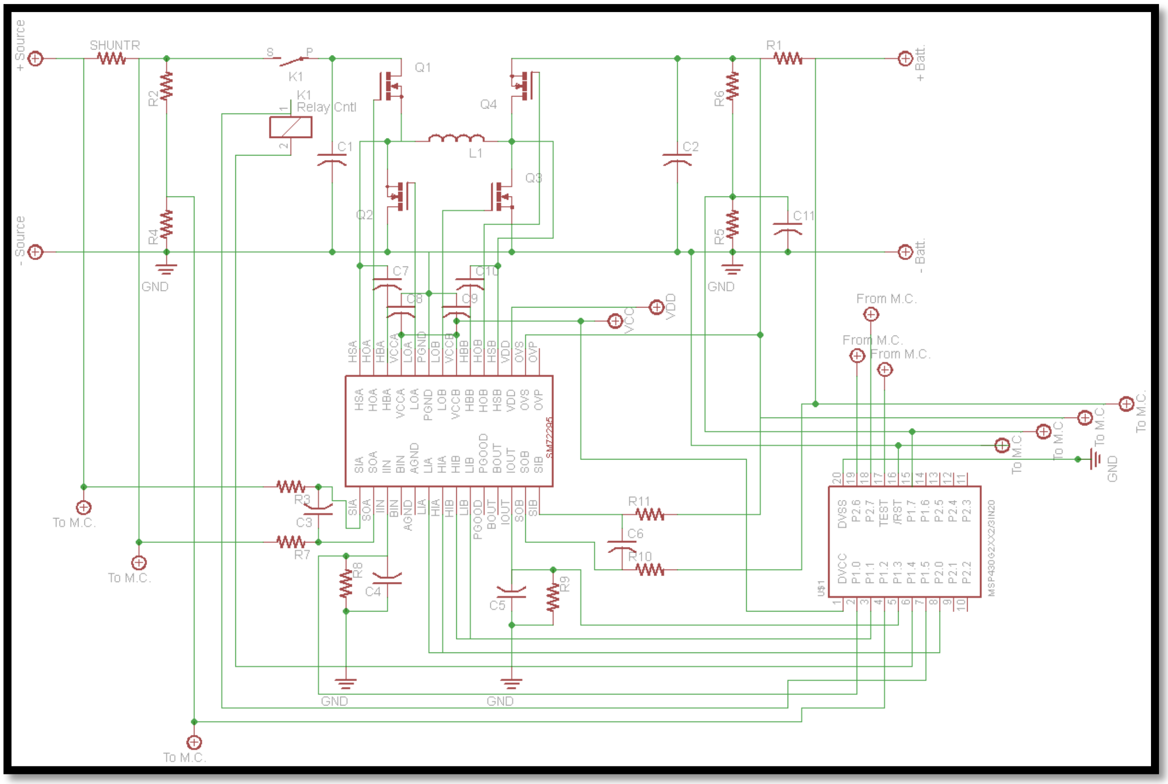

Figure 52 Charge Control Hardware Schematic

4.3 Battery Design

In the project picking the right battery is fundamental, since a lot of factors had to be considered; cost, efficiency, capacity, voltage, safety, durability (number of deep cycles), CCA (cold cranking amps), C-rate, weight and practicality. In the research section the different electrochemistry were described; lead-acid (Pb-acid), lithium-ion (Li-ion), molten salt, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), lithium-polymer (Li-poly) and zinc-air. These were compared and analyzed to pick the right battery.

The nickel-cadmium (NiCd), have a longer deep cycle life, and are more temperature tolerant than the lead-acid batteries. However, this electrochemistry has a memory effect, which degrades the capacity if not used for a long time. In addition, cadmium has recently come under environmental regulatory scrutiny. For these reasons, the NiCd is being replaced by NiMH and Li-ion batteries.

The nickel-metal hydride (NiMH) offers an step up in energy density over that in NiCd, improvement on the environmental concerns of cadmium and its enhancement that it has negligible memory effect. However, is less capable of delivering high peak power, has high self-discharge rate, and is vulnerable to damage due to overcharging. For these reasons this battery does not qualify for our project.

The zinc-air battery has high energy densities and is relatively inexpensive to produce. However good air management is essential for the performance and self-discharge rate is the biggest disadvantage.

The lithium-polymer (Li-poly) is basically very unsafe and dangerous for the project; it contains metallic lithium which is highly flammable thus presents a major concern when implementing this technology in the design.

Molten salt batteries great advantages are its high conductivity which leads to very high energy density and the very long storage life without maintenance of the thermal batteries. It makes them preferably appropriate to providing electrical power storage for power systems. Nevertheless their high cost and high temperature requirement is their main disadvantage; they need to be set to high temperatures for these batteries to function; which is problematic for the design and the resources available.

Lithium-Ion batteries our best second choice, has highest energy density thus highest voltage per cell, fastest charging time and very low toxicity level. However its low tolerance to overcharge, demanding charging circuitry design and high cost makes them unpractical and inaccessible for us. Lastly we end up with our most compromising type, lead-acid; is the most favorable and accessible technology. Below a breakdown of some typical characteristics of these types of batteries are shown in Table 20

Table 20 Characteristics of Commonly Used Rechargeable Batteries [50]

Specifications	**Lead Aid**	**NiCd**	**NiMH**	**Li-ion**		
				Cobalt	**Manganese**	**Phosphate**
Specific energy density (Wh/Kg)	30-50	45-80	60-120	150-190	100-135	90-120
Internal resistance (mΩ)	<100 12V pack	100-200 6V pack	200-300 6V pack	150-300 7.2 V	25-75 per cell	25-50 per cell
Cycle life (80% discharge)	200-300	1000	300-500	500-1000	500-1000	1000-2000
Fast-charge time	8-16h	1h	2-4h	2-4h	<=1h	<=1h
Overcharge tolerance	High	moderate	low	Low. Cannot tolerate trickle charge		
Self-discharge/month	5%	20%	30%	<10%		

(room temp)						
Cell voltage (nominal)	2V	1.2V	1.2V	3.6V	3.8V	3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge by voltage signature		4.2		3.6
Charge cutoff voltage (V/cell, 1C)	1.75	1		2.50-3.00		2.8
Peak load current	5C, .2C	20C, 1C	5C, .5C	>3C,<1C	>30C, <10C	>30C, <10C
Charge temperature	-20 to 50°C (-4 to 122° F)	0 to 45°C (32 to 113° F)		0 to 45°C (32 to 113° F)		
Discharge temperature	-20 to 50°C (-4 to 122° F)	-20 to 65°C (-4 to 140°F)		-20 to 65°C (-4 to 140°F)		
Maintenance requirement	3-6 months	30-60 days	60-90 days	Not required		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	very high	very high	low	low		

The figures are based on average ratings of commercial batteries at time of publication; experimental batteries with above-average ratings are excluded.
There are many concerns that can arrive when choosing the right battery, therefore a breakdown comparing the different types of electrochemistry is provided in the following order:

- Lead acid:
    - Batteries come fully charged. Apply topping charge
    - It should not be store partially charged. Always keep fully charged because it can cause sulfation on the battery
    - It is not recommended to use all the battery energy before charging it because it wears the battery down
    - There is no need to worry about the memory, due that there is not memory in the battery
    - It can deliver and charge simultaneously
    - Depending on charger, when the correct voltage is on float it may be removed.

  - For storage purposes must keep cells above 2.10V, charge every 6 months
  - When cold, it must perform a slow charge (0.1): 0–45°C (32–113°F) and fast charge (0.5–1C): 5–45°C (41–113°F)
  - According to chargers should float at 2.25-2.30 V/cell when ready

- Nickel-based (NiCd and NiMH)
  - New batteries should be charge 14-16h priming to used
  - Battery is robust and the performance will improve with use
  - Partial charging will not damage the battery, but interruptions in the cycle can cause heat build up
  - When using all the battery energy should apply schedule discharges only to prevent memory
  - This battery has energy memory, therefore discharge NiCd every 1–3 months
  - In order to calibrate apply discharge & charge when the fuel gauge gets inaccurate, and repeat every 1–3 months
  - If the load device is on it is best to turn the device off; parasitic load can alter full charge detection and overcharge battery or cause mini-cycles on it
  - When cold, it perform same as lead acid batteries
  - It will not fully charge when hot, and when connected to device it should not get hot because it includes temperature sensor

- Lithium-ion
  - New batteries should apply a topping before use.
  - Always keep some charge because low charge can turn off protection circuit
  - For this battery, a partial charge is better than a full charge
  - Deep discharge cause the battery to wear down over time
  - In order to calibrate apply discharge & charge when the fuel gauge gets inaccurate, and repeat every 1–3 months
  - If the load device is on it is best to turn the device off; parasitic load can alter full charge detection and overcharge battery or cause mini-cycles on it
  - There is no need to remove it when fully charge because the charger turns off
  - When high temperatures Battery may get lukewarm towards the end of charge
  - For storage, it should place in a cold place partially charged and not fully drain.
  - Do not charge below freezing point, or above 122°F
  - And lithium batteries must stay cool, and no trickle charge when ready.

4.3.1 Batteries Safety

Figure 53 Safety Label of battery

There are a few things to know and to consider in order to handle batteries in a safety manner. The first thing to look at is the physical appearance of the battery, identify if the container has any cracks, or signs of fluids on or around the battery. If this were found around the battery, then it could be that the electrolyte is spilling, leaching or leaking out. If any of this signs are present, gloves or any kind of protection should be used since the electrolyte is a solution of acid and water, therefore skin contact should be avoided. As a result, the battery would need to be replaced immediately. Figure 53 above shows the safety label of the battery.

It is also important to keep the connection terminals free of dirt in order to have a flaws connection. The cables used to connect to the battery should not be extremely tight because it could lead to post breakage or meltdown. It is important to be aware of the weather condition the battery is going to be exposed to. It is important to keep the battery above freezing temperature and limit exposure to heat. Temperatures above 80°F degree will accelerate the discharging process of the battery. Finally, it is important that during any process of using the batteries, the terminals should not be shorted, since this will cause a very high current flow from one terminal to the other, therefore draining the battery and could potentially cause an overheat in the shortage object and cause a fire.

4.3.2 Battery Model

The Intimidator AGM Deep Cycle Series provides an ideal solution for heavy marine house power, renewable energy powered equipment, portable power needs, golf cars and other types of electric vehicles. Completely spill-proof and maintenance-free AGM technology eliminates watering and unnecessary maintenance. Intimidator Deep Cycle batteries spend less time on the charger and more time in service by actually recharging faster than conventional batteries. A high deep discharge abuse tolerance provides added resiliency for dependable deep cycle service.

Intimidator AGM deep cycle series has extra protection against deep discharging. Ultra-deep discharging is what causes life-shortening plate shedding and accelerated positive grid corrosion, which can destroy a battery. Intimidator deep cycle batteries are designed to use the optimized amount of acid (no more, no less). This means that the power in the acid is used before the power in the plates. This design, along with the enhanced durability in the glass mat and plate construction, protects the internal components from ultra-deep discharges. Figure 54 below shows the average of lead-acid AGM deep cycle batteries, discharge % over Cycles.

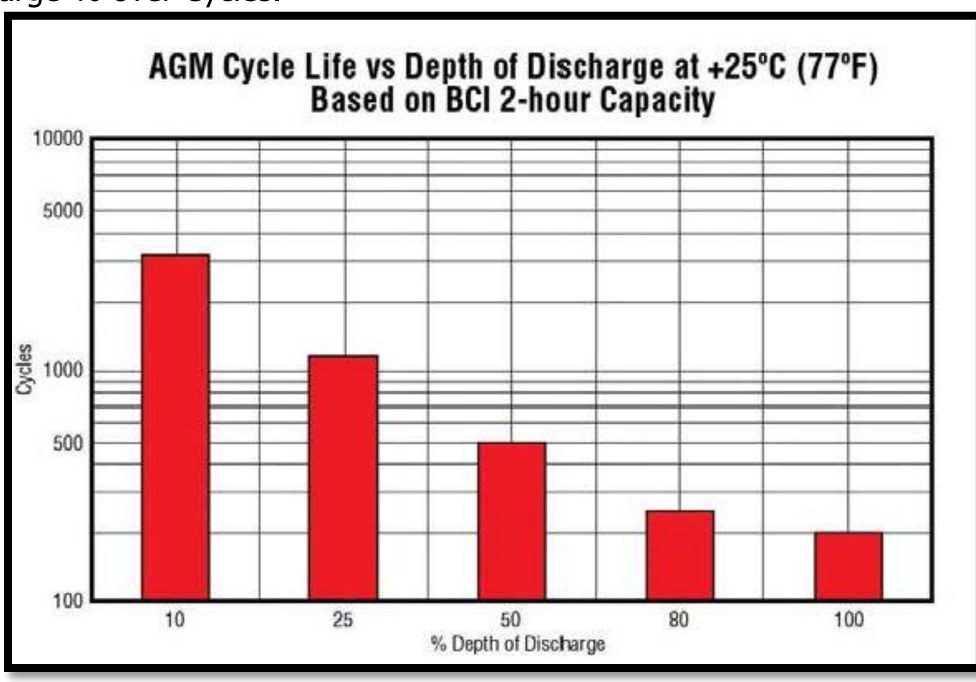

Figure 54 Average Of Lead-Acid AGM Deep Cycle Batteries, Discharge % over Cycles.

In this project deep cycle AGM Batteries were used. This enhanced electrolyte suspension system absorbs more electrolyte, protects internal components and enhanced micro-porous glass separators prevents acid spills and terminal corrosion. In addition it has lower internal resistance which ensures higher discharge rates, also extra deep discharge protection that withstands damaging ultra-deep cycle service two times the cycle life of traditional batteries. This battery also extends performance and life of the battery; it allows 20 times more vibration protection and resists vibration and electrical loading damage. The design is also Spill-proof that enables flexible installation (upside-down not recommended). Most importantly this battery model requires less charging time for more optimized battery use.

In the project two 12 Volts battery were used, meaning the charging algorithms will increment by a product of two, since instead of having a 6 cell battery, the system will have an equivalent of 12 cell since two 6 cell batteries were connected in series. Table 21 below illustrates the different models with its characteristics and also show the selected battery model for this system. For testing purposes two used 12V Lead Acid batteries were used, but for South Africa six Intimidator 31M were purchased. Model is described below

Table 21 Deep Cycle Intimidator AGM Batteries Models. [51]

Group No	**Part No**	**Performance Level**				**Approx. Weight (lbs.)**	**Maximum Overall Dimensions**		
		CCA @ 0°C	***RES CAP***	***REF. MCA***	***20AH RATE***		***Length***	***Width***	***Height***
U1	8AU1	200	48	240	32	24	197	130	184
U1	8AU1H	200	48	240	32	24	211	130	184
22NF	8A22NF	350	82	420	55	38.5	238	140	235
24M	8A24M	525	135	800	79	53	276	171	251
24	8A24M	525	135	800	79	53	276	171	251
24	8A24NH	525	135	800	79	53	260	171	251
27M	8A27M	580	175	900	92	63	324	171	251
27	8A27M	580	175	900	92	63	324	171	251
31M	8A31DTM	800	200	1000	105	69	329	171	238
4D	8A4D	1110	380	1420	198	129	527	216	254
8D	8A8D	1450	480	1800	245	158	527	279	254

Battery model number (31M) $276.46

4.3.2.1 Receiving Inspection

Upon receipt, and at the time of actual unloading, each package was visually inspected for any possible damage or electrolyte leakage. If either is evident, a more detailed inspection of the entire shipment should be conducted and noted on the bill of lading. Record receipt date, inspection data and notify carrier of any damage.

4.3.2.2 Unpacking

1. Always wear eye protection.
2. Check all batteries for visible defects such as cracked containers, loose terminal posts, or other unrepeatable problems. Batteries with these defects must be replaced.
3. Check the contents of the package against the packaging list. Report any missing parts or shipping damage to your East Penn agent or East Penn Mfg. Co. immediately.
4. Never lift batteries by the terminal posts.
5. Always lift batteries by the bottom or use the lifting handles.

4.3.2.3 Storage

1. Batteries should be stored indoors in a clean, level, dry and cool location. Recommended storage temperature is 0°F to 90°F (– 18°C to 32°C).
2. Stored lead-acid batteries self discharge and must be given a charge six months from date of manufacture to prevent permanent performance degradation. Record dates and conditions for all charges during storage.
3. Recommended charge during storage is at a constant voltage of 13.80V (6.90V for 6V battery) for 24 hours at 77°F (25°C).
4. Do not store beyond 12 months.

4.4 Inverter

After doing the research on inverters we purchased an inverter rather than build one because of the complexities involved with building an inverter. This is a good option for us because we already have the MPPT charge controller and main controller to design and build meeting our requirements for the class. Our budget also allows us to do this because of Progress Energy's contribution to our project.

The main advantage with buying an inverter is the fact that no matter how much research and design we do it would be very difficult to build our own with the same quality as a reputable manufacture could do. The quality of a manufacture is not only a quality power output with low harmonics but also the robustness. The fact that our project needs to be able to be almost maintenance free and last years into the future is important to our project. Manufactures take into account lots of factors that help protect their inverters. They take into account low output voltage or an overload situation saving the device that electrically comes before the inverter as well; surge protection that will protect the townships electronic devices; a low battery alarm that will give our system two independent sources checking the batteries.

We also have many inverter choices if we buy rather than design and build giving us almost as much freedom for specific feature that we might want. In Table 22 and Table 23 are the possible choices of inverters that meet our main specifications defined at the beginning of our paper on section 2.4. The only decision points for which inverter would be the best option is mainly the price then if surge protection and efficiency. It is important when talking about the efficiency to note both peak efficiency and full load efficiency when every Watt counts. The AIMS 2.5KW Inverter was purchased.

Table 22 Inverter Specs

Inverter	**Continuous Power (in Watts)**	**Surge Power (in Watts)**	**Input Voltage**	**Dimensions (inches)**
Cobra	2500	5000	10.4VDC – 14.4VDC	11 x 9.6 x 3.3
Samlex	2750	4000	20VDC - 33VDC	12.2 x 8.74 x 3.46
AIMS	2500	5000	20VDC - 30VDC	15.5 x 9.3 x 3.6
Xantrex	2500	3000	10.5VDC–15.5 VDC	18.5 x 9.5 x 4.5
Wagan	2000	4000	10.5VDC–15.5 VDC	17.0 x 9.5 x 3.8

Table 23 Inverter Specs

Inverter	**Peak Efficiency**	**Full Load Efficiency**	**Warranty**	**Price (estimate from manufacturer or Amazon)**
Cobra	88%	83%	2 years	$319.95

Samlex	90%	N/A	2 years	$780.02
AIMS	95%	90%	1 year	$279.00
Xantrex	90%	N/A	.5 years	$359.31
Wagan	90%	N/A	2 years	$759.2

After looking at the table AIMS 2500 watt power inverter model number PWRINV2.5K24 was the best option. With the lowest price and one of the highest continuous power rating and the best efficiency in both peak and full load efficiency this is our choice of inverter. For the budget this fit perfectly allowing us more money for the other components. Another major benefit is that it had a remote on/off switch allowing us to have a single interface for the end user.

The final conclusion is that we bought the inverter rather than designed one. This gave us more time on the MPPT charge controller and main controller. We had a more reliable and stable inverter that we can count on, even if conditions were not perfect. This did not affect our overall look of the system because of the on/off remote control and the end user will not have to open the embodiment of our design to work with the inverter. Also with the remote control our main controller is able to control the inverter and completely free the end user from any interaction with the inverter. Also for our final conclusion the AIMS 2500 watt power inverter model number PWRINV2.5K24 was our choice in inverters.

4.5 Enclosure

The enclosure housed all other components protecting them from the environment and protecting inexperienced persons from tampering with the equipment or hurting themselves. The enclosure protects the equipment inside from excess dust, water, and people, but it also adds thermal complications. The enclosure needed to be well ventilated and cooled by fans to prevent any overheating. The enclosure also provides a safer way of shipping the project to South Africa.

The enclosure was made of wood providing structural support and Plexiglas sheets to enclose it. The batteries were housed in a separate compartment with its own ventilation. Even though the batteries are sealed they are still capable of leaking fumes and spilling. By separating the batteries from the rest of the enclosure, the other components are safer. The batteries also have their own ventilation system for the same reasons.

The front panel of the enclosure was cut to fit the LCD screen, input and output plugs including the USB ports, and fans.
All electrical components were electrically isolated from the enclosure. This is to help prevent any problems with static electricity and accidental electrocution from a person touching the enclosure.
The below figures are a representation of the enclosure. The enclosure needed to be designed once all other components were built to get a clear reference to how big the enclosure needed to be. The enclosure was designed to hold at least 6 batteries in the bottom compartment.

Figure 55 Front side of the enclosure

Figure 56 Back cutaway of the enclosure

4.6 Input and Output Connectors

As the world's environmental issues become more of a concern. The implementation of off grid renewable energy systems are quickly becoming a solution. There are multiple concerns when designing or purchasing a complete system; the demanded output, the efficiency of the charging method and the source. However, we must also take into account the small pieces that interconnect all the components on our system. The wires and connectors are essential aspects of our design. Regarding the input and output sources we will include precise dimensions that will satisfy the desire specifications. Below are some of the specifications the system design will be based on:

- Input connectors rated for 1000 Watts or more
- Wiring that can handle large amounts of current
- Output connectors for various standards to add functionality
- Robust and safe input/output connector
- Rust and tarnish protection
- All connectors need to be grounded

4.6.1 Input Connectors

The input connectors are the ones that received the initial source, in this case the power from the PV panels or the wind turbine. Then, they are connected to the charge controller, which controls the amount and the rate the current flows to charge the batteries. There are several connections that go from the charge controller to the inverter and battery bank, and then for final destination to the outlets or dummy load; all this connections are taking into account as input connectors because they contained within the system and are important for the life span and longevity of each component and the entire system as well.

This section will explain why is it important to use the right connectors and pieces to link all the components for a complete and successful flow of power within the system. In Figure 57, it shows the flow diagram on how a proper connection should be performed when putting together the entire system. The following are the input connectors that will be explicit in the below sections:

- PV panel DC
- Charge Controller (Input)

Under the diagram, the connector's specification and prices will be listed, and on of them will be chosen for the design making sure it follows all the details on the current and voltage flow through the system; reliability and price will be analyzed as well. The following

Table 24 shows the list of connectors purchased:

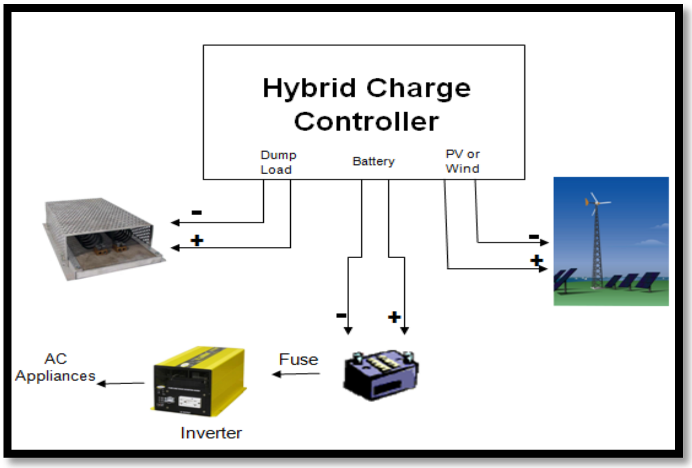

Figure 57 PV Charge Controller Connection [56]

Table 24 Connectors

Type Connector	Maximum Current	Specifications	Price
HQRP® Pair MC4 Connector	25 amp	Male & female; 2.5mm2 4mm2 6mm2	$9.99
HQRP® Pair MC4 T-branch	25 amp	1F2M & 2F1M; 2.5mm2 4mm2 6mm2	$14.95

The MC4 was the best way to go for the type of connectors that will be installed from the PV panel to the charge controller. It has a maximum amperage rate for 25 amps, and it fits according the design of 1k watt system.

4.6.2 Output Connectors

Output connectors are elements employ in our system that will be managed by the user directly. As mentioned in the objective, the purpose of this project is to provide a reliable source of power to an underprivileged community in South Africa. Due to that the electricity guidelines differ depending on the country, we will compare different standards and the reason we will choose the specific one for implementation. The design has the most common used standard for voltage and frequency, the American and European, 110-120volts 60Hz, and 220-240volts 50Hz respectively.

Since the inverter has American standard voltage and frequency as an output, the design has only one AC to AC converter for the European outlet. As it was mention before, our main goal was to have a reliable and robust design for our client. Reliable meaning that can be adapted for different devices that want to be used by the community center.

4.6.2.1 European Standard Connectors

The European version of electricity is generally supplied at 220 volts and a frequency of 50 Hz. In reality the range is at 230 volts plus or minus 10%. Any device rated between 200 volts and 250 volts works fine.
The electrical sockets used in the Republic of South Africa follow similar to same specifications as the European standards which are 15 amps BS-546 sockets shown in Figure 58. An adapter is needed for appliances on power ranges different than the area.

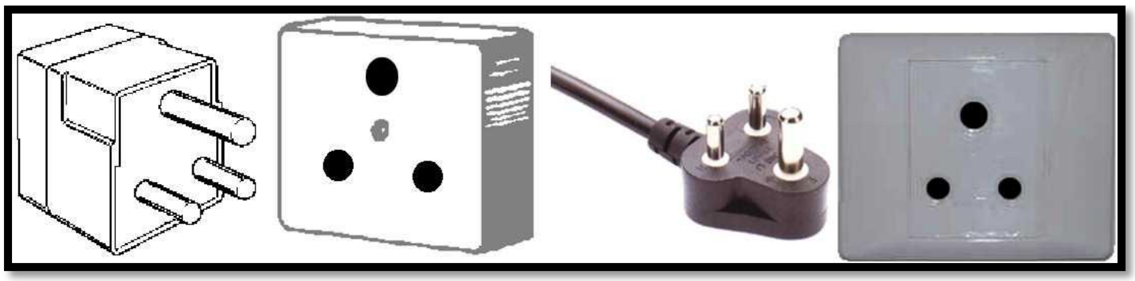

Figure 58 type "M" South African socket

Due that the purpose of this project is to install a standalone system in the community center in South Africa, it includes both types of outlet sockets. The European appliances are similar to the South African as well which are specify above in the introduction. The African sockets will be purchase once the system gets to South Africa, which helps reduce costs of shipping and handling.

4.6.2.2 American Standard Connectors

In the United States household electricity is normally supplied by the local power company or utility which is at 110 or 120 volts at a frequency of 60 Hz. Any device rated between 100 volts and 130 volts works fine when plugged into the outlet. The quantity available in American homes is generally 15 to 20 amps at a single outlet or for the total of all outlets served by a single fused circuit. Thus, one circuit may provide from 1650 to 2400 watts of power. Many homes have multiple outlets for a single circuit, having the ability to plug in several appliances and lights that can cause blown fuses. However; instead of fuses, in the last decades the majority of homes have circuit breakers as electricity circuit.

According to the National Electrical Manufacturing Association (NEMA) there are multiple socket designs used in North America which differ upon the output current from the inverter. The most typically used connector for single phase equipment is the 120 volt and 208 volt shown in Figure 59

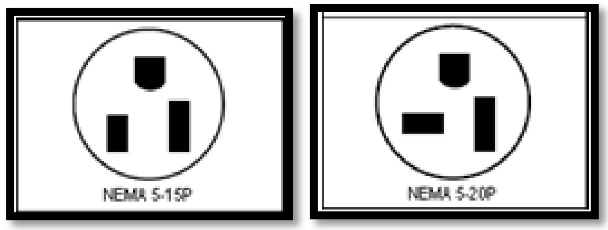

Figure 59 NEMA 120 volt 15 amp & 20 amp

The design includes two different outputs sockets, European and American standard. This is implemented because there are appliances from different countries and it is necessary to take this into consideration. The US American socket was found at a local tools store for about $2 dollars

4.6.2.3 USB Connectors

One of our output connectors in our design is a Universal Serial Bus (USB) the most common type of computer port used in today's computers. Our project will include the USB port as a charging method. The purpose of having a USB port on the same outlet socket is to have an extra advantage to charge a cell phone or a small electronic device that have a USB port. Out system is using a USB 2.0, being the most common in the market. One important fact about the charging method of USBs is that it exists one host and one device. In our design the outlet socket is the host, and the cell phone or camera is the device. Power always flows from the host to the device. Data is also transmitted through the USB, however, in our design we will not have the USB as a data bus, and we will use it as a choice of charger.

Continuing researching the specifications, it is known that a USB socket has four pins and the cable has four wires. The inside pins carry data, and the outside pins provide a 5 volt power supply shown in Figure 60.There are three kinds of current specs on USB ports: a standard downstream port, a charging downstream port, and a dedicated charging port. In our design the charging downstream and dedicated charging ports provide up to 1.5A

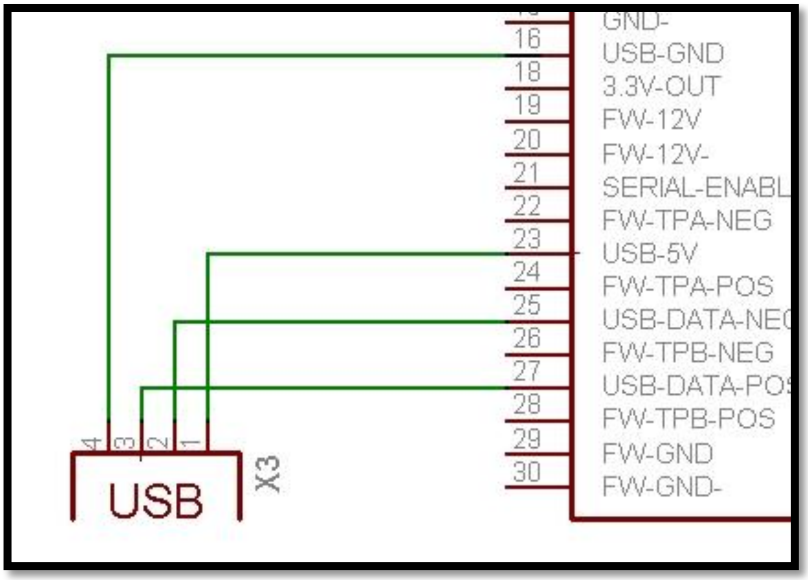

Figure 60 USB Socket and Cable Design

As a result, the implementation of USB ports as part of the outlet sockets it is to provide another method of charging for multiple functions. We will include 4 USB ports, each with a standard 5 volt and up to 2A max, which will result with up to a 7-10 Watt outer power. The USB were purchase and attached to the sockets, and it cost $3 dollars.

4.7 AC to AC Converter

After researching on all the different topologies on the AC to AC converters, it helped to understand how to design the converter the right way and choosing the right components to build it. It had been decided different type of adapters that was going to be purchased rather than built one because of the complexities involved with building an actual ac to ac converter that an adapter can do the same function. This is a better option because the project includes a design of the MPPT charge controller and main controller, which have a great part of designing and building itself following all the requirements for the class.

The main idea of the design output is to include the two main common voltages and current output for our output load. After the power has passed through the inverter, an adapter circuit was placed on one part of the inverter, thus the power can be used at two different operating outputs:

- 110 Volt/60Hz
- 220 Volt/50Hz

Nowadays, many devices or products are not affected by the cycle change or frequency because they contained an internal converter from AC to DC Voltage.

Products such as analog devices can interfere with the frequency and might not operate properly. Therefore, many people use a voltage transformer to step down or up the voltage on the outlet, depending on the requirement of the device. Due that the change in frequency will not affect the devices; it will only not let it work at a proper way. However; the voltage is the variable that can affect or damage a product or apparatus, and the main concern when designing a converter. Therefore, it has been chosen that the project design implements a voltage converter or a transformer that can convert the voltage from North American standard to European standard, due that the inverter implemented provides North American standard, 110 volt/60 Hz.

The reason we focused on the voltage transformers that are over 1000W of power it is because the inverter supplies approximately 2000 Watt power out for the consumer. Even though the user will not use as much power as the specification of the transformer, in the design it provides a power that exceeds the maximum amount.
After researching multiple vendors online for voltage converters and step up/step down transformer, it narrowed down to the following shown in Table 25, which shows the name of the transformer, dimensions, features and price of the main brands.

Table 25 1000 Watt Dual Step Voltage Transformer Converter

Voltage Transformer	**Dimensions**	**Outlet**	**Price**
Simran AC-1000	7.25"x7.75"x6"	1-American 110V 2-European 220	$62.99
VT 1000	12" X 9" X 7"	2-American 110V 2-European 220	$65.99
Goldsource STU-1000	10” x 9” x 7”	1-USB 1-US 110V 1-European 220V	$52.85
Sevenstar THG-1000	7”x 8”x 6.5”	3 or 2 prong US and Europe plug	$29.08
Power Bright VC1000W	8.2 x 7.2 x 5.9	1-US 110V 1-European	$50.70

After looking at the table, the SevenStar THG-1000 Watt transformer with model B003XM374I was the best option for the design. Having the lowest price, and approximately the same dimensions and weight compared to the others, this transformer was suitable to our design specifications. According to the budget this fitted perfectly, due that it became a low cost, robust and reliable stand alone system. Lastly, some advantages of these transformers are that are high power voltage converter, can step up or down depending on the consumer desire, and are heavy duty.

4.8 PV Panel

Even though there are many options for solar panel technologies that could be used for this project, the best option was the polycrystalline solar panel technology. Polycrystalline solar panels achieve almost the same efficiency level as their monocrystalline counterparts and are much cheaper. Thin film solar panel technologies such as Amorphous Silicon, Cadmium Telluride, and Copper Indium Gallium Selenide (CIS/CIGS) were not considered appropriate for this project because of their low efficiency level compared to silicon based photovoltaic panels. The company that builds the solar panel that was chosen is SunWize Tecnologies which is considered one of the pioneers and premier provider of solar electric solutions. The solar panel that was chosen for this project is the SunWize SW-S65P Solar Module. The cost of this specific solar panel is about 250$. [57]

The following Table 26 shows the electrical and mechanical specifications of the SunWize SW-S65P solar panel.

Table 26 Manufacturer's Specifications for SW-S65P

Model	**SW-S65P**
Power (Watts)	65
Voltage (Vmp)	17.4V
Current (Imp)	3.7A
Voc	22.0V
Isc	4.1A
Dimension (Inches)	31.10x26.06
Weight (lbs)	14.1

The SW-65P solar module can be used in single-module and multiple-module installations. For this specific project, this solar panel is used as a single-module for testing purposes. A key factor that made this solar panel the best option for this design is that SunWize offers a 2-Year limited warranty of materials and workmanship, and 10-Years limited warranty of 90% minimum power output.

The following Table 27 shows the Thermal Parameters of the SunWize SW-S65P solar module that was used:

Table 27 Thermal Parameters for the SunWize SW-S65P [57]

Thermal Parameters	Values
Max System Voltage	600Vdc
Series Fuse Rating	8 Amps
Voltage Temperature Coefficient (Voc)	-0.35%/C
Current Temperature Coefficient (Isc)	0.065%/C
Power Temperature Coefficient (Pmax)	-0.5%/C
Peak Power Tolerance	+/- 5%

4.9 LCD

For the purpose of this project it was found that the best option that could be used for the display was a character LCD screen. One of the key advantages of a character display is its low power consumption when compared to other display technologies. In fact, a character display consume less than 100mA of current. Also, since LCD character displays are specifically designed for basic text, they are less complex, less expensive and easier to use. Graphic displays on the other hand, are best for projecting images and therefore more complicated, costly and difficult to install because of all the pins. Graphic displays require more programming complexity which for the purpose of this project is not justified to use because of the low requirements needed for the information that will be displayed. Moreover, the power consumption of graphical LCD screens is much higher than the power consumption of a typical character LCD. Another benefit of using a LCD character display is that it is lightweight, and inexpensive.

Eventually it was determined that based on the requirements of this project, the best option was to use the serial enabled LCD-09395. This LCD is manufactured by spark fun electronics. The LCD-09395 is a 16x2 character LCD which will be implemented into the charge controller. In this system, the on-board PIC microcontroller takes a TTL serial input and prints the characters it receives onto the LCD. The PCB measures 103x36mm while the actual LCD screen is 71.4x26.4mm. This display is monochrome (White on Black) and has a processing speed of 10 MHz. The backlight brightness is adjustable giving the option to dim the backlight in situations where power consumption is a concern. This display also has a potentiometer on the back which is advantageous to adjust the contrast of the display. The cost of the LCD-09395 is 25$. [58]

The serial enabled 16x2 LCD screen (LCD-09395) shown in Figure 61 communicates with the microcontroller MSP430 manufactured by Texas Instruments. In order to complete this communication successful, the use of a voltage leveler was a must. Therefore the TCA9406 voltage lever was used to level the voltage from 3.3 to 5V. Using I2C communication protocol help The main advantage of a serial LCD is that it is easier to wire up, since the microcontroller communicates to the LCD over a single pair of wires.

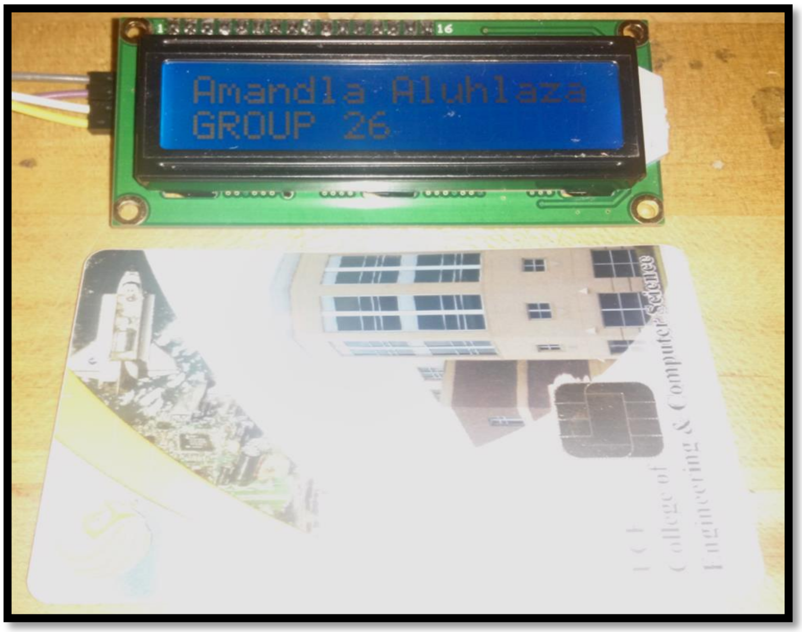

Figure 61 Serial Enabled White on Black LCD (LCD-09395)

The LCD-09395 is powered by 5V DC line from the circuit board. Due that our since a voltage higher than 5.5V will cause damage to the PIC, LCD, and backlight. This specific display uses 3mA of current with the backlight turned off and about 60mA when the backlight is activated. Therefore, the maximum power consumption of this character LCD is estimated to be 15 watts.

4.10 Design Summary

Finally the design has been modified many times with the purpose of making it more practical and applicable to the people in the community of South Africa. Shipping cost and transportation fees had limited the selection of some of the components being used, one great example were batteries. More importantly the system had to adapt to the available resources in Johannesburg so if the system fails, the technicians in South Africa have available resources to replace the damaged parts.

In conclusion the design had to be robust and automated since none of the members of the group are going to be available for maintenance. A brief description of Amandla Aluhlaza's design finalization is provided. The design consisted of a main controller which will control and monitor the energy coming from the renewable sources going to the charge controller; which function is to provide best charging rate conditions going to the battery bank. Sensors were integrated into the circuit to maximize efficiency and provide safety. Next an inverter was introduced to convert DC power into AC power, with the idea of giving users common forms of output power. It is important to know that this sophisticated and engineered system was controlled by a main controller with many more applications and many more components, which in other words was the brain of this whole project. To conclude it is important that users fully read and understand this report so the designed system works at best possible conditions and performs as expected in South Africa.

5. Testing

5.1.1 Photovoltaic Panel Testing

One important part of this project was to create a suitable testing procedure for the photovoltaic panel that will be used. The complete procedure will provide a thorough analysis of the power flow and overall efficiently of the photovoltaic panel. The solar panel used which is the SunWize SW-S65P consists of 36 solar cells connected in series and it is rated for a power output of approximately 65watts. The following tables show the differences testing procedures and steps that will be used in order to test the solar panel:

Table 28 Starting Testing Procedures

Step	Procedure
1	Find Voltage and Current ratings for the Solar Panel
2	Check that sunlight conditions are suitable
3	Place the solar panel in the open sun
4	Place the PV panel with the best orientation (best angle-of-incidence)
5	Observe polarities when connecting the solar panel and battery
6	Insert a power resistor to simulate load
7	Verify the system wiring is correct
8	Check all the connections and terminals for good electrical contact

Table 29 Test Open Circuit Voltage (Voc)

Step	Procedure
1	Disconnect the solar panel completely from the battery and regulator
2	Place the solar panel in the open sun
3	Place the PV panel with the proper orientation (best angle of incidence)
4	Using a multimeter, measure the voltage between the terminals of the solar panel

Table 30 Test Short Circuit Current (Isc)

Step	Procedure
1	Disconnect the solar panel from battery and regulator
2	Place the solar panel in the open sun
3	Place the PV panel with the proper orientation (best angle of incidence)
2	Ensure Multimeter is set to measure current
3	Using the multimeter, measure current between the terminals of the solar panel

Table 31 Test Operating Current (Il)

Step	Procedure
1	Connect the panel to the regulator and battery
2	Disconnect the positive cable between the battery and the regulator
3	Measure operating current by connecting the positive lead from the multimeter to the positive cable from the regulator, and the negative lead from the meter to the positive battery terminal
4	Make sure battery is not full, which would result in a low reading

It is worth mentioning that testing a solar panel requires an assortment of power resistors capable of handling the power. In most cases, ordinary resistors are not suitable for this type of measurement because small resistors tend to overheat and burn out. Power resistors are made to handle more wattage, although they will become hot over time and can burn out too. In this test, adjustable power resistors will be used because they will be useful to vary the load values. In order to avoid overheating problems when testing, high wattage resistors will be used and individual measurements will be made as quickly as possible. The objective of solar testing is to fully understand and derive the panel output in order to calculate the time it would take to fully charge the system's batteries. Finally, with all the information obtained from the different testing procedures, a plot of current vs. voltage (I-V curve) will be made.

5.1.2 Battery Testing

In order to make sure that this project worked as expected, a series of several testing procedures were performed. Table 32 the procedures that will allowed to make sure that the batteries selected were the most appropriate for this design application and to know whether the batteries meet the manufacturer's specification or not.

Table 32 Battery Test

Casing	Tolerance To	Mechanical Tests	Environmental Tests
Strength, Rigidity	Overcharge (Time)	Impact Test	Heating
Venting	Overcharge (Voltage)	Drop Test	Humidity
Insulation	Over-discharge	Shock Test	Temperature cycling
No Leakage	High Temperature	---	Exposure to Fire
No fire risk	Low Temperature	---	---

Load Testing: In order to verify that the batteries used delivered their specified power it was necessary to perform a load testing. The load will be representative of the expected conditions in which these batteries were used. First, the load testing consisted of a constant load of about 1Kwatt. It is worth mentioning that the battery may appear to have a greater capacity when it is discharged intermittently than it may have when it is discharged continuously. This is because the battery is able to recover during the idle periods between heavy intermittent current drains. Thus testing a battery capacity with a continuous high current drain does not necessarily give results which represent the capacity achievable with the actual usage. The following Table 33 and Table 34 represent the charging and discharging testing procedure:

Table 33 Battery Charging Testing Procedure

Procedure	Expected Results	Actual Results
Connect Battery to the system with no load	Battery should start charging	Completed
Use multimeter to check battery terminal voltage	Multimeter should read a voltage corresponding to the charging state of the battery	Completed
Review the time it takes for the battery to fully charge	It should take the battery to fully charge about XXX hours	Not Completed

Table 34 Battery Discharging Test Procedure

Procedure	Expected Results	Actual Results
Connect Battery to the system with a predetermined load	Battery should start to supply power	Completed
Use multimeter to check battery terminal voltage	Multimeter should read full battery voltage, and should start decreasing	Completed
Record the time it takes the battery to reach float state	It should take the battery t about XXX hours	Not Completed

5.1.3 Sensor Testing

Table 35 Temperature Sensor Functionality

Step #	Procedure	Expected Results	Actual Results Stat.
Temperature Sensor Functionality (TMP75)			
1	The Temperature sensor is connected in the bread board as circuit defined.	Have to check for right connectivity and ground.	Complete
2	Sensor is then connected to the MSP430	A respective value should be output by the sensor	Complete
3	Heat is applied to the thermometer and the temperature sensor	The increase readings on the thermometer should be the same as the temperature sensor	Complete

A testing plan, shown in

Table **35** Table 36 has been utilized to effectively verify that all the analog sensor work the way they are suppose to work. The following table contains the sensor that was tested the procedure and the results of the test.

Table 36 Voltage Sensor Testing Functionality

Step #	Procedure	Expected Results	Actual Results Stat.
Voltage Sensor Specifications			
1	Voltage divider is calculated and connected to breadboard	Have to check for right connectivity and ground.	Complete
2	Turn power supply and connected to voltage divider	Check for readings with multimeter	Complete
3	Vary the voltage input on voltage divider	Check for readings with multimeter	Complete

Table 37 Current Sensor Testing Functionality

Step #	Procedure	Expected Results	Actual Results Stat.
Current Sensor Specifications			
1	Shunt resistor is placed and connected to breadboard	Have to check for right connectivity and ground.	Complete
2	Turn power supply and connected to input terminal	Check for readings with multimeter through MOSFET	Complete
3	Vary the voltage input	Check for readings with multimeter through MOSFET	Complete

5.1.4 Software Testing

Table 38 Software Testing Functionality

Step #	Procedure	Expected Results	Actual Results Stat.
Software Testing: Relays/KillSwitch/Readings			
1	Connect both input sources, wind and solar. Push right-hand switch	Text display on LCD: "PV:ON WIND:OFF PowerOut: #Value"	Complete
2	Connect both input sources, wind and solar. Push right-hand switch twice	Text display on LCD: "PV:OFF WIND:ON PowerOut: #Value"	Complete
3	Connect both input sources, wind and solar. Push left-hand switch	Text display on LCD: "KILLSWITCH ON"	Complete
4	Connect both input sources, wind and solar. Push left-hand switch twice	Text display on LCD: "KILLSWITCH OFF"	Complete
5	Connect both input sources, wind and solar. Push both switch simultaneously	Text display on LCD: "PV:OFF WIND:OFF"	Complete

The software implemented in the design encompasses the switching of input sources, from PV panel connected to Wind turbine connected. Also, the readings of temperature, current and voltage sensors on the circuit board, as charge controller.

Table **38** shows the design has a killswitch to shutdown the system whenever an emergency requires it.

6. Operator Manual

CAUTION: Read Section 4 - Design on final paper before proceeding with the integration of the system.

All connections should be made prior to exposing the PV panel to the sun and before wind turbine is an active source.

Step 1: Pick location of enclosure; make sure it is placed on ventilated area and not exposed to water.

Step 2: Load batteries in bottom compartment.
Figure 62 below better illustrates this step.

Figure 62

Step 3: Wire two 12V batteries in series. Note: Enclosure Maximum capacity (8 Batteries of 14"X10" and 500 Lbs. Total)

Step 4: Wire positive terminal and negative terminal wires to Terminal bus on middle compartment of enclosure. Figure 63 below better illustrates this step.

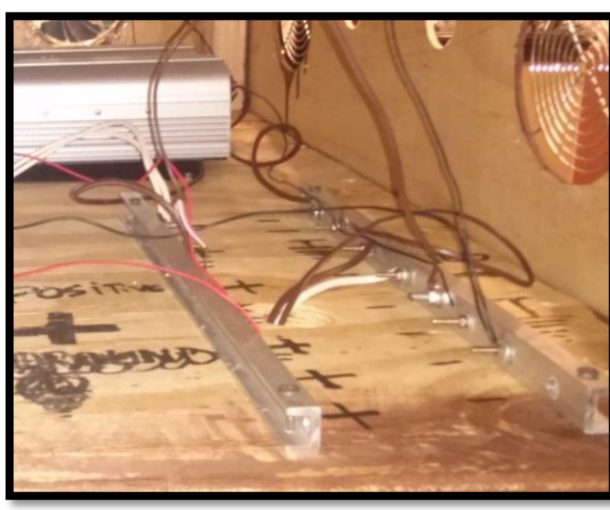

Figure 63

Step 5: Install Dummy loads on back enclosure. Figure 64 below better illustrates this step.

Figure 64

Step 6: Connect the positive and negative terminals of sources to terminal bus.

Step 7: Connect the battery bank terminals to terminal bus.

Step 8: Connect the inverter clamps to the correct terminals on the battery. And screw it in middle compartment for stability.

Step 9: Connect the transformer's input to one of the inverter's output terminals. And screw it in middle compartment for stability.

Step 10: Place main controller PCB board in top compartment. Place screws on screw holes for stability.

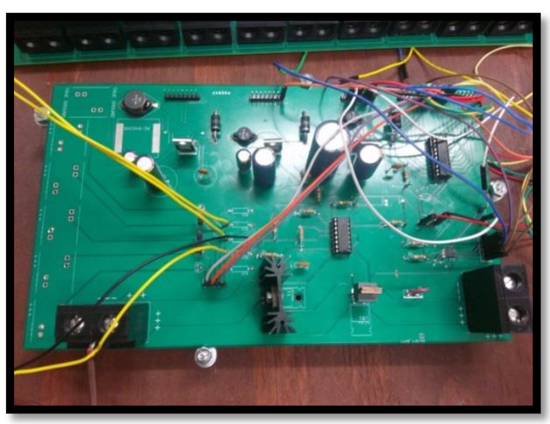

Figure 65

Step 11: Connect output of PCB board to terminal Bus.

Step 12: Connect the LCD cord to the PCB. And screw into front top panel. Figure 66 better illustrates this step.

Figure 66

Step 13: Install fan switch in front top panel of enclosure. Figure 66 above better illustrates this step.

Step 14: Install power switch in front top panel of enclosure. Figure 66 above better illustrates this step.

Step 15: Place and secure fans with screws and nuts in top front and middle front panels of enclosure. Figure 67 above better illustrates this step.

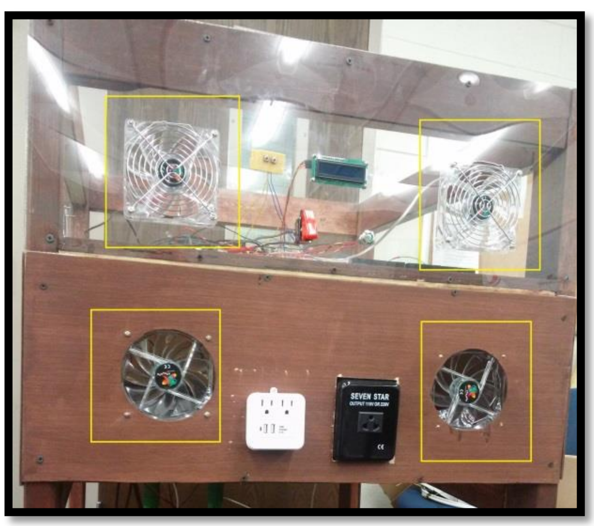

Figure 67

Step 16: Once everything is connected and sources are active turn power switch on and watch LCD for power input, output and battery voltage being displayed.

Note: This project has an automated feature that controls and regulates power from the sources through the main controller distributing the ideal amount to the battery. Everything is controlled and regulated by itself. In case of an emergency use the kill switch in the top front panel and it will shut the system down. Figure 68 above better illustrates this switch.

Figure 68

CAUTION: Do not connect a load higher than the rated output power on the inverter (1.5KW).

7. Conclusion

It is easy to say that this project is a combination of power systems and power electronics. The purpose of selecting this project was not just to put into action all of the knowledge achieved through the four years or more of hard work and dedication to the electrical engineering field, but to come together as a group of electrical engineers to solve an immense problem for an impoverished community located in Johannesburg, South Africa who's answers to the problem seem for them impossible to find due to cost and lack of knowledge in the power system and power electronics field.

Amandla Aluhlaza group's main goal was to come up with a design that would help find a solution to their energy crisis. Amandla Aluhlaza consist of a design that transfers the energy acquired from renewable (Solar and Wind) sources to a storage unit, which the people in Johannesburg will have access to for a couple of hours every day so that they can charge their cell phones and other personal electrical devices. In addition the system is capable of delivering enough energy to power up a computer, a projector screen, and a stereo system that will be used with the main goal of educating and entertaining the people who have never had access to this type of technology.

Overall this sophisticated design which was described and researched in this report was based on organized procedures, data analysis and meticulous calculations that lead to the right and most efficient solutions, by which the group Amandla Aluhlaza worked together to find the most practical and robust design for the specified conditions. In this project the group worked with physical concepts that have been demonstrated in this last phase of senior design2; Research, hypothesis, design, and testing.

Appendix A: Works Cited

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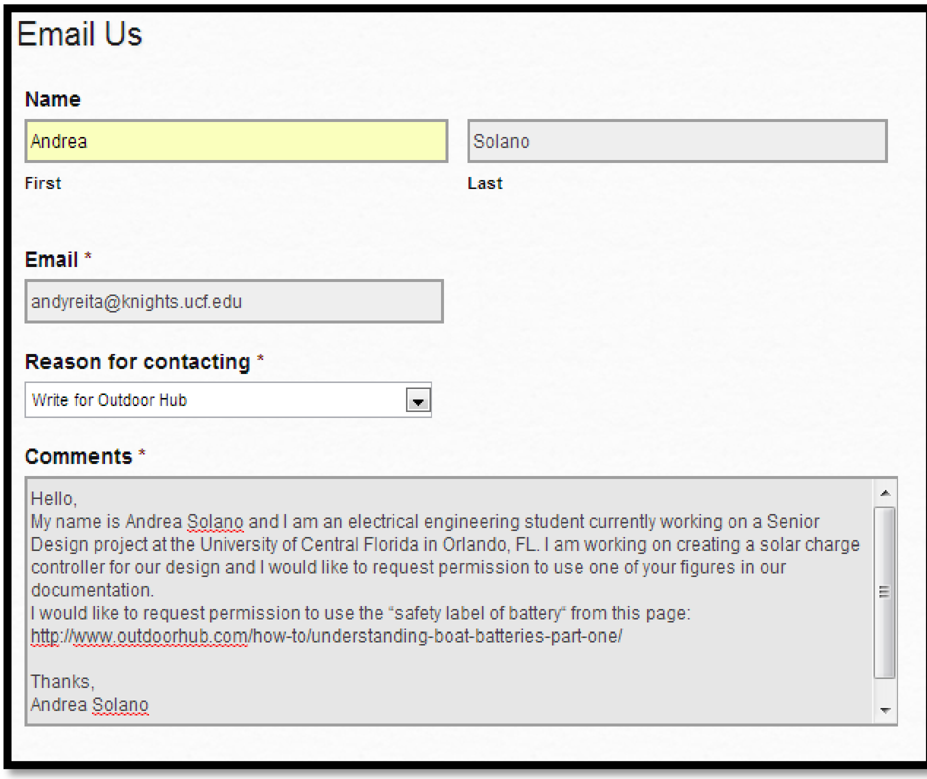

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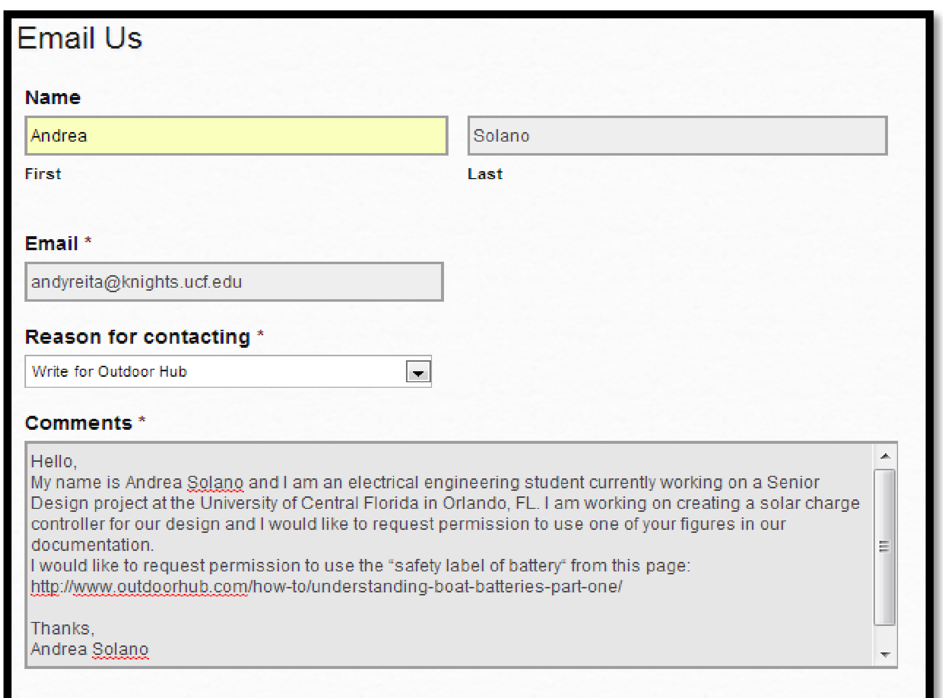

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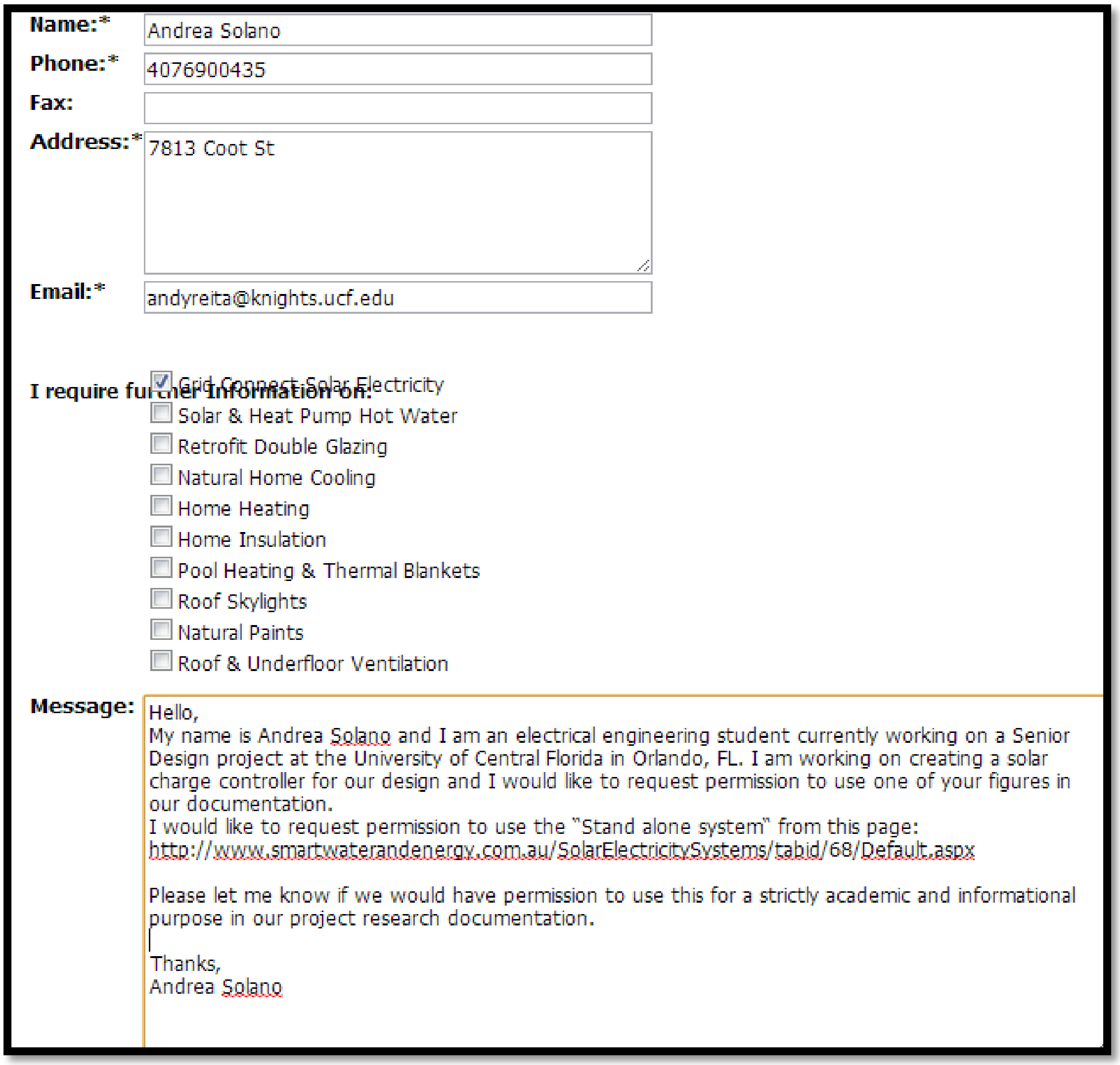

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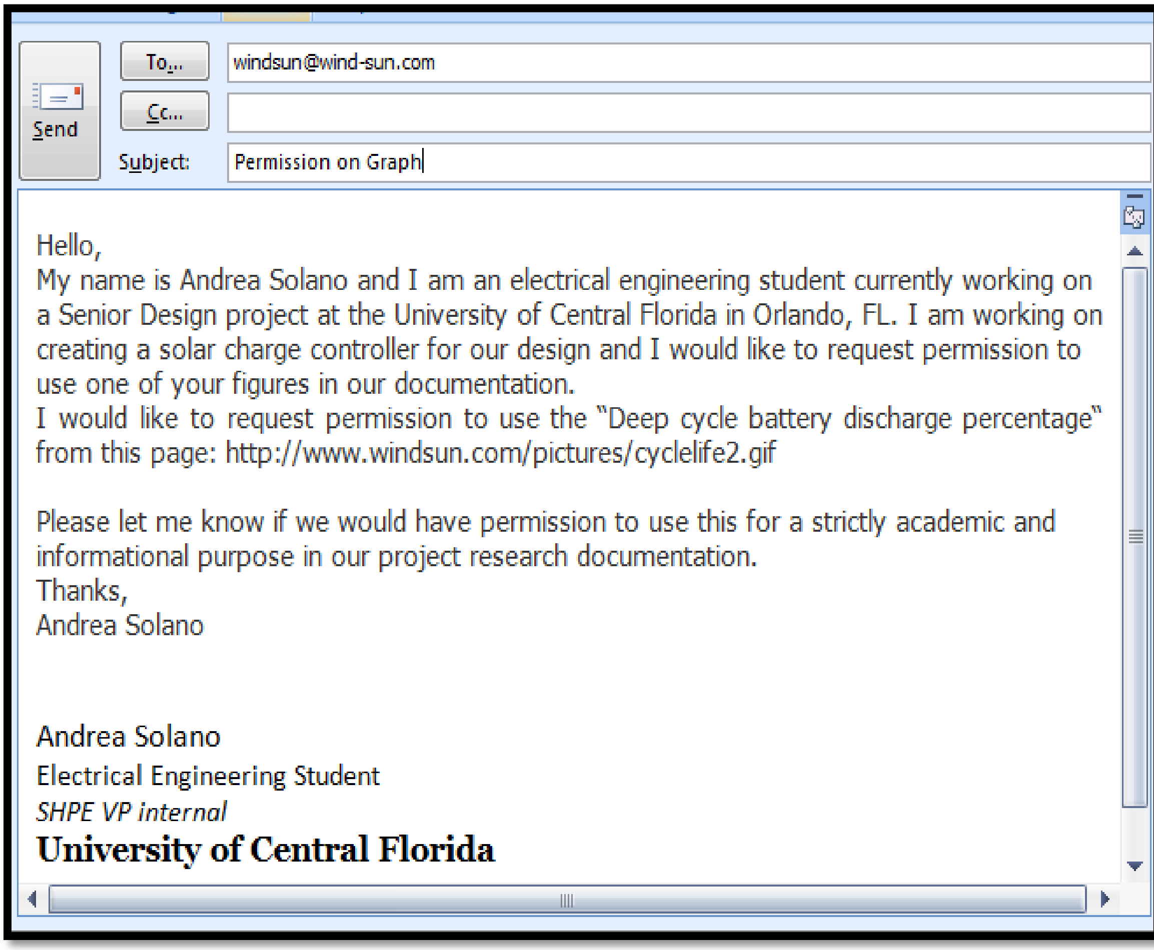
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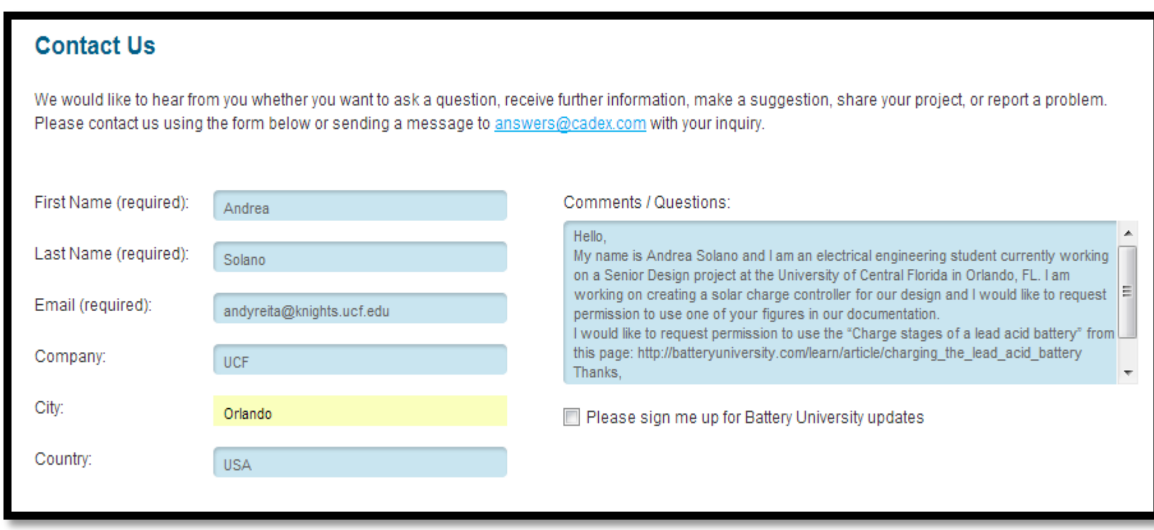
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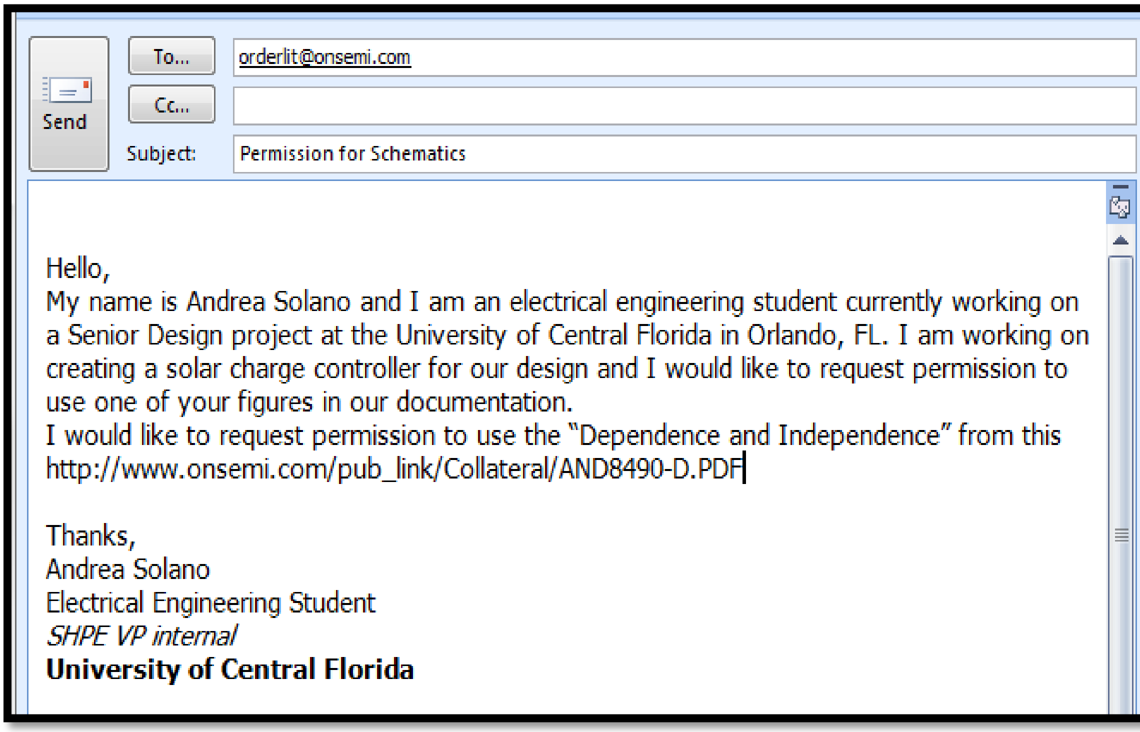

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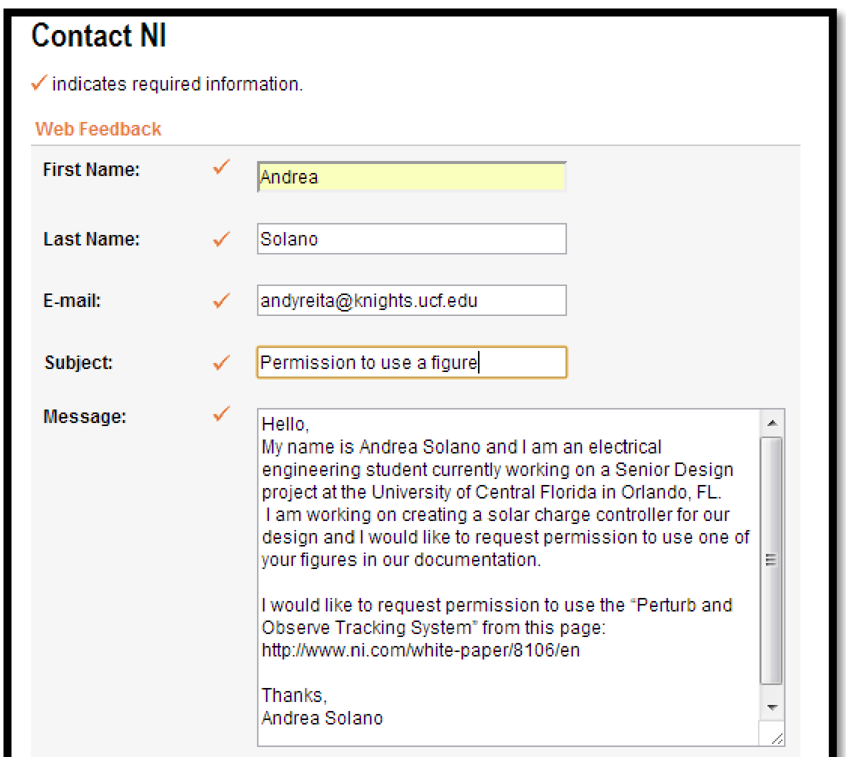

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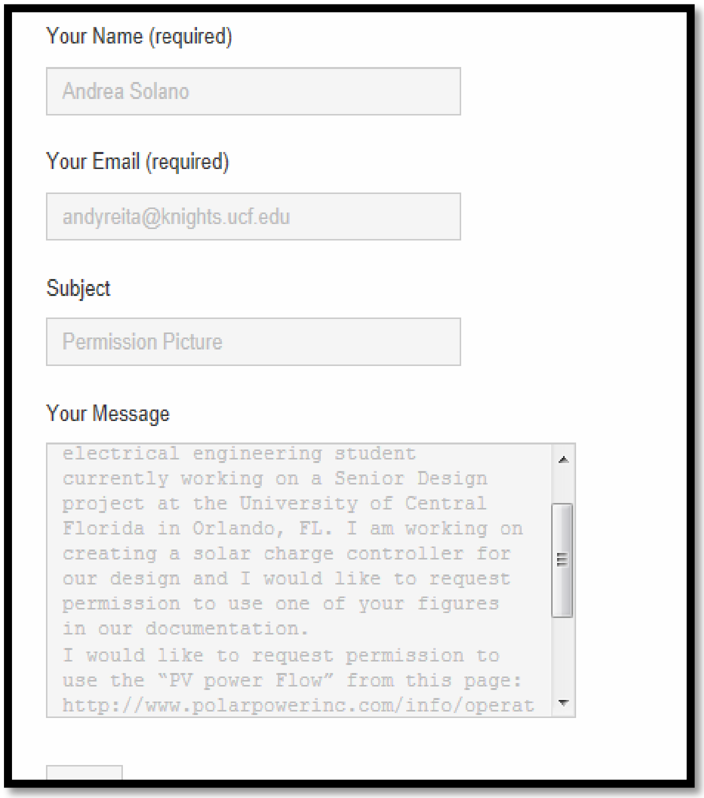
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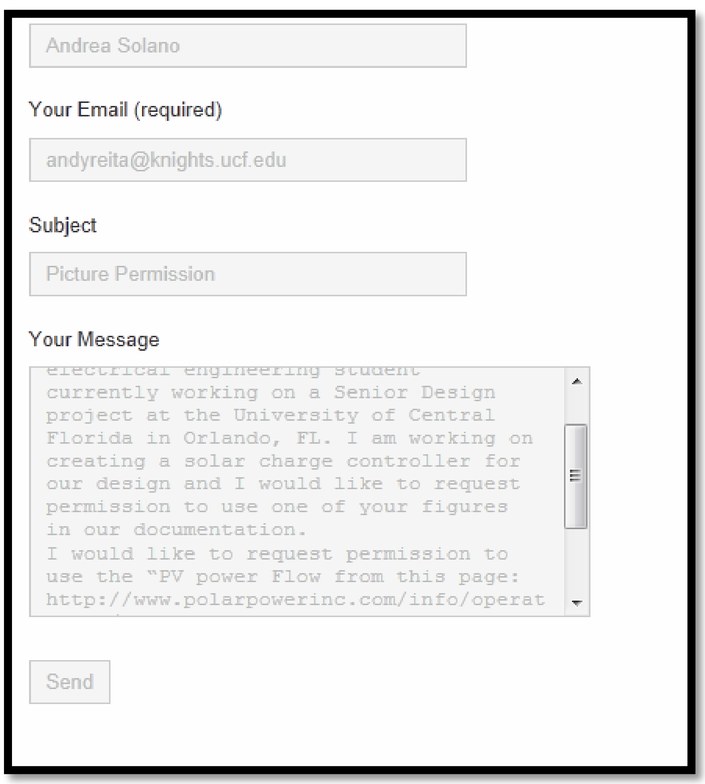
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our design and I would like to request
permission to use one of your figures
in our documentation.
I would like to request permission to
use the "PV power Flow from this page:
http://www.polarpowerinc.com/info/operat

Send

Windfinder

To... windfinder.com

Cc...

Subject: Permission of picture

Send

Hello,
My name is Andrea Solano and I am an electrical engineering student currently working on a Senior Design project at the University of Central Florida in Orlando, FL. I am working on creating a solar charge controller for our design and I would like to request permission to use one of your figures in our documentation.

I would like to request permission to use the "Wind Table" from this page:
http://www.windfinder.com/windstats/windstatistic_Johannesburg_or_tambo_airport.htm

Thanks,
Andrea Solano

Andrea Solano
Electrical Engineering Student
SHPE VP internal
University of Central Florida