Group 7
South Africa Power (G7-SAP)
Power Generation

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1.0 Executive Summary

The Group 7 South Africa Project (G7-SAP) is a power system intended to make energy from renewable fuel to help the Pomolong Township of South Africa power their community center. The power system will also store any power generated and provide interfaces to the community center that allows for easy practical use of the power.

The main purpose of The G7-SAP is to allow an impoverished village to be able to be entirely energy sufficient by giving them the tools to help sustain themselves through the means of a green energy solution. The power system is user friendly and easy to monitor and maintain, because it is intended to be used by individuals with little to no technical background.

The ultimate goal of this project was to create an off-the-grid stand-alone photovoltaic (PV) system that utilizes maximum power point tracking (MPPT) to maximize efficiency. Photovoltaic systems have many inherent losses, so it is essential for the maximum power to be extracted. The intent was to create an extremely efficient charge controller that is able to monitor the power generated by the photovoltaic array and deliver the maximum amount to the battery bank during varying atmospheric conditions. This combined with a modified sine wave inverter ensures that the community center is able to use every little bit of power generated.

In order to achieve the desired functionality, several major components were integrated into the final system. First, compact power generation devices were researched and implemented such that they produced practical amounts of energy, and were easy to use requiring no specialized knowledge. A power storage subsystem was also designed and implemented to provide an efficient means of transferring the power generated into a stored and ready to use form available for use. This includes a charging system utilizing maximum power point tracking, as well as the most efficient battery given the typical anticipated usage patterns of the project. An inverter was also designed and implemented that converted the stored energy into the familiar AC and DC sources that the end consumer would prefer. A monitoring system was also planned to be designed and implemented which allows the user to have a convenient way to know how much power they are generating, how much energy is stored, and other diagnostic information. All of this was done while still employing all of the best electrical safety principles, given that this system is intended for to be used by villagers with minimal technical education.

2.0 Project Descriptions

The project descriptions section of this paper is intended to describe both tangible and intangible parts of the project, such as reasons for undertaking this project, how long it will take specific objectives, and brief descriptions of different components of the project as a whole.

2.1 Project Motivation and Goals

There is great need of electricity in the small South African community of the Pomolong Township, which is occupied by the less fortunate people of South Africa due to the aftereffects of apartheid. They are cut off from the rest of the world because they do not have electricity that will enable them to use electronic devices such computers, cell phones, and TVs. Due to the extreme poverty in the community, they cannot afford the cost of power utilizing the power grid from the local utility company. Even if they could afford the cost of power, the township is not close to the power grid. When added together, the combination of these factors have put the people of the Pomolong Township in a difficult situation. To solve this problem, a device that utilizes renewable energy to generate power for this village was planned and designed. This device will allow the villagers to have a source of energy that is be self- sustainable.

Now that the problem and the solution are known, research was done to conclude which source of renewable energy should be chosen to be harnessed for this Senior Design project. Some of the sources that were considered were wind, hydro, solar, and mechanical/kinetic energy. After research of the area, it was observed that there is not much wind flow in the area and that mechanical/kinetic is not the best choice for the Pomolong Township. The use of hydro was not feasible, since the project will be located in the Pomolong Township community center, meaning that the project cannot be located near a river or other major water system. Also, there are droughts and South Africa has a sub-tropical climate system. With all other sources invalidated, utilizing solar energy as a renewable energy source was the only realistic choice.

In the present time, an internet connection is critical to the accumulation of knowledge, and through a projector people will be able to learn by watching educational videos, presentations, and documentaries. Being able to connect to the internet will give the villagers the opportunity to gain knowledge, which in turn will give them the tools and the power to improve their standards of living. They will be able to have tutorials, guides, eBooks, etc. at the tips of their fingers. Not only will the energy source project help in educational ways but it will give the township a source of entertainment as well. Movies will be shown during the evenings where township people can relax after a long day. Imagining a day without energy is hard to picture for most first world citizens where energy is almost always present, but for the Pomolong Township and many other places on Earth this is not something that is readily available or even expected.

According to United States-Central Intelligence Agency, about 30% of the population of South Africa is 0-15 years of age. In addition, the life expectancy is about 49 years of age [1], which is attributed to many reasons such as food shortage, clean water, and lack of medical supplies. However, one of the major motivating reasons why this project was chosen was to fulfill the lack of education, which was seen as the underlying factor for such substandard living conditions. Simple things such as knowing why one should wash their hands as to more complex things such as how to make a homemade water filtration system can be learned from the internet. An internet connection can help in other things that are overlooked such as employment. According to the United States-Central Intelligence Agency, about 24.9% of South Africa's population is unemployed. This number is very high and through an internet connection, employment search can be easier. The amount of internet users in South Africa is ranked 54th in the world which is considerably low considering its population size [1], but a consistent power source is needed before consistent internet can even be considered.

Our energy project is to be placed in the townships community center, which will be able to host most of the township. The project is designed to be weatherproof and robust, even though the project will probably be under a roof. After reviewing the energy requirements, a goal of about 500W an hour at operation time was made. The township will be in need of the equipment for about 4 hours in the evenings. This means that during the day the solar panels will be gathering energy and at night the Pomolong Township will consume the stored energy. Given the location of the village, it was estimated that about 6 hours of sunlight a day will be available, and two 250W solar panels were designed and are planned to be used. The goal is to store approximately 3000W a day. This should be more than enough to power the instruments of the people of Pomolong Township. The ability to monitor the charge of the batteries, to check if the charge of the batteries is low, will also be planned. The battery life depends on complete depletion of batteries, so knowing the levels of charge are necessary at all times.

Another goal is to make the system portable ergonomic, and as compact as possible. Since there will probably be no access to sunlight from inside the community center, ensuring that the project is easy to move in and out of the community center is a major design consideration. As stated before, the systems enclosure is weatherproof and durable enough to last a long time.

In conclusion, there is strong motivation to make an efficient and reliable energy source for the people of Pomolong Township. Giving them power and the benefits that come along with it are desirable. If successful, other areas in South Africa can benefit from this project and the idea of renewable solar energy can be expanded. There are many areas around the world which have no power but can harness a natural resource for their power needs. This project can be used as a base that others can model in order to help provide power to other impoverished areas of the world.

2.2 Objectives

There are several objectives that need to be addressed for the completion of the project. The following are objectives and explanations:

2.2.1 Safety

The absolute most important objective is safety, because ensuring that the system is safe protects lives and mitigates damages. There are many precautions to make when it involves electricity, because even though electricity is beneficial and the entire point of this project, it will mean nothing if the device is not safe. To ensure safety, precautions such as fuses and safety designs will be implemented. If the project were not safe, then the villagers that are being helped would be worse off than if nothing had been done at all.

2.2.2 Efficiency

A major objective of this project is for the power generating system to be extremely efficient, because the resources are scarce and utilizing every bit of energy gives the townspeople more time to enjoy the electricity. The more time the villagers have socializing and utilizing the facilities, the greater the impact the project will have. With all of these considerations, inefficiency is not an option.

2.2.3 Ease of Use

Keeping in mind the technology aptitude of the users, ease of use became an unavoidable objective. Overall design will cater to being simplistic, portable, and color coded to prevent and reduce user error. A monitoring system on an LCD screen connected to the charge controller and indicating all conditions of the project such as current levels, voltage levels, and temperature will be included

2.2.4 Charge Controller

One of the objectives is to successfully capture as much sunlight energy as possible. This is done through a MPPT charge controller system. The reason behind this controller is to vary the electrical operating point of the modules so that the modules produce the maximum power possible, regardless, of the climate conditions. This is very critical for the system because this eliminates the need to manually alter the current and voltage coming from solar panels. To do this, the MPPT charge controller changes the incoming current and voltage and matches it to the batteries voltage and current, resulting with the maximum power.

2.2.5 Batteries

Batteries are also important to the project design. Deep cycle batteries are what were implemented for the project, because deep cycle batteries are made to be complete drained and completely recharged. They are made to cycle between being completely full and almost empty charge positions many times. However, the AH (amperes per hour) needs to match the system as best as possible with minimal deviations, or there may be safety problems with the system. The ultimate goal was to find the right number of batteries to include in our system, because too many batteries will never be fully charged and too few batteries will be completely charged too quickly.

2.2.6 Inverter

The inverter is a part of the system that is critical to the project. The inverter takes the power from the charged batteries in the form of a DC input. The inverter then outputs AC which can be used by instruments such as laptops, TVs, and cell phone chargers. In order to get the most stable flow of current from the batteries, a modified sine wave inverter was designed. If the AC is not in a sine wave then some instruments plugged into the system may not function properly such as printers, chargers, and laptops.

2.2.7 Solar Panels

Solar panels are the part of the system which captures solar energy and converts it into usable power. Simply put, if the solar panels stop working then the rest of the system will be useless because there will be no input energy. No expense will be spared on the solar panels. The best quality solar panel made with grade A Mono-crystalline silicon solar cells were obtained. The difference between Mono-crystalline and Poly-crystalline cells is important, because Mono-crystalline cells are cut into thin wafers from a singular continuous crystal that is only used for this purpose. Poly-crystalline cells are made by melting the silicon material and pouring it into a mold [2]. This means that Mono-crystalline cells are more efficient because they have fewer impurities.

2.2.8 Enclosure

A robust, weatherproof, and safe enclosure to keep all of the entire system secure is a crucial part of the project. A gutted computer chassis was used to encase the inverter and the charge controller. The solar panels will be mounted to the community center, but will be designed to be detachable in order to be more convenient for storage. Batteries will be covered in a wooden container with vents, to prevent harmful gas accumulation. The equipment was designed to be easy to access for maintenance or any other reason.

2.2.9 Wires

Finally, the highest quality wiring possible was used. Wiring can be dangerous, and if the incorrect wire gauge is used for anything other than its intended purpose, the results would be disastrous and potentially fatal. This is critical because a hot wire can cause a fire and/or damage the system. For the batteries, low gauge wire were used and a medium to high gauge wire were used for the electronic components. As far as wire material, copper wiring were used because it is the preferred choice for any electrical application and has proven itself through time.

2.3 Project Requirements and Specification

The main requirements for the solar energy power generator are to provide the township of Pomolong with about 500 Watts of power an hour for about 4 hours every evening. Thus, the solar panels will charge the batteries with power during the day and at night the power will be used. The output is 220V power as opposed to 120V that is used in the United States. Even though newer electronics and laptop adapters are able to work from 120-220 V, this will guarantee that all electronics in South Africa be able to work with the system.

Safety is a major concern, so the highest measures were implemented. Batteries were ventilated, and the highest quality wires were used throughout the system. All electronics were kept in metal enclosures to protect them from adverse weather a temperature changes. Last but not least, fuses and other electrical safety designs were incorporated into the design to prevent electrical fires due to overcurrent.

The complete system incorporates solar panels, a charge controller, batteries, and an inverter. Each has important requirements in order for the system to work together and for the objectives to be achieved. The following table summarizes the requirements and specifications for our project:

Table 1 Specifications

Spec. #	Specification
1	Ability to capture about 6 hour of solar energy by our 500 W solar panel system. Solar panels will be two 250 W solar panel each which will be mounted on the roof of the community center of township.
2	Must be able to power up to 500 W electronics for a period of 4 hours daily.
3	Must be robust, weatherproof, safe, long lasting, and easy to maintain.
4	There must be a gauge to measure battery charge.
5	Inverter must support input of 12V and output 120V
6	Batteries must last at least 4 years. They will be placed in parallel making a 12V unit. Each battery will be 12V.
7	Charge controller must implement MPPT for the solar energy capture.

2.4 Block Diagram

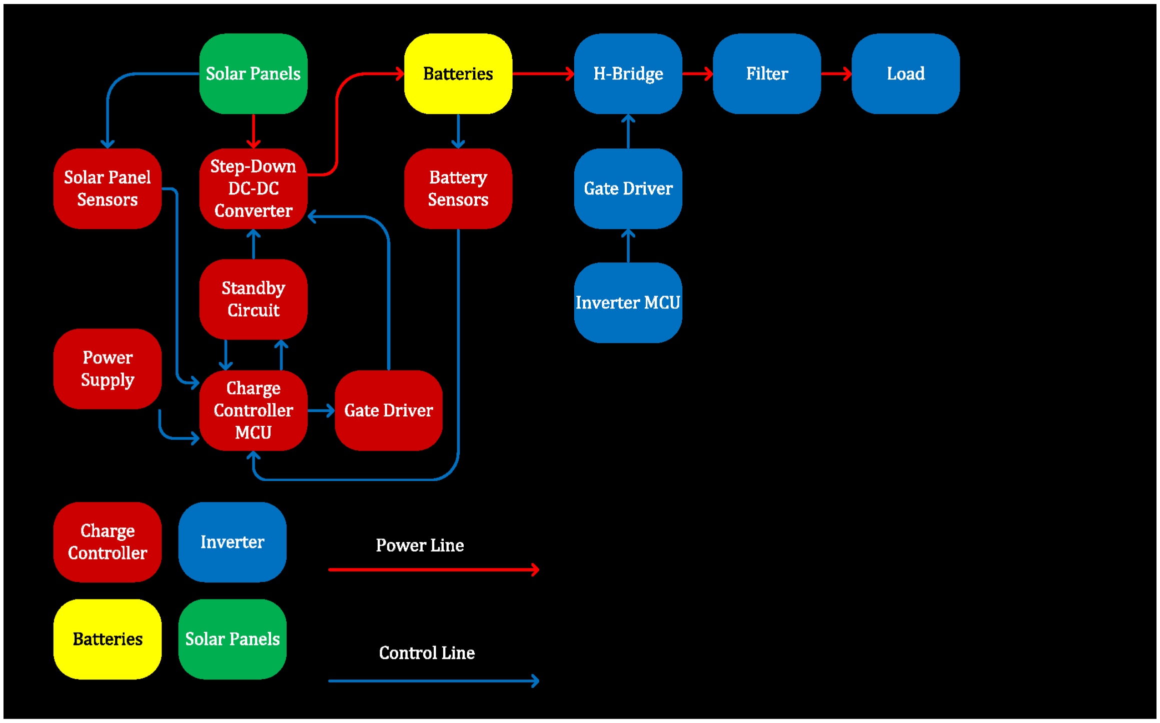

Figure 1 Project Block Diagram

2.5 Timeline

By the final week of Senior Design I, the 120 page research paper will be completed. As the following table displays, the majority of the research and part selections will be completed by the end of the first semester. The second semester would be dedicated to hardware assembly and testing. The project will be completed in its entirety and the final project will be operational and will output usable power.

Table 2 Senior Design 1 Project Milestones

Week #	Action	Description
1	Choose Project	Think about different ideas for projects and what needs to be worked on.
2	Group Selection	Pick team members for the group
3	Project Selection	Arrive to a final decision on the project to be constructed
4	Identify Parts	Start selecting parts to be implemented for the project
5	Initiate Proposal	Using the information from the previous week, begin documentation for parts proposal
6	Research Project	Begin researching every aspect of the project including hardware components, assembly, circuitry, and location of final residence
7	Research Project	Same as above
8	Begin Documentation	Begin writing documentation of the project
9-12	Continue Documentation	Start writing schematics for the project and studying individual components and continue writing documentation
13	Review Documentation Draft	Review the documentation and make final touches
14	Turn in Documentation	Turn in the documentation for Senior Design I
15	Order Parts	Start ordering parts for the project

2.6 Milestone Discussion

During the first weeks of the semester, brainstorming began for various project ideas. Several ideas went by. Some were very far-fetched while others were very practical. However, it was decided that the best idea would be to wait and listen to some of the projects presented by the sponsors. Dr. Wang's presentation for supplying power to people in need was really attention grabbing because it was challenging but at the same time humanitarian. Once all the presentations were over, a conclusion was made to work on a renewable energy source for the township of Pomolong in South Africa.

During the first few weeks, research of the project began. At first, a dual powered system with wind power and solar power was the focus of the research. However, after research of the location of the township of Pomolong, it was concluded that there was not enough wind for a wind powered generator to be beneficial. The wind was very minimal and it would take a big wind turbine with blades approximately15 feet long to make the power generation of the required scale viable. Thus, it was decided that concentration solely on solar power would be the best option. The benefits of solar power are plenty. The only real downside is that during low sunlight and night time it generates little to no power. This was an unavoidable problem that had to be endured.

Research on solar powered systems began in earnest. From the research, the system was simplified into manageable parts. All the parts that were needed to build a complete system were studied in full. After a week or so of research, it was decided that the main parts of the project would involve solar panels, wiring, a charge controller, an inverter, and batteries. From then on, pricing data was collected in order to form a proposal. Keeping costs low was a major factor when drafting the initial proposal. From what was seen, the most expensive part of the project was going to be the solar panels which took up almost half of the budget. The second most expensive part of the project were the batteries which are a crucial part of the project. The rest of the parts were much more cost efficient because the executive decision to build them from scratch.

From then on, vast amount of research was done, and documentation for the research section began. Collecting part numbers, conducting research on the location of the project, and designing sections of the project took up the majority time of the Fall semester.

Throughout the Fall semester which started in August and ends in December, most of the focus was spent on research. In order to have a successful project, it was established biweekly that every member of the Senior Design group needed to provide an update on work currently being worked on, and a complete evolution and process of their work. This enabled the group to be on the same page and work with the same pace. Between September and November the primary focus was to conduct thorough and well-documented research. The majority of the research was done between October and November as depicted in the table below.

Table 3 Research Milestone

	Research					
	Solar Power	**Batteries**	**Inverter**	**Charge Controller**	**Microcontrollers**	**MPPT**
10- OCT		🟦				🟦
22- OCT	🟦	🟦	🟦			🟦
31- OCT	🟦	🟦	🟦	🟦	🟦	🟦
10- NOV	🟦	🟦	🟦	🟦	🟦	🟦
15 - NOV	🟦	🟦		🟦	🟦	
29 - NOV	🟦			🟦		

The design phase overlapped with the research section. The design phase also overlapped with the parts acquisition portions of the project. The design began once each section was researched and the parts that need to be purchased were identified. As indicated in the chart below, the design stage will take place in the final weeks of Senior Design I and will continue through the first month of Senior Design II. During the Christmas break, the parts will still be investigated as the design progresses. Initial design concepts were presented in the Senior Design I documentation.

Table 4 Design Milestone

	Design					
	Solar Panels	**Inverter**	**Charge Controller**	**Microcontroller**	**MPPT**	**Batteries**
26-NOV	🟪					
5-DEC	🟪		🟪		🟪	
12-DEC	🟪	🟪	🟪	🟪	🟪	🟪
28-DEC	🟪	🟪	🟪	🟪	🟪	🟪
8-JAN	🟪	🟪	🟪	🟪	🟪	🟪
12-JAN		🟪	🟪	🟪	🟪	🟪
16-JAN		🟪	🟪	🟪	🟪	
22-JAN			🟪	🟪		

Over winter break as certain aspects of the design were finalized, some parts were ordered for early prototyping in the Spring semester. Parts acquisition increased significantly following the break and continued until April. The goal was to have ordered all of the necessary parts for the project by mid-February. The parts necessary for the packaging of the final circuit board and electronics were acquired later, as shown in table below, once the design was been tested and the final board was fabricated.

Table 5 Acquisition Milestone

	Acquisition				
	Solar Panels	**Micro Controller**	**Batteries**	**Sensors**	**Circuit Board**
19-DEC	🟥	🟥		🟥	🟥
27-DEC	🟥	🟥	🟥	🟥	🟥
5-JAN	🟥	🟥	🟥	🟥	
12-JAN	🟥		🟥		
20-JAN			🟥		
23-JAN					
28-JAN					
4-FEB					

The table below shows the schedule for prototyping. This phase began immediately following parts acquisition and also included component level testing. Once a part was acquired, the component testing consisted of individual parts testing to confirm that it works and provides reasonable information. This was especially important with sensor implementation, to make sure they were scaled correctly and provided meaningful data. The circuit design was first prototyped on a solder less breadboard. As previously stated, the development of the packaging did not commence until the main modules were finalized.

Table 6 Prototype Milestone

	Prototype				
	Solar	**Batteries**	**Microcontroller**	**Inverter**	**Charge Controller**
13-JAN					
20-JAN	■				
7-FEB	■	■		■	
14-FEB	■	■	■	■	■
23-FEB	■	■	■	■	■
9-MAR	■	■	■	■	■
18-MAR		■	■	■	■
26-MAR				■	■

The final stage of the project consisted of testing. The testing plan and methods covered component level, module level, and system level testing. The table below shows that testing should commence in March, overlapping with the final stages of prototyping. The testing and documentation encompassed all of April up until the last week in which the final presentation took place.

Table 7 Testing Milestone

	Testing					
	Solar Panel	**Batteries Charging**	**Safety Procedure**	**Packaging / Transport**	**Hardware**	**Entire System**
16-MAR		🟩			🟩	
19-MAR		🟩			🟩	
22-MAR	🟩	🟩			🟩	
29-MAR	🟩	🟩	🟩		🟩	
5-APR	🟩	🟩	🟩		🟩	🟩
16-APR	🟩	🟩	🟩		🟩	🟩
20-APR	🟩		🟩	🟩	🟩	🟩
26-APR	🟩		🟩	🟩		🟩

2.7 Budget and Finance Discussion

The main purpose of the project is to design a robust solar energy power generator. To do this, fully functioning solar panels, a charge controller, batteries, and an inverter are needed. The proof of the final project was a working standalone photovoltaic power system. The following is the preliminary Budget which includes the parts that were obtained in order to create an off-grid photovoltaic power system.

Table 8 Budget

Part	Vendor	Quantity	Price ($)
250 Watt Solar Panel 72 Mono Crystalline Cells 33 Volt 7T2300-2	Helios	2	700.00
T105-RE 6V 225 Ah Flooded Battery	Trojan	3	400.00
Charge Controller based on MPT612	N/A (Designing	1	300.00
Pure Sine Wave Inverter	N/A (Designing	1	300.00
Chassis and Weatherproofing	N/A (Designing)	1	100.00
Miscellaneous Electronic Components and Wires	N/A	N/A	195.00

Total: **$1995.00**

As explained before, the project can be broken down into four main sections. It is divided into solar panels, the charge controller, batteries, and the inverter. Two 250W 33 V solar panels were obtained and set up in parallel to deliver a constant voltage level of 12V to the system. For the second section of the project, the charge controller and other minor electronics will be discussed in detail. Before ordering the printed circuit board there was a period of testing and building of the completed circuit on a solder less plug-in breadboard. Once the circuit on the breadboard was tested to perform all of its required, it was found to not be very cost effective to order a PCB for the charge controller so it was built using perf boards. The third component is composed of the batteries which did not require allot of design. They were be wired up to the system in order to create a fully working photovoltaic power system which has the ability to store and distribute power. The fourth component, the inverter, was also fully designed. Like the charge controller, the circuit was first designed and tested on a solder less breadboard. Once the required tasks were checked to be fully working, then the final circuit board was ordered.

To fund the South Africa project, sponsorship and funding by Progress Energy which give grants according to energy sustainability projects, was heavily relied upon. Since the project involves a renewable and self-sustainable energy source it falls in accordance to their Senior Design project funding requirements. Groups wanting to claim this sponsorship along with the funding had to submit proposals which included the above budget table along with project objectives, specifications, a block diagram, the project's impact on renewable energy and sustainability, and the timeline of project completion.

3.0 Research Related To Project Definition

The research related to the project definition section of this paper is intended to show all the research done on all of the parts of the project. The research done will show what was discovered to already exist and comparisons in options available that will affect the overall design of the project.

3.1 Existing Similar Projects and Products

This project is not the first time that an MPPT charge controller has been used to control the charge levels coming from photovoltaic panels going into a battery bank. In fact, this general idea was derived from the numerous other projects that experimented with this concept. Although the ideas and technology used for this project are not completely unique, the condition in which this project is being applied for has the potential to make the greatest societal impact.

Previous senior design projects conducted by students at the University of Central Florida in the summer of 2009 [3] provided insight into a solar project that fulfilled the requirements of a UCF senior design. Another UCF project designed in the fall of 2011 [4], made further advancement by using an MPPT charge controller in their design. This documentation provided a large amount of insight into the processes and features needed to design a stand-alone charge controller. The third most influential project was the Pure Sine Inverter project designed a senior design group from the Worcester Polytechnic Institute in the A-B-C term of 2006 [5], which showed all the advantages of a pure sine inverter, as well as providing a good basis for a model design.

This project has been influenced by the ideas above, but the incorporation and application of these ideas are unique to this project because this project will be used for an actual group of people who actually need power in reality. This project is turning efficient but abstract ideas into tangible tools that render assistance to those most in need.

3.1.1 Solar Panels

With the knowledge that the goal of this project is to produce power, it became necessary to find a reliable energy source to be utilized as fuel. Using energy from the sun through the use of photovoltaic panels was an obvious idea to think about because South Africa is known for being sunny. The object of this research section on energy production due to the conversion of solar radiation into electricity using semiconductors that exhibit the photovoltaic effect is to display the current status of solar technologies and to discuss the best options that can be used for this project. This can be shown by an exhibition of the latest improvements in photovoltaic cell technology, price comparisons of current models of PV panels, and climate conditions of the Pomolong Township that may affect the final decision making processes.

3.1.1.1 Photovoltaic Cell Technology

The first way to obtain solar energy is with Concentrated Solar Power. This way involves the use of mirrors and lenses to intensify sunlight. The thermal energy from the intensified sunlight is used to heat up water to produce steam. The steam is used to turn steam turbines connected to a generator, which then produce electricity. This method of generating energy from solar power is a strong competitor for large scale power, but uses many unique parts that are hard to replace. This kind of device is not as scalable as photovoltaics, making it less practical for use in the South Africa Project.

The second way to obtain solar energy is by using photovoltaics. With photovoltaics photons are absorbed by a photovoltaic cell, which contains a semiconducting material such as silicon. The energy from the photon is then transferred to an electron in an atom of the photovoltaic cell. The energized electron is then able to escape its bond with the atom and generates an electric current [6].

Photovoltaic cells, also known as solar cells are primarily made of crystalline silicon. When the cells are interconnected they form a solar panel that produces a direct current. Aluminum is used to build the panels in order to increase their durability. The cells are then placed behind tempered glass which keeps the cells safe, durable, and protected against adverse weather conditions. A clear resin is used to insulate the back of the solar cells and also keep them in place against the top panel glass. It is clear that solar panels are made to be robust and sturdy and that many manufacturing designs have been made with the understanding that the panels will spend the duration of their use out in the elements.

This project used solar panels, because it was concluded to be a more practical and durable measure for use in South Africa, where replacing specialized parts are difficult, and protecting fragile parts are not possible.

Further research on the different kinds of panels, their costs, and their levels of efficiency were required in order to select the best solar panels to use for this project. Panel placement and panel temperature were also important in increasing the efficiency at which solar panels capture solar energy.

3.1.1.2 Types of Photovoltaic Cells

This section is going to describe the different kinds of photovoltaic cells available, and what makes them different. The amount of different kinds of PV cells is daunting, which makes organizing them into groups the first thing that should be done in this section. Solar cells can be generally be grouped by generation of their technology. Silicon is first-generation technology and Thin-film is second-generation technology. Silicon can be further subdivided into being either Mono-crystalline or Poly-crystalline. Thin-film is further subdivided into Gallium-arsenide, amorphous silicon, Cadmium telluride, and Cadmium indium selenide. A third-generation technology is also emerging in the form of Polymer solar panels. This new technology is an extension of Thin-film technology and is currently being heavily researched, because of a potential decrease in production cost, but the technology is still under development.

In order to discuss the strengths and weakness of each of the major kinds of photovoltaic cells, each of the cells will be reviewed in detail chronologically. The first solar cells that were commonly used are Mono-crystalline silicon cells. Although they are no longer commonly used, this first-generation technology is the oldest and most tested photovoltaic. As its name suggests, Mono-crystalline solar cells are made from the same silicon crystal, ensuring that minimal impurities, irregularities, and imperfections are maintained. To produce this kind of silicon, the Czochralski process is used. To do this, a crystal silicon seed is dipped into molten silicon and withdrawn slowly. At the end of this process, when the molten silicon crystallizes around the seed, a two meter long cylindrical single-crystal ingot is produced. The ingots are then doped in proportions based on intended future use and cut into wafers. The silicon wafers can then be used for semiconductor devices or for photovoltaics.

The main advantage to this type of production is that when the impurities are minimized, the photovoltaic cell is more efficient. Efficiency is a based on percentage of how much current is produced given the amount of light that is absorbed. Mono-crystalline cells can achieve efficiency of about 17% [7]. Due to their high efficiency, these panels are expected to have an above average life expectancy, and are usually rated to last for around twenty-five years, with some actually lasting fifty years.

Despite being efficient when used, Mono-crystalline cells are expensive to produce, because the Czochralski process results in excessive waste of silicon. As a result of this waste the production cost is high, so the price per panel stays high. However, you can maximize the amount of watts per square foot of panel used, since these panels are so efficient. This is an important design feature if limited space is an issue. Another one of the disadvantages of Mono-crystalline solar panels are that they are very fragile, and care must be given during the shipping and installation processes. Although the cost to produce these panes have increased, most online solar panel retailers have recently dropped the prices for these panels due to decrease in demand, making their prices competitive with the prices of the Poly-crystalline panels. With higher efficiency, and similar cost to its competitors, Mono-crystalline photovoltaic cells are ideal for the South Africa project.

The second kind of solar cell that was commonly used are Poly-crystalline silicon cells. In the present market, Poly-crystalline solar cells are the most popular for home installations. They are popular because they are cheaper to produce than Mono-crystalline panels. To make these cells, molten silicon is cast and cooled in a rectangular shape. The rectangular block is made up of tiny silicon crystals that look like broken glass. This block is then sliced into thin sheets. Compared to Mono-crystalline cells, the process to make Poly-crystalline cells is much cheaper and faster. This means it is more profitable, but there is a tradeoff to this reduction of cost. Poly-crystalline cells are typically less efficient than their Mono-crystalline counterpart, having an efficiency to convert photons to electrons of approximately 10% [8]. This reduction in efficiency is due to a decrease in the grade of silicon as well as an increase in the amount of imperfections. The imperfections cause energy to be lost at fusion points between two adjacent crystals. This loss in energy causes a decrease in efficiency.

The third kind of solar cell that will be discussed is part of the second-generation technology of Thin-film cells. Before going into detail about the various kinds of Thin-film photovoltaics, a brief summary of Thin-film technology is necessary. Thin-film solar panels are made by placing thin layers of semiconductor material onto glass or other similar material. The reason they are called Thin-film is because of the amount of semiconductor material used, giving the appearance of a thin film in the form of a flexible semiconductor laminate. The flexible laminate makes the panels bendable. This makes the Thin-film cells easier to mount on uneven surfaces and also makes them durable during extreme weather conditions. Being weather resistant is a major reason why Thin-film technology is increasing in popularity because panels need to be continuously exposed to weather elements. Thin-film cells even work when they are damaged, but at a lesser rate. This is a major advantage over silicon panels, because if a single cell of a silicon panel is damaged, the entire thing ceases to work entirely.
To add on even more advantages, Thin-film cells are much lighter than their silicon counterparts. This makes them easier to mount and work with for residential use.

Another important feature that Thin-film solar panels exhibit that must be noted is that they do not have a significant decrease in performance when exposed to high temperatures or when in there is shade due to their material properties. With all of this in mind, it is generally easier to design solar panel systems with Thin-film technology because of their advantages in weight, durability, and usability in generally adverse weather conditions. At this point, it may seem pointless to use first-generation technology over the send-generation Thin-film, but Thin-film photovoltaics also have disadvantage. The largest quantifiable disadvantages that Thin-film cells have are their low efficiency at converting light to electrical current. The efficiency of Thin-film technology is generally around 7% [8]. This is significantly less efficient than Poly-crystalline silicon and about a third of the efficiency of Mono-crystalline silicon. Additionally, Thin-film solar panels are fairly new compared to their predecessors, so how they endure the test of time has still not been seen. Hopefully, Thin-films prove to be as good as the lab models suggest.

Although a general review on Thin-film technology has been made, there are different kinds of Thin-film technology, and discussing the physical properties that make them unique will prove beneficial in deciding the optimal technology that should be used for the South Africa project. The first Thin-film that will be discussed specifically will be amorphous silicon Thin-film, mainly because of their widespread use and popularity. Amorphous silicon Thin-films were among the first thin films and were originally popular for use in small electronic devices that needed a small amount of power like pocket calculators. These are inefficient and are not practical for larger scale power generation. The reason that this particular photovoltaic was mentioned was because of its historical significance to the advancement of Thin-film technology, and because of its impact on most Thin-film panels researched today.

There are three major kinds of Thin-film photovoltaic cells that are currently popular in the market, and they will be discussed in full. The first Thin-film that will be discussed in detail will be the Copper Indium Gallium Selenide panel, also known as CIGS. These panels are made in the general method made to make Thin-films, where the compound is layered on glass, but their fabrication process is vacuum based. The advantages of Copper Indium Gallium Selenide are that they do not lose as much efficiency as their temperature increases compared to their crystalline counterparts, giving them an edge in warmer climates. To top that off, the CIGS compound has a panel efficiency of around 10% to 15% with a peak of 19.9% [9]. Because of these impressive numbers, increases in the production of CIGS panels are projected to increase in the future. The only downside to using these panels currently are that they are expensive and scarce due to being relatively new, being in low supply, and having an expensive fabrication process.

The next Thin-film that will be discussed will be the Cadmium Telluride Thin-film panel, also known as CdTe panels. They were one of the first semiconductors that were used in Thin-film technology to improve the low efficiency experienced with amorphous silicon. CdTe panels are produced similarly to CIGS panels. They are the most common type of Thin-film solar panel on the market, due to being the most cost-effective Thin-film solar panel to manufacture. Similarly to CIGS panels, CdTe panels also perform better in higher temperatures and low-light conditions compared to crystalline panels. As for efficiency, Cadmium Telluride Thin-film panel range in efficiency from 7% to 12% with a peak of 16.5% [10]. The major disadvantages of these panels are that they are dangerous to the environment because Cadmium is toxic, and they are expensive because Tellurium is rare.

The final panel that will be discussed in detail are Gallium Arsenide Thin-film panels, which are also known as GaAs panels. GaAs panels are very similar in properties to CdTe panels in respect to the fact that the materials to make the compound are rare and dangerous, and the fact that GaAs panels maintain their performance in higher temperatures. GaAs panels are made up of a mixture of Gallium, which is a rare metal and Arsenic, which is a poisonous metalloid. The reasons that GaAs panels are so special are their efficiency. Their efficiency ranges from 20% to 25% with a peak of 30% [11]! According to the National Renewable Energy Laboratory, the high efficiency was a result of GaAs having an almost ideal bang gap. Using these panels reqires a tradeoff, and for most people, the prices for Gallium Arsenide Thin-film panels are far too high for the benefit of the impressive increase in efficiency.

3.1.1.3 Factors that Affect Performance

When it comes to the overall performance of solar panels, the ideal conditions of a lab are not present in the real world, and the efficiency of any given panel could be affected by an array of possibilities. Factors that could change performance are important, because solar panels are the largest investment in the project, and performance is one of the major considerations when implementing a photovoltaic in a design. To best understand the factors that affect performance, this section will look at the physical properties of solar panels, as well as discuss the conditions that could alter those properties, making the photovoltaic less than ideal.

To describe the physical properties of solar panels, a brief overview of the photovoltaic effect is necessary in order to explain factors that can change the physical property of a solar panel. Simply put, the photovoltaic effect is the physical phenomenon that allows a photovoltaic cell to convert solar energy into usable electricity. The photovoltaic cell is usually constructed of some light absorbing semiconductor material like silicon. All semiconductors are associated with a specific energy band gap [12]. The energy band gap is the potential difference between the lowest energy level on the energy conduction band and the highest energy level on the energy valence band. The conduction energy band is the range of energy that allows an electron to become free from an atom. The energy valence band is the range of energy where the electrons on an atom are not free. When electrons are in the energy valence band they are considered to be in steady state. If given input energy, the electrons can become excited. If given enough energy, they will jump to the energy conduction band, and will be considered to be in an excited state. The electrons in the energy current band are responsible for the direct current that is produced by the solar cells. In the case of solar cells, the input energy will be solar energy in the form of packets of photons containing different levels of energy corresponding to the different wavelengths in the light spectrum. When the input energy matches the energy of the band gap in the material, the photons with energy levels equal to the energy band gap are absorbed by the semiconductor, the photons with energy greater than the energy band gap are. The photons with higher energy levels than the energy band gap are dissipated in the form of heat and the photons with lower energy levels than the energy band gap are not absorbed at all. With this in mind, when designing a solar cell, choosing a semiconductor material with an energy bang gap as close to the center of the solar radiation spectrum would yield optimal results. The full solar radiation spectrum ranges from infrared to ultraviolet. Unfortunately, there is no semiconductor found to date that responds to the full solar radiation spectrum. There have been solar cells recently invented that can respond to the entire spectrum [13], but they are unavailable for widespread commercial use.

Another way that a solar cell can be viewed would be to compare it to a diode. Photovoltaic cells can be compared to a diode because of the p-type and n-type semiconductor materials used to fabricate them are similar in application to the p-n junction in a diode. Like diodes, there are two metal contacts attached to each side of this p-n junction. When the electron-hole pair is formed across the p-n junction, a forward voltage is created between the two photovoltaic cell terminals.

Crystalline or first-generation photovoltaic cells are usually protected from the outside elements with a protective layer of glass or clear plastic cover. A clear layer of silicone is used to attach the rest of the cell to the glass. An antireflection coat covers the n-type terminal. The n-type terminal is then connected to the n-type silicon. Below the n-type silicon layer is the p-type layer needed to form the p-n junction in-between them. The p-type terminal is beneath the n-type layer, and lies on top of a conductive contact. The entire structure and process can be seen in the image below.

Figure 2 Silicon Solar Cell Structure and Mechanism **[14]**
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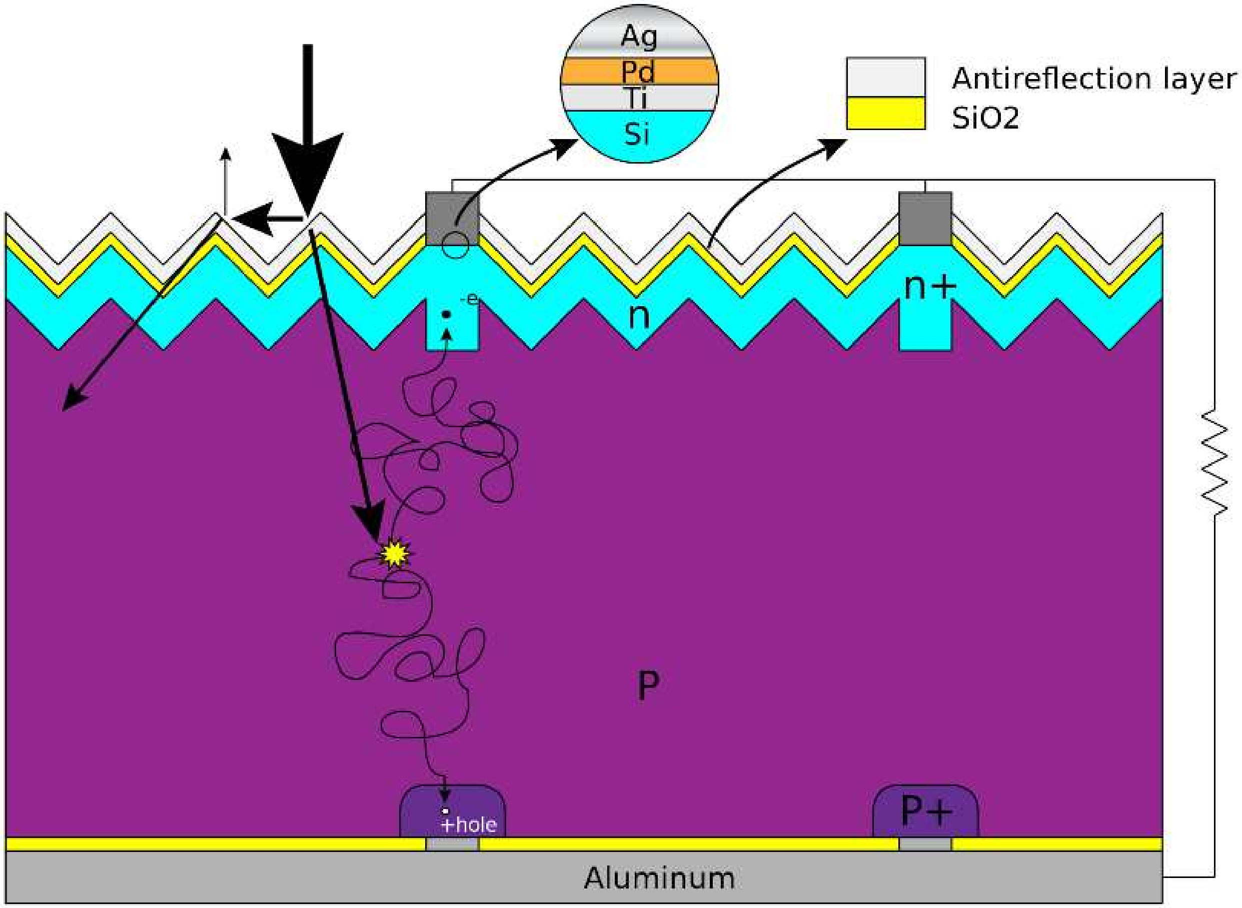

Solar panels in all sorts of various makes and models are not very efficient at converting solar energy, noting that the highest efficiency made is 30%, which is not even available for general consumer use. Due to this solemn realization, panel performance and any means to increase it are very important to this project. All solar panels suffer from naturally caused issues that may decrease performance such as temperature, electron-hole recombination rate, and light absorption efficiency. How these different factors affect performance were addressed.

The first factor that was addressed was electron-hole recombination. The rates of electron-hole recombination for Mono-crystalline photovoltaic cells are the main reason why they perform better than Poly-crystalline cells. In Poly-crystalline photovoltaic cells, the impurity concentration and the structure abnormality associated with multiple crystals of silicon increases the electron-hole recombination rate. If the electron-hole recombination rate is increased, then the efficiency of the panel decreases.

The next factor that was taken accounted for was temperature. Temperature is another negative factor that affects solar panel performance. Crystalline silicon panels suffer the most when their cell temperature rises. When the temperature of the semiconductor rises, the conductivity also rises. If there is an increase in conductivity, the electric field of the p-n junction decreases. If the electric field decreases, then the voltage across the photovoltaic cell decreases. Less voltage across the solar cell results in a smaller power output and lower efficiency [15]. New research is being done using non-silicon semiconductor materials on thin film panels to circumvent the restriction that occurs as a result of a reduction of panel sensitivity due to temperature. The ideal weather conditions that will put solar panels at their peak performance are cold and sunny days. Those kinds of days are not typical in most places in the world. Understanding this, the project took the temperature effects on the selected solar panel with great consideration.

Every Solar panel has a temperature coefficient and an I-V curve that describes its I-V characteristics. The temperature coefficient is the rate of power reduction for every degree above the operating temperature. The standard operating temperature is 25 degrees Celsius. The I-V curve that describes the photovoltaic's I-V characteristics shows the relationship of current and voltage for different degrees of temperature. The area under the I-V curve is an approximation of the maximum power that the photovoltaic would produce if operating at both open-circuit voltage and closed-circuit current. From the figure below, it is shown that total photovoltaic cell power diminishes as the temperature of the panel increases.

Figure 3 I-V Curve **[16]**
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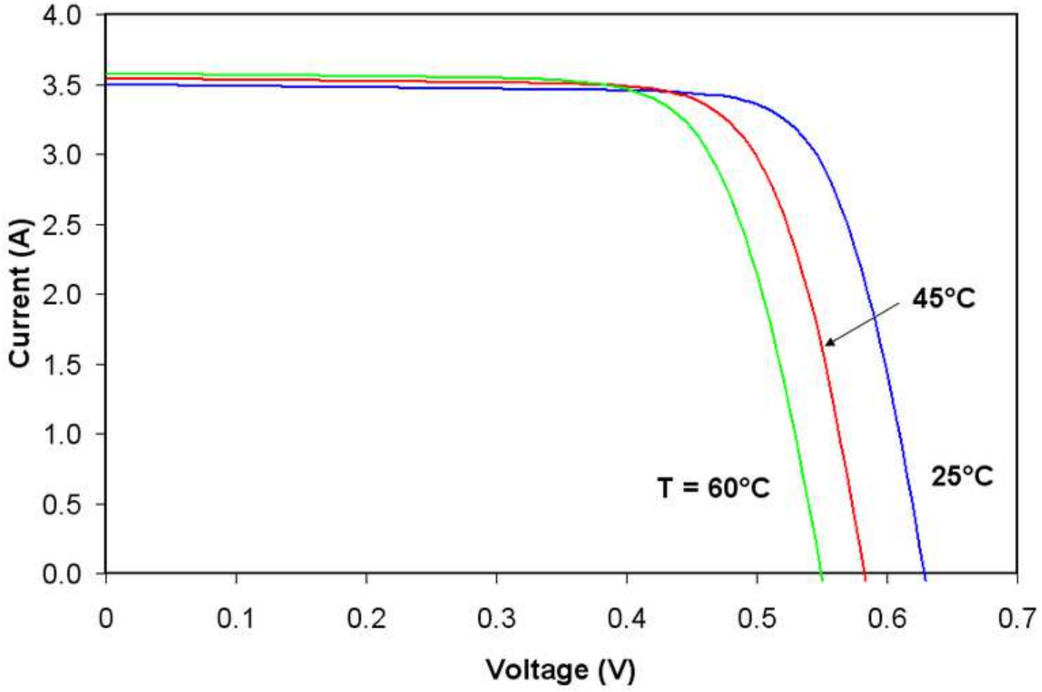

As seen previously and in the figure above, solar panel temperature must be as close to an operational temperature of 25 degrees Celsius in order to optimize efficiency. Right now, research is underway to on developing cooling methods that will maintain low temperatures in solar cells. There are currently two major ways to cool the cells. The two major ways in maintaining a lower solar panel temperature are active cooling methods and passive cooling methods. An example of an active cooling method would be pumping a coolant or a refrigerant through the backside of the solar panels. An example of a passive cooling method would be attaching a heat sink or cooling fins to dissipate heat from the panels. The problem with most cooling methods available right now is that the efficiency gained by utilizing them does not offset the cost to implement them.

The last inefficiency associated with solar panels that will be discussed is their ability to absorb light. Most solar panels cannot use the entire light spectrum to convert light into current. Light energy is lost in several ways. Some energy is lost from photons being reflected. To mitigate this loss, an antireflection coating is used on almost all solar panels. Some energy is lost because the photons of light do not get absorbed because they do not have the right wavelength to match the semiconductor band gap.

As a result, more than half of the light spectrum available becomes useless to the solar panels. To help fix this issue, band gap engineering has been developed as one of the leading methods used to increase light absorption efficiencies. Electrical design engineers maximize power by maximizing photo current or photo voltage individually.

Photo current is maximized when the amount of photons of light from the solar radiation spectrum captured are maximized. To perform this method, a small energy band gap is selected so that photons with low energy can excite electrons in the energy conduction band. The downside to using a small energy band gap is that it lowers the photo voltage and photons with higher energies become dissipated as heat instead of being converted into electricity. Photo voltage is maximized when the electrical design engineers choose a higher energy band gap. The problem with this method is that photons from lower energy levels than the energy band gap will not be captured or absorbed. This will result in a lower photo current which will reduce the total output current. The two competing energy band gap methods are balanced by choosing optimal band gaps near the middle of the energy spectrum for solar radiation.

High-quality silicon wafers, with a band gap of 1.1 eV, and GaAs, with a band gap of about 1.4 eV, are readily available and have nearly the optimal band gap for solar energy conversion in a conventional single-junction solar cell [12].

3.1.1.4 Climate Conditions of the Pomolong Township

The Pomolong Township is located at 28°14'39.82"S, 29° 6'46.02"E, which is 265 kilometers southeast of Johannesburg, South Africa and 304 kilometers northwest of Durban, South Africa. The closest developed town to Pomolong is Harrismith, which is 7.6 kilometers south, so there isn't a lot of climate data for the exact area of the township, such as precise numbers regarding hours of available sunlight to the township.

Figure 4 Geographic Location of Pomolong Township in Relation to Harrismith
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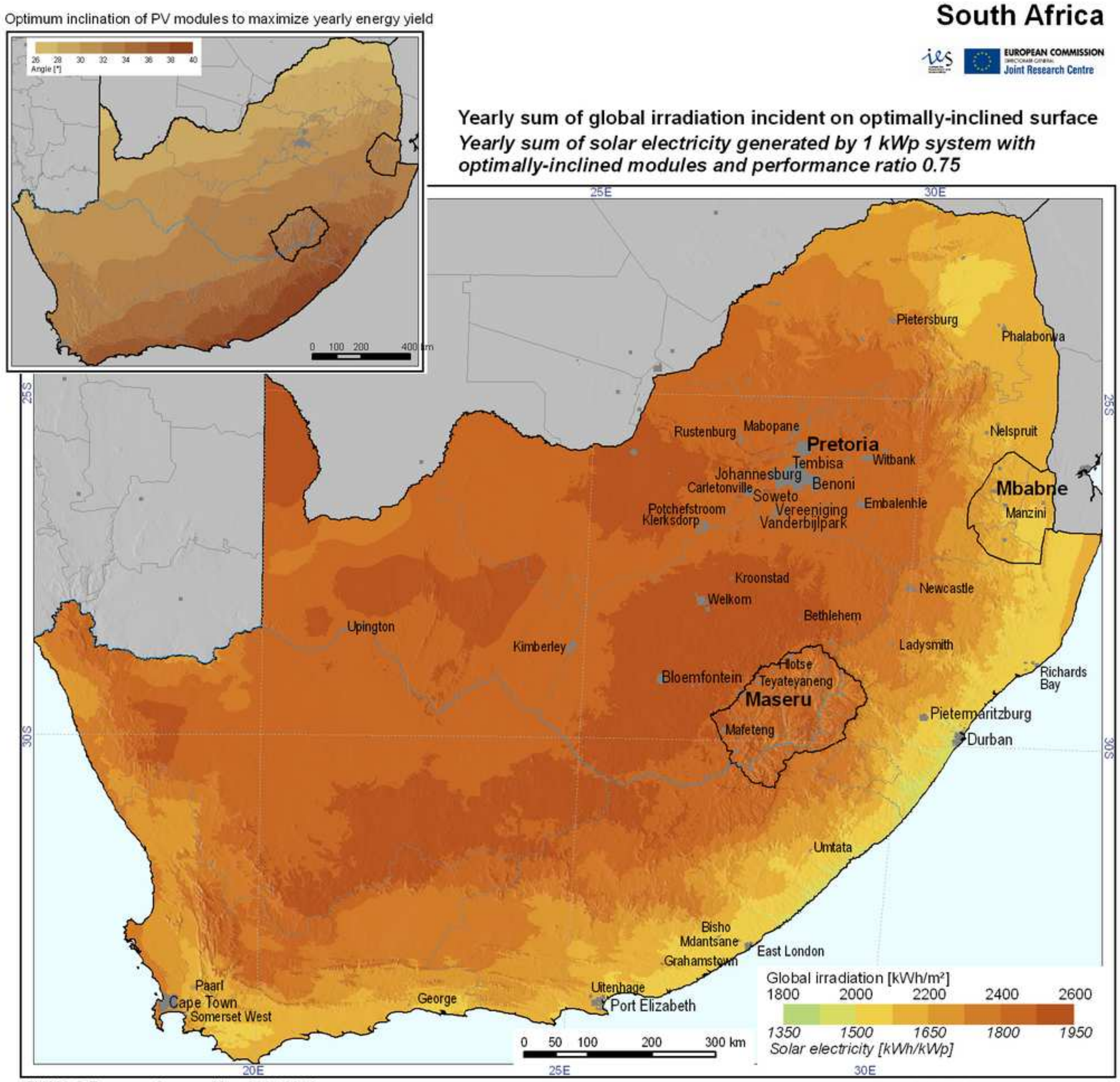
The average sunlight hours of Johannesburg is 8.67 hours per day and the average sunlight hours of Durban is 6.58 hours giving the Township approximately an average of 7.63 hours of sunlight per day, which makes it a great location to utilize the sun as an energy source. With that said, it is important to know how much energy from the sun will actually be supplied to Pomolong. To do this, a little bit of knowledge of irradiance and how it affects solar panels is needed.

Why do solar panels perform better in the middle of the day versus morning or evening? It was discussed earlier that solar panels actually decrease in efficiency as the temperature goes up, so it is known that the increase in performance is not due to an increase in temperature. In actuality, the intensity of solar radiation or irradiance is the main reason which explains why solar panels perform better in the middle of the day versus in the morning or in the evening. Solar radiation is the electromagnetic radiation emitted from the sun. Insolation is the amount of solar radiation received on a particular surface area over a period of time measured in power per surface area. To put it in perspective, the amount of insolation from the Sun on Earth's surface averages at 1368 W/m$_2$. The figure below shows the irradiation levels of South Africa.

Figure 5 Irradiation Levels of South Africa



Optimum inclination of PV modules to maximize yearly energy yield

South Africa

Yearly sum of global irradiation incident on optimally-inclined surface

Yearly sum of solar electricity generated by 1 kWp system with optimally-inclined modules and performance ratio 0.75

PVGIS © European Communities, 2001-2006
HelioClim-1 © Ecole des Mines de Paris/ARMINES, 2001-2006

http://re.jrc.ec.europa.eu/pvgis/
http://www.helioclim.org/

Since insolation affects performance it is important to find out how to mitigate low insolence and to find out how to increase insolence. Although the Pomolong Township is relatively sunny, they do not have a high level of irradiance. There are a few methods that can be made to increase solar panel performance to make up for the low levels of solar radiation. There are direct methods and indirect methods.

Direct methods are like solar tracking, which involves having sensors on solar panels and motors that point the solar panel in the direction of the highest intensity of sunlight. Solar tracking optimizes the amount of sunlight that makes contact with the solar panel by making sure that the panel is always facing the sun. Another direct method to increases solar radiation is by using light concentration. Light concentration is when mirrors or lenses are used to intensify the sunlight on the solar panel.

Indirect methods to increase solar panel performance include using a Maximum Power Point Tracking system, also known as MPPT. This system maximizes delivery of electricity by managing the charge of a battery bank in relation to the solar panels. MPPT systems are charge controllers that use an MPPT chip to optimize the output voltage of the photovoltaic panels to match the voltage levels of the batteries. To do this, the MPPT charge controller constantly maintains the power of the solar panel as it monitors the voltage level of the batteries. As the voltage level of the battery increases, the charge controller decreases the amount of photovoltaic panel output voltage while increasing the photovoltaic output current. This setup ensures that the photovoltaic's power level remains relatively constant without causing possible problems with the batteries.

3.1.2 Charge Controllers

A charge controller circuit was required in between the PV panels and the battery bank to perform crucial protection functions, as well as implementing the maximum power point tracking (MPPT) algorithm in order to extract as much energy as possible out of the PV panels. Several approaches exist, varying from a purely analog topology to using micro-controllers, Arduino, and specialized integrated circuits.

3.1.2.1 – 555 Timer

One of the simplest charge controllers considered during research was based on the ubiquitous 555 timer. This controller used the 555 timer IC to compare the battery voltage to a predefined level which was determined by a potentiometer. When the threshold was reached, a transistor would switch on a relay which in turn diverted the PV energy to a dummy load. One of the implementations which were looked at that utilized this chip also included switches for manual operation of the controller. One switch was for diverting the load to the dump resistors, and another switch for diverting it to the battery. Additionally, monitoring LEDs were included; one for indicating the controller is in dump mode, another for indicating the controller is in charging mode.

Some of the advantages of the 555 timer based charge controller are cost, availability, and simplicity. The 555 timer is one of the most mass produced and most popular integrated circuits in history. Thus, it is extremely cheap. One of these can be purchased for just a few cents just about anywhere on Earth. The simple design and high component availability would make this charge controller extremely reliable, easy to build, maintain, and repair. Not much electronics knowledge would be required to understand and repair this charge controller.

While the 555 timer itself is very highly available and would have made the charge controller cheap and easy to repair, the same cannot be said for the rest of the solar generator system. The PV panels are costly components and the pure sine wave inverter is a complex circuit. Thus, trying to optimize only one part of the system for low cost and high reliability is not practical. Furthermore, the 555 timer based circuit is just too simplistic. It does not have any sort of charge profile to maximize the battery life, circuit protection, logging and monitoring support, nor does it implement any maximum power point tracking algorithm for efficiency. With a lack of these essential features, the 555 timer based charge controller was not chosen for this project.

3.1.2.2 – Arduino PPT Solar Charger

The next charge controller implementation which was considered during research was built around the Arduino platform. The Arduino PPT Solar Charger is a small circuit board module which piggybacks on top of the Arduino board. It uses the Arduino's microcontroller to implement the maximum power point tracking algorithm, control the DC-DC converter, and provide optional logging and data output. In this sense, the charge controller is modularized.

This is the first implementation found during research which contains the required MPPT algorithm. Since the maximum power point is not fixed for any solar panel, the feedback loop for the DC-DC converter differs than that of converter found in a traditional power supply. While a DC-DC converter for power supply applications uses a fixed input/output voltage ratio, for a solar charge controller the ratio is constantly in flux due to the constantly changing maximum power point. Thus, MPPT controllers typically use software algorithms to control this. The Arduino PPT uses an iterative approach known as the Hill Climbing algorithm. The Hill Climbing algorithm works by first increasing the conversion ratio of the DC-DC converter, and measuring the wattage output by the panels. If the output is greater than the last measurement, then increase the conversion ratio again and measure again. Otherwise, if the output is less than the last measurement, then decrease the conversion ratio and loop again. This implementation loops through the algorithm at about 1Hz.

While it is slightly more complex than the 555 timer based controller and does provide the desired MPPT behavior, as well as support for monitoring and logging, the Arduino PPT solar charger was not chosen for use in this project because there is still little to no circuit protection, and the use of an Arduino was considered to be a cop out in the context of a computer engineering senior design project.

A micro-controller based IC approach is preferred, which makes it easier to provide digital real time charge information and data logging, as well as current and voltage monitoring for circuit protection. All of these features can be implemented with only a moderate increase in circuit complexity. Several integrated circuits exist with embedded micro-controllers which are specifically made for use in solar charging applications. Three of the chips considered were the Texas Instruments BQ24650 Synchronous Switch-Mode Battery Charge Controller, SM72442 Programmable MPPT controller also by Texas Instruments, and the NXP Semiconductor MPT612 Maximum Power Point Tracking IC.

3.1.2.3 – Texas Instruments BQ24650

The BQ24650 offers a highly integrated charge controller with MPPT capability by input voltage regulation, three phase charge profile, as well as charge status LED indicator outputs.

The MPPT algorithm is implemented slightly differently in this chip compared to the Arduino solution. In this setup, the input voltage is monitored in the feedback loop, not the input/output ratio. This is known as the Constant Voltage algorithm and is considered by Texas Instruments to be the simplest MPPT method. The BQ24650 automatically reduces charge current to maintain MPP behavior. If the solar panel cannot provide the power required to run the charge controller, then the input voltage begins to drop. If the sensed voltage drops below a certain threshold, the controller will reduce charge current to attempt to maintain the voltage. If the sensed voltage drops further, charging is disabled entirely.

While the BQ24650 has a lot of the features required for this project, specifically the MPPT algorithm and basic protection and monitoring, it was not chosen because of the lack of flexibility and documentation. It did not quite compare to the other two chips with regard to availability of reference designs, application and design notes, and software programmability.

3.1.2.4 – Texas Instruments SM72442

The SM72442 Programmable MPPT controller, also by Texas Instruments, was a close second in the charge controller decision process. Part of the SolarMagic group of components, the SM72442 features an integrated 8-channel, 12 bit A/D converter used to sense input and output voltages and currents for protection and monitoring, as well as a four PWM gate drive signals for a 4-switch buck-boost converter. Along with the SM72295 Photovoltaic Full Bridge Driver, this controller can operate with efficiencies up to 99.5%. The MPPT performance of the SM72442 is very fast. MPPT is achieved by varying the PWM duty cycle of the switching transistors to maximize energy transfer, and convergence to the MPP is achieved typically within 0.01. This enables the controller to maintain MPP behavior even under the most erratic and fast changing conditions.

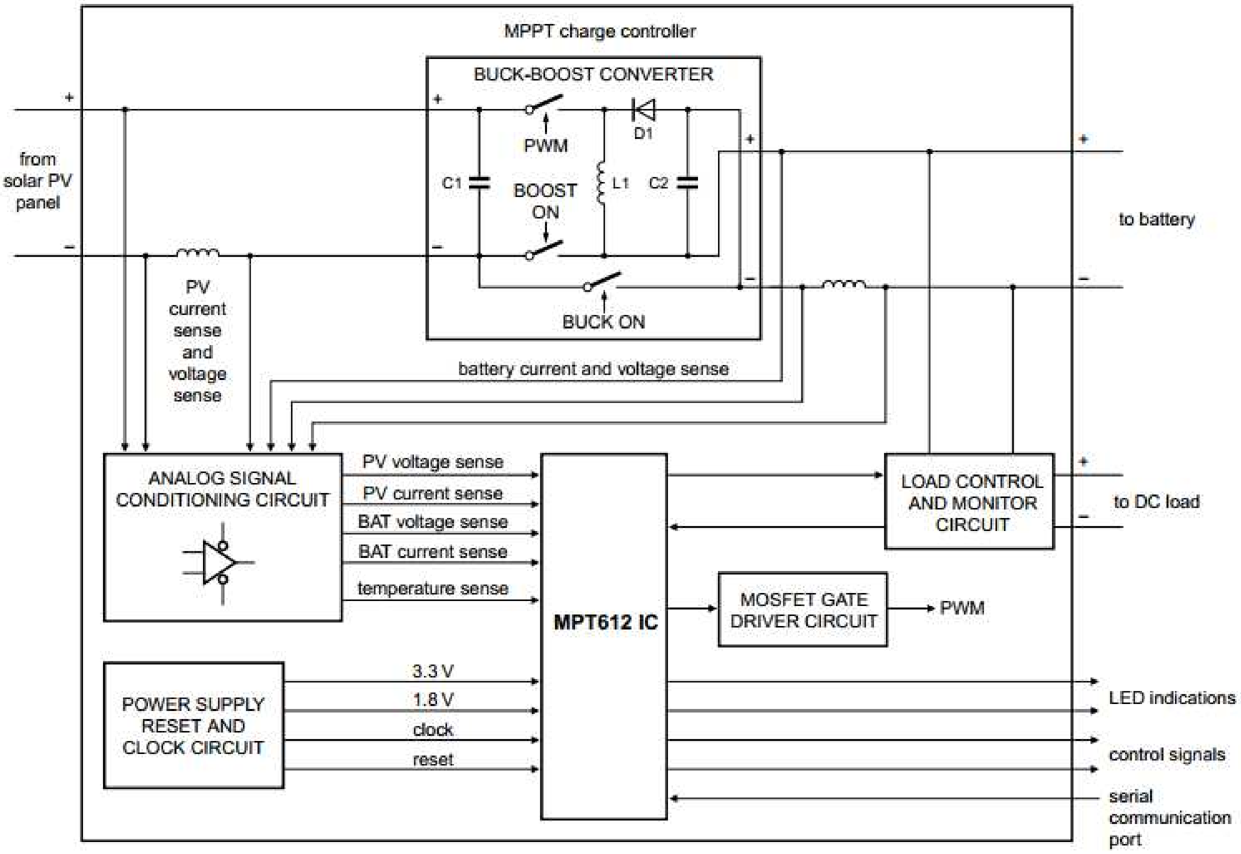
This chip does have the required MPPT behavior like the BQ24650 and also provides programmability. It was not chosen in favor of the MPT612 because of increased complexity using four PWM signals, a full bridge driver, and using it would have required the entire controller be redesigned using the SolarMagic family of components.

3.1.2.5 - NXP Semiconductor MPT612

Thus, the MPT612 from NXP was selected as the charge controller of choice. It not only includes all of the features of the BQ24650, is simpler than the SM72442, but an application note from NXP Semiconductor also provides detailed design information, equations, and parameters for a prototype development board. In other words, this charge controller was chosen because it is the “goldilocks” of all of the controllers researched.

The MPT612 has an embedded RISC processor with patented MPPT algorithm included. It also supports over voltage and over current protection, thermal protection, has programmable libraries for different charge profiles, alarm conditions, and vast documentation and flexibility for use in any environment and with any size panel and battery bank.

Figure 6 MPPT Charge Controller Reference System Block Diagram **[17]**
Permission Pending



The core of the charge controller is the buck-boost DC-DC converter which transfers energy from the PV panels to the battery in short pulses via a switching MOSFET which is controlled by the MPT612. The duty cycle of the MOSFET is varied by the MPT612 based on the demands of the MPPT algorithm. The other elements of the charge controller include the voltage and current sensors, a power supply and clock generator, gate driver, and serial/UART communications.

3.1.3 Batteries

For our project the batteries are required to store and smooth out the electricity from the renewable source. The five factors that will be considered while choosing the batteries are: (1) Cost, (2) performance, (3) safety, (4) size and (5) availability. The main purpose of this section is to give a general review of different kinds o batteries, and to highlight features

Table 9 Factors for Choosing Battery

Cost	**At most $125 can be allotted to one battery.**
Performance	The batteries are expected to be able to store the maximum of energy coming from the power source.
Safety	The batteries have to be safe for the people and the environment as well.
Size	Small or regular size batteries are preferred to facilitate transportation.
Availability	The batteries should be easy to find in South Africa.

3.1.3.1 Primary and Secondary Batteries

Batteries are categorized into two major types: primary and secondary. Primary batteries are disposable because they “irreversibly (within limits of practicality) transform chemical energy to electrical energy” [18]. Secondary batteries, on the other hand, are rechargeable in that “they can have their chemical reactions reversed by supplying electrical energy to the cell, restoring their original composition” [18].

Primary batteries have higher energy densities than secondary batteries and are usually utilized when recharging is not demanded. However, the solar system in the Pomolong Township project requires recharging, so secondary batteries type will be the focus of battery research.

There are a plethora of chemistries to choose from within primary and secondary batteries. The most prevailing chemistries used in batteries are lithium, lead, and nickel. Batteries are also rated according to the following attributes: capacity in ampere-hours (AH), voltage, specific energy and power, C-rate, and cold cranking amps (CCA). More details concerning such attributes will be addressed in the following sections.

3.1.3.2 Chemistries in Secondary Batteries

The most common chemistries used in secondary batteries are nickel cadmium (Ni-Cd), nickel-metal-hydride (NiMh), lithium-ion, and lead-acid.

Ni-Cd batteries utilize nickel oxide hydroxide and metallic cadmium as electrodes. They have many advantages when compared with other rechargeable batteries. Ni-Cd batteries are able to tolerate deep discharge for long periods; they also have a higher number of charge/discharge cycles. Size wise, they are smaller and lighter than comparable lead-acid batteries due to their much higher energy density. However, the disadvantages of Ni-Cd batteries are not negligible. Performance speaking, there is a significant negative correlation between the internal resistance and the cell temperature, which can result in considerable charging problems. Besides, Ni-Cd batteries also suffer from a "memory effect", which "causes them to gradually lose their maximum energy capacity if they are repeatedly recharged after being only partially discharged" because the batteries "appear to 'remember' the smaller capacity" [19]. Other than unsatisfactory performance, Ni-Cd batteries are more expensive than lead-acid batteries due to the higher cost of nickel and cadmium. Furthermore, the fact that Ni-Cd batteries contain between 6% and 18% cadmium, which is a toxic heavy metal, makes them an environmental hazard.

Ni-MH batteries are very similar to Ni-Cd batteries in that they both use nickel oxide hydroxide as positive electrodes; however, Ni-MH batteries use a hydrogen-absorbing alloy instead of cadmium. Therefore, they have many advantages of Ni-Cd batteries without endangering the environment or any higher forms of life. Besides, they are comparable to lithium-ion batteries in providing specific energy and power with a significant lower cost to produce. One of the most particular advantages of Ni-MH batteries is their performance for high current drain applications, where "over the duration of single charge use they outperform primary batteries [20]. However, one disadvantage of Ni-MH batteries makes it unsuitable for the Pomolong Township project: the high rate of self-discharge. Research shows that "Ni-MH batteries lose up to 20% of their charge on the first day and up to 4% per day of storage after that" [21], which would waste a considerable amount of energy that is painfully collected from the solar panels.

Lithium-ion batteries have a unique characteristic. Their ions move from the negative electrode to the positive electrode during discharge, and go back to the negative electrode when charging. As one of the most popular secondary batteries for portable electronics, lithium-ion batteries have "one of the best energy densities, no memory effect, and only a slow loss of charge when not in use" [22]. Size wise, they are much lighter than other secondary batteries and come with a wide variety of shapes and sizes. However, one disadvantage of Lithium-ion batteries disqualifies them to be a part of the power generation system: high cost. Lithium-ion batteries are more expensive than any other secondary battery type. Due to limited budget, lithium-ion batteries are not an option for the Pomolong Township project.

Lead-acid batteries, on the contrast, have the lowest cost and highest price-to-power ratio among the four secondary battery types. They are the oldest secondary battery technology, and they are the most widely available in the world. Performance speaking, lead-acid batteries have low internal resistance and can deliver very high currents. They are also tolerant to abuse and overcharging. In short, lead-acid batteries are currently the best option due to cost, availability, and functionality.

Thus for G7-SAP, the research focus is on the lead-acid batteries.

3.1.3.3 Cycles in Lead-acid Batteries

Lead-acid batteries are divided into three categories: starting, deep-cycle, and marine.

Starting lead-acid batteries are designed for starting automotive engines. Obviously, their most significant specialty is the ability to output a high current with almost no delay. In order to achieve this ability, starting lead-acid batteries have many thin plates designed to maximize surface area, which allows for maximum current output. However, they are also vulnerable to deep discharge and “repeated deep discharges will result in capacity loss and ultimately premature failure”.

Deep-cycle lead-acid batteries, on the other hand, have thicker plates. Although they do not output as high current as starting batteries do, they can endure frequent discharging and recharging without degradation.

Marine batteries have thicker plates than starting batteries, but thinner plates than deep cycle batteries. They are designed to serve as a compromise between the two lead-acid batteries above, and therefore have a current output and life time lying between starting batteries and deep-cycle batteries.

Since the goal of the Pomolong Township project is to construct a power generation system, high endurance in frequent discharging and recharging are more important than high current output. Therefore, deep-cycle lead-acid batteries are chosen for the design.

Batteries are also rated in amp-hours, which are usually abbreviated in the label by AH. An amp-hour is one amp for one hour. The generally accepted AH rating time for period of batteries used in solar power is the 20 hour rate, even though the 6 hour rate and 100 hour rate can also be used. The amp-hours should be specified at a particular rate because some vendors have chosen to rate their batteries at the 100 hour rate, which makes them look a lot better than they really are. For instance, see table below.

Table 10 Sample Battery Specs

Battery type	100 hour rate	20 hour rate	8 hour rate
Trojan T-105	250 AH	225 AH	n/a
Us battery 2200	n/a	225 AH	181 AH
Concorde pvx-6220	255 AH	221 AH	183 AH
Surrette s-460(L-16)	429 AH	344 AH	282 AH
Trojan L-16	400 AH	360 AH	n/a
Surrette cs-25-ps	974 AH	779 AH	639 AH

The internal resistance of a battery affects its performance. The higher the internal resistance, the higher the losses of energy will be while charging or discharging the battery. In other words, the batteries with a lower AH will discharge very fast while the one with the higher AH will discharge really slowly. That is why batteries with high amp-hour are served as an optimal choice for the Pomolong Township project. Decisions have been made that the batteries rated at 20 hour rate are chosen for the design of power generation system.

3.1.3.4 Types of Deep Cycle Batteries

There are three types of deep-cycle lead-acid batteries: flooded, gel, and absorbed glass mat (AGM). The comparison among the three battery types above in their advantages and disadvantages are listed below:

Table 11 Advantages and Disadvantages of GEL Batteries

Advantage	**Disadvantage**
Totally Maintenance-Free	Higher Initial Cost
Air Transportable	Heavier Weight
Spill Proof / Leak Proof	Water Cannot Be Replaced If Continually Overcharged
No Corrosion	Typically Cannot Be Used To Replace Flooded Or AGM Types Without Adjusting Or Replacing The Applications Existing Chargers.
Superior Deep Cycle Life	Automatic Temperature-Sensing, Voltage-Regulated Chargers Must Be Used And Charge Voltage Must Be Limited (14.2 To 14.5 Volts Maximum At 25°C/77°F
Installs Upright Or On Side	
Very Low To No Gassing Emission	
Compatible With Sensitive	
Electronic Equipment	
Superior Shelf Life	
No Recharge Current Limitation At 13.8 Volts	
Rugged And Vibration-Resistant	
Very Safe At Sea With No Chlorine Gas In Bilge	
Operates In Wet Environments Even Under 30 Feet Of Water	
Will Not Freeze To –20°F/-30°C	

Table 12 Advantages and Disadvantages of AGM Batteries

Advantage	**Disadvantage**
Totally Maintenance-Free	Shorter Cycle Life Than Gel In Very Deep Cycle Applications
Air Transportable	Automatic Temperature-Sensing, Voltage-Regulated Chargers Must Be Used
Spill Proof / Leak Proof	Water Cannot Be Replaced If Continually Overcharged
No Corrosion	Charge Voltage Must Be Limited (14.4 To 14.7 Volts Maximum At 25°C/77°F)
Installs Upright Or On Side	
Compatible With Sensitive Electronic Equipment	
Very Low To No Gassing Emission	
Excellent For Starting And Stationary Applications	
Work Well Under Extreme Cold Conditions	
Superior Shelf Life	
Fast Recharge Ability	
Rugged And Vibration-Resistant	
Very Safe At Sea With No Chlorine Gas In Bilge (Due To Sulfuric Acid And Salt Water Mixing)	
Operates In Wet Environments Even Under Water -Typically No Need To Replace Or Adjust The Applications Existing Chargers When Replacing The Batteries.	

Table 13 Advantages and Disadvantages of Flooded Batteries

Advantage	**Disadvantage**
Lowest Initial Cost.	Spill Able
Good For Higher Current Applications	Operates Upright Only
Water Can Be Added	Shorter Shelf Life
Excellent For Starting Applications	Fewer Shipping Options
More Tolerant Of Improper Recharge Voltages	Cannot Be Installed Near Sensitive Electronic Equipment
Certain Designs Are Good For Deep Cycle Applications	Watering Will Be Required
Replacements Readily Available	Requires Maintenance And Safety Practices
Work Well Even Under Extreme Hot Conditions	

Now that the advantages and the disadvantages of the deep-cycle lead-acid batteries are listed, a choice among flooded, gel-electrolyte, and absorbed glass mat (AGM) needs to be made.

Flooded batteries are the most inexpensive deep-cycled batteries and work well under extremely hot conditions. Performance speaking, they have a low amount of discharge rate due to their low internal resistance; they can keep the charge even after being placed in the storage for months without usage. Their low internal resistance also enables them to handle shock and vibration very well. Flooded batteries are very reliable and work well with all types of design. Their life expectancy is between 5 and 15 years, depending on the battery. For maintenance purpose, flooded batteries are required to be watered and ventilated in order to expel the gas that they produce.

Gel-electrolyte batteries are almost twice the price of the flooded battery. However, they are maintenance free and do not need watering. They also do not have the risk of leakage because they are sealed. Gel batteries works well under the extremely cold condition. Their life expectancy is 5 to 10 years depending on the manufacturers. Gel batteries use a recombination reaction to prevent the escape of hydrogen and oxygen gas that is normally lost in a flooded lead-acid battery. Gel batteries can also be operated at any position. However they have a short lifespan in hot climates because the water in the electrolyte evaporates; the water cannot be replaced since it is sealed.

The AGM batteries cost about the same price as the gel batteries. They are also maintenance free. The AGM batteries are sealed and have a low internal resistance. They have almost the same property as the Gel battery.

For the Pomolong Township Project, flooded batteries will be chosen for their low cost and favorability for the Climate in Pomolong Township.

The specific flooded battery chosen for the project is the Trojan T-105 Battery (shown below). Two will be used for the device. This battery is manufactured by Concorde and will be bought from www.wholesalesolar.com for $139. The battery is rated for nominal 12V and 225Ah capacity at a 20h (0.042C) charge rate. The battery can deliver about 40 CCA and can be deep-cycled 1000 times if never discharged lower than 50% capacity. For the project, when the battery bank reaches 50% depth of discharge (DOD), no power will be delivered to the load. This battery has the dimensions 7.71 x 5.18 x 8.05 cubic inches and weighs 30 lbs. This battery is also extremely resilient to shock and vibration forces. In addition, the Trojan T-105 can withstand very hot temperatures, which would ruin AGM and GEL lead-acid battery. The battery also features small self-discharge of 1 to 3% per month. This battery is a great battery for solar energy purposes for it provides a high capacity, long deep-cycle lifetime, and efficient energy storage.

The comparison among three types of deep-cycle batteries are summarized below according to the six factors: (1) Cost, (2) performance, (3) safety, (4) size, (5) availability, and (6) maintenance.

Table 14 Types of Deep Cycle Batteries

	Flooded	Gel	AGM
Cost	UB-GC2, 6V 225 AH is $139	UB-GC2, 6V 225 AH is $280	UB-GC2, 6V 225 AH is $265
Performance	88% charge/discharge efficiency	90% charge/discharge efficiency	98% charge/discharge efficiency
Safety	Hazardous	Hazardous	Non-hazardous
Size	6V, 12V,24V	6V,12V , 24V	6V , 12V , 24V
Availability	Easy to find Internationally	Hard to Find Internationally	Hard to Find Internationally
Maintenance	Add water	No Maintenance needed	No Maintenance needed

3.1.4 Inverter

The inverter will enable the system to deliver power stored in the batteries to the user efficiently and safely. This is the final part of the project and is the final major section of the system. The main function of the inverter is to convert direct current to alternating current, similarly found in a household power outlet. Inverters are not only used in off grid power systems but also inside electronic devices such as computers as small switching power supplies. There are many types of inverters, the following is a table of the different kind of inverters [18].

Table 15 Different Inverter Types

Inverter Type	Description
Square Wave	Square wave output arrived with the first inverters. They have a high distortion level and cannot power most AC loads.
Modified Sine Wave	Also called quasi square, these waves are similar to square waves. However, the output goes to zero for a time before switching. This is done to closer simulate a sine wave. Most AC loads will work with this signal, however, at a lower efficiency.
Multilevel	These inverters output an AC signal composed of many DC voltage levels inputs to create an even closer wave to a sine wave. The efficiency for powering AC loads is higher than a modified sine wave but not as efficient as a pure sine wave.
Pure Sine Wave	These inverters are the best in their field. They produce a nearly perfect sine wave with less than 3% distortion, which is the same as a supplied power company's AC signal. This comes at a higher cost due to its complex design. All AC loads will work with these inverters.

The table above are the main types of inverters, It is worth mentioning that there are other less used and/or known type of inverters such as resonant, grid-tied, synchronous, stand-alone, solar, solar micro, air conditioner, and CCFL inverters.

3.1.4.1 Inverter Applications

Inverters can be used in many applications, as stated before. Their main purpose is to convert a DC power source to an AC power source. This can then be used to power AC loads. However, with this in mind there are other applications in which inverters can be used which are summarized in the following table.

Table 16 Inverter Applications

Purpose	Description
Uninterruptible Power Supply	An uninterruptible power supply is a type of backup system which supplies AC power, when the main power source is not available.
Induction Heating	A low frequency AC power is converter to higher frequency AC power which heats an electrical conducting object, typically a metal.
Variable Frequency drives	Controls speed of an AC motor by controlling the AC source frequency and voltage
Electric Vehicle Drives	Motors used in electric vehicles use inverters. Also, they are used in regenerative braking technology which takes energy from heat to charge batteries. Also the gas engine charges the batteries.
Air Conditioning	Uses a variable frequency drive to control the speed of the motor and activation of compressor.

3.1.4.2 Basic and Advanced Inverter Circuit Design

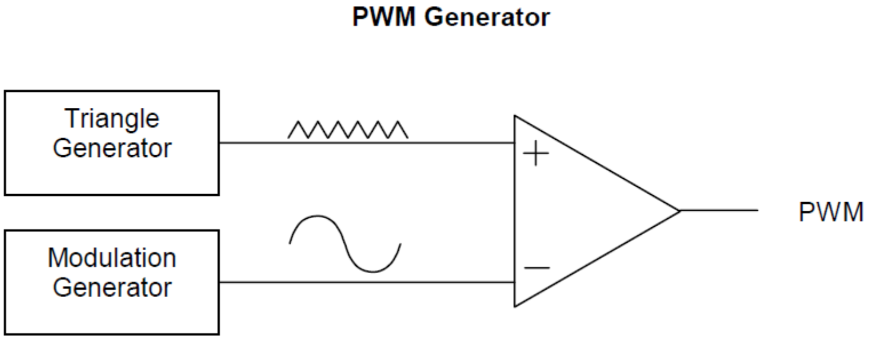
At the basic level an inverter circuit consists of a DC power source connected to a transformer. A transformer is a power converter that transfers AC power, so it is effectively an AC to AC converter. These are used widely for electronic appliances that work with 110V AC in a place where there is only 210V AC available. In order to prevent damage for the electronic appliance, a transformer must be used. So the transformer is switched rapidly back and forth to allow current to flow back and forth, thus creating AC in the circuit.

Back in the day, when inverters were first used, an electromechanical device had to be used to perform the switching. So this device consisted of two stationary contacts and a spring moving contact. The spring is used to hold one contact to a stationary one, then a electromagnetic force pulls it to the other stationary contact. Once it reaches the other contact the electromagnetic force is interrupted by the contact of the spring and the other stationary contact. Therefore, the contact of the spring is continuously moving back and forth between stationary contacts creating a switch. This form of electromechanical inverter switch is called a vibrator or buzzer. Of course, nowadays this method has been replaced by transistors and other semiconductor based electronics [19].

In more advance designing, there are many different circuit designs and control strategies. Depending on how the inverter is to be used, the different inverter designs differ. So to begin with, we specify the kind of waveform we want by filtering using capacitors and/or inductors. For example, low pass filters are applied to allow the important parts of the waveform but not allowing distortion to go through the signal. If one wants to keep a constant frequency in the signal a resonant filter can be used, the opposite can be done as well as long as the maximum frequency supported by the filter is higher than the waveforms frequency could ever be. Now, feedback is required around each semiconductor switch because a path is needed for loads that contain inductance. So when the switch is turned off there exists a path for the peak inductive load current. The feedback can be implemented through rectifiers or anti-parallel diodes.

Now, to create the AC signal output from the Pulse Width Modulation(PWM) technique is used. As mentioned before, to create the signal a switch that turns on and off fast is used. To expand on that, all the electric components of the inverter are turned on and off to generate proper RMS voltage levels. Today, a microcontroller is used to control this switching as oppose to using a magnetic field tied to a spring that was historically used. The following is a picture of PWM generator.

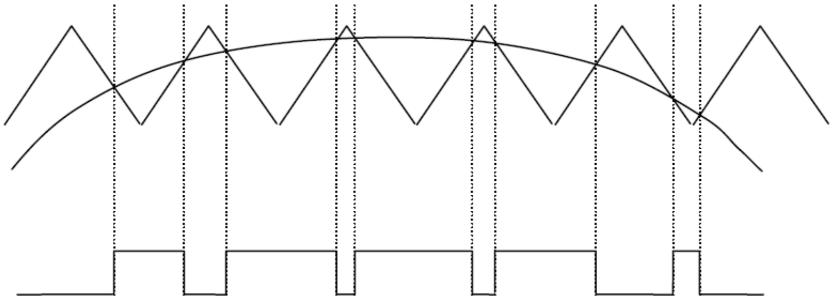
Figure 7 Simple Diagram of PWM Generator
Permission Pending



So a triangle wave generator and a modulation sine wave generator go into an Op-amp to produce PWM from the diagram above. The triangle generator is called the carrier signal and it controls the frequency of the switching. The modulation generator produces the signal that determines the width of each pulse hence the RMS voltage level of the signal. Next, the output of the PWM Generator will be seen.

Figure 8 Output of PWM Generator(6)
Permission Pending

Output of PWM Generator



Now, in the figure above, the carrier signal can be seen with the modulation signal on top of it. The bottom signal is the actual PWM signal. If observed closely, it can be seen that the bottom signal is constructed by the modulation signal setting the width of the pulses in the PWM signal. all of this happens while the carrier controls if those pulses are on or off. Due to the microcontroller mechanism, the inverters that use the PWM scheme have varying levels of control. There are four basic types of control for AC drives. They are shown in the following table [20].

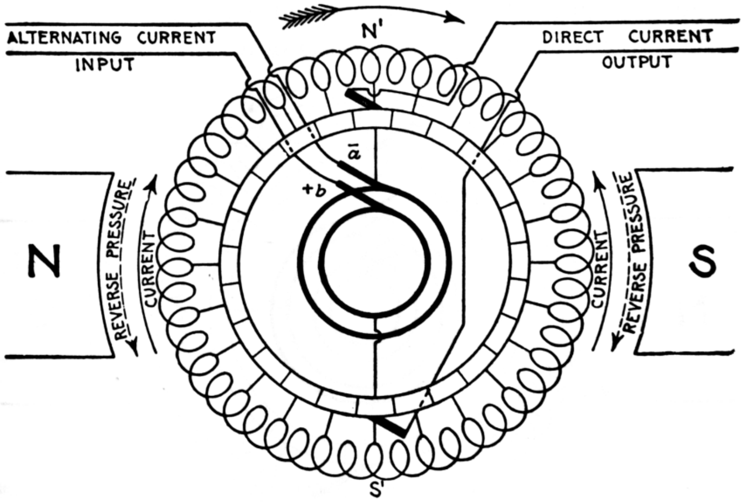
Table 17 Types of Control for AC Driven Loads

Type of Control	Description
V/Hz	Basic control method which provides variable frequencies, thus providing control over speed and power.
Sensorless Vector	Improves control of speed and starting power.
Flux Vector	Gives more precise control of speed and power control with dynamic response
Field Oriented	Provides the best overall control over AC motors giving DC performance

3.1.4.3 History of Inverter

Inverters have been used since the late 1800s. However, in their inception, they were not called inverters. These inverters were actually motor generators or similar machines which would convert DC to AC power. It was not until the 1950s where the that the modern day inverter was invented. The following is a figure of a rotary converter machine which was used as a rectifier in the 1800s [19].

Table 18 Rotary Converter **[21]**
Public Domain Image, Copyright expired



Electromechanical inverters were originally not made to convert DC power to AC power. They were actually intended to perform the opposite function. They used induction from synchronous AC motors directly connected to a generator. Inside the generator, a commutator would reverse its connections at the right moments to produce DC power. A commutator is a rotary electrical switch in certain types of electrical motors or generators. After a few years a synchronous converter was introduced which does what a rectifier does today. To put it simply, it converted AC power to DC power. This brought both the motor and generator into one section with motor slip rings in one end and the commutator at the other. Now, given the right control equipment an eletromechanical rectifier can run backwards to convert DC to AC , thus , making an inverter [19].

Next, transistors that are common today were not available back in the 1950's. Back then they only worked with low voltage and current. However, with the introduction of silicon controlled rectifiers, the production of inverters commonly known today began. Rectifiers do not turn off when the gate control signal is off, they only turn off when the current being passed is below the minimum holding current. Different kinds of rectifiers have different minimum holding current levels. So for rectifiers connected to an AC power source, rectifiers turn off every time the source voltage reverses. However, for rectifiers connected to DC power, the current would have to be forced to be below the minimum holding current in order to shut off the rectifier. So, we see that an AC source is a more natural way to work with the rectifier than a DC source [19].

Rectifiers are often classified by the number of current pulses that come from the DC source to the output AC. There are one pulse, two pulse, three pulse, and six pulse circuit rectifiers. To calculate the pulse, the phase of the rectifier and its wave output needs to be checked. There are half wave and full wave rectifiers. Half wave rectifiers have a one pulse and full wave rectifiers have two pulses. To get the number of pulses in a circuit, the phase number must be multiplied by the number of pulses in the rectifier. Depending on the phase of the rectifier and the desired output, a higher voltage or current can be obtained by connecting rectifiers in series or parallel. Although inverters can work backwards as rectifiers, inverters are also classified by pulses. The higher the pulse number in a rectifier system, the less the harmonic content in an AC input while outputting reduced distortion to the DC output voltage. In the inverter mode, a higher pulse number gives lower distortion to the AC output waveform [19].

In order to create an inverter a DC source is needed. This means that circuits that would force a rectifier to shut off would have to be implemented in the inverter design. This is not a problem. High quality transistors that can be turned off by control signals can solve this problem. A separate controlling circuit is not needed to force a shut off. In all inverter designs today, transistors are the way to go.

3.1.4.4 Characteristics of an Inverter

Important characteristics of an inverter to pay attention to when purchasing or constructing one fall into four categories. These categories are input voltage, surge power, the wave output of the inverter, and load that needs the power in the form of a sine wave.

The first is to take note of the input voltage of the inverter. It is important to match the power source voltage to the operating voltage of the inverter. If the voltages do not match, it could be hazardous. This is because the inverter is in danger of catching on fire due to overvoltage.

Next, is the peak or surge power. The surge power is the initial power to first start up an electronic device. For example, when turning on a television or a washing machine the lights may begin to dim. This event is an example of a surge power to the television or washing machine affecting the lights. When a high power consumption machine turns on the effect of surge power is more evident. It is important to note the surge power rating of an inverter to tell if it will deliver enough initial power for a device.

Third, the wave output of the inverter is a very important characteristic. There are two distinct kinds of output waves. The output wave could be a sine wave or a square wave. The output coming from a standard power outlet is a pure sine wave. With that said, it is obvious that having an inverter output a sine wave is the most desirable wave output. However, due to requiring more electronic components and having a more complicated design, pure sine wave inverters cost more than square wave inverters. Square wave inverters are much simpler because they simply vary by three different voltage levels. Some electronic devices will work with square wave input. Unfortunately, most electronic devices are only sensitive to the signal produced by an AC wave. These electronic devices typically receive or transmit signals themselves. examples include TVs and projectors. The trouble occurs in the form of distortion in the video image. To clean up a square wave as stated before, a variety and a vast amount of electronic components such as filters, inductors, and capacitors are needed. Commercially, all kinds of inverters are sold. Usually the square wave inverters are really cheap and the pure sine wave ones are very expensive. For the purpose of the project, the option to design and build an inverter that produces a pure sine wave was chosen.

The last part of an inverter's characteristic that should be taken into account is what needs to be powered with the output of the inverter. This is not really a characteristic of the inverter itself per se, but is a major consideration when designing an inverter. For the purpose of the project, the inverter should not have to output more than 700W of power at any given point in time. This means that the maximum power coming out of the inverter should exceed the combined power consumption of the electronic devices being used. Another way to look at it, is that the total load should not be greater than 700W.

3.1.4.5 Commercial Inverters

As stated before there are many power inverters out there in the market today. They range with wide varieties of characteristics, prices, and sizes. The most well-known brand for power inverters is Power Bright. A close second would be the Cobra power inverters. For the purpose of this section, three of both brands of power inverters with similar characteristics are compared in the following table.

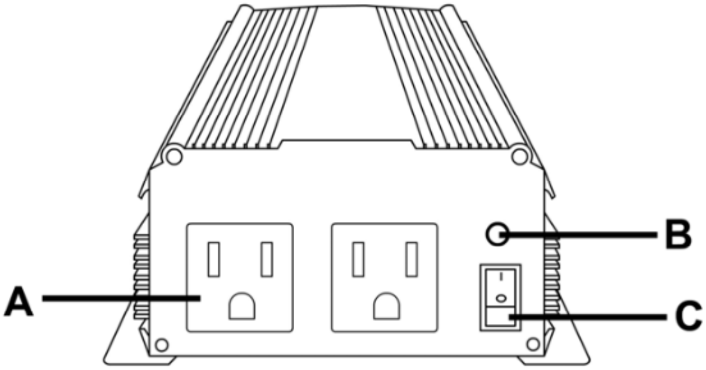
Table 19 Commercial Power Inverters Comparison **[22]**

	Power Bright Power Inverter	**Cobra Power Inverter**
Continuous Power	900W	800W
Input	12V DC	12V DC
Output	110V AC	110V AC
Peak Power	1800W	1600W
Number of Outlets	2	2
Price	$58.00	$80.00
Continuous Power	1100W	1000W
Input	12V DC	12V DC
Output	110V AC	110V AC
Peak Power	2200W	2000W
Number of Outlets	2	2
Price	$90.00	$120.00
Continuous Power	900W	1500W
Input	12V DC	12V DC
Output	220V AC	220V AC
Peak Power	1800W	3000W
Number of Outlets	1	3
Price	$84.00	$135.00

To conclude, it can be seen that the input seems to be pretty standard throughout commercial inverters. Also, since the group is located in North America, the output seems to be 110V AC standard. However, some brands offer European standard power which is 210-220V AC. Another thing to note is that the Peak Power is usually two times as much as the Continuous Power. As for price, the power inverters above seem to range from $50 to $150. However, it is very crucial to remember that all of the power inverters above are square wave power inverters. Pure sine wave power inverters cost about four times as much as these inverters.

Next, the controls for most Power Bright power inverters will be looked at.

Figure 9 General Power Bright Inverter
Permission Pending



A. Two standard North American AC outlets, each rated at 15 Amps

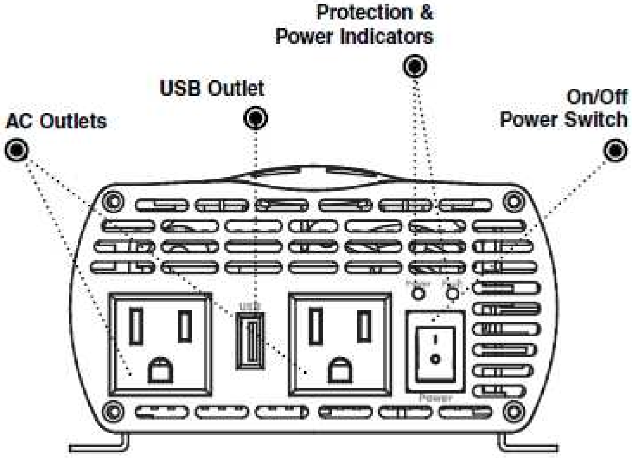
B. Overload LED Indicator. If continuous power draw of appliance(s) exceeds the inverters continuous power, this light will turn ORANGE/RED and the inverter will automatically shut down. When this occurs, turn off the inverter and determine the cause of the overload before turning the inverter and the appliance back on.

C. ON/OFF Switch. Turns the inverter circuits ON and OFF.

As seen, the Power Bright power inverters are pretty simple and easy to use. There is a switch to turn the inverter on and off and two North American power outlets. Also take note of the fins of the enclosure to keep the power inverter cool and the LED indicator if the appliance power consumption being powered exceeds the output power of the inverter.

Next, the controls of a general Cobra power inverter will be looked at.

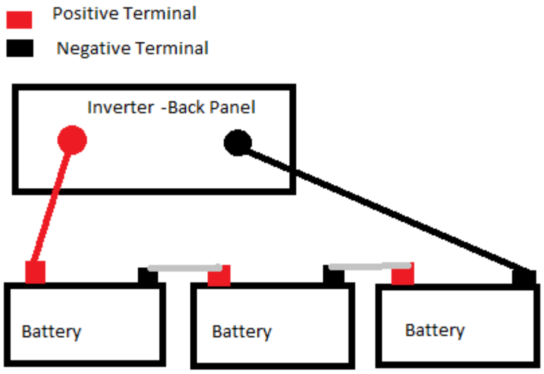
Figure 10 Cobra Power Inverter
Patent Pending



For the most part the Power Bright power inverters and the Cobra power inverters are pretty much the same. However, most of the Cobra power inverters have a USB outlet to power small devices like iPods, cell phones, and other such things.

The following is a picture of how a battery bank, wired in series in the figure, is typically attached to a power inverter.

Figure 11 Battery Bank Connected to Power Inverter



3.1.5 Encasing

Good battery enclosure design and construction will protect the people of the Pomolong township from potential battery mishaps, and can enhance the effectiveness of the battery bank as well. Battery enclosures serve four main functions:

1. Provide physical protection to the batteries from tools, falls, dust, debris, etc.
2. Isolate and safely vent hydrogen gas to the outdoors.
3. Maintain a consistent temperature among the cells.
4. Meet the requirements of the *National Electrical Code*, Articles 480 and 690 (Section 690.71)

The Batteries store electrical energy using a chemical reaction, and can cause acid burn, electrical burns, or be an explosive hazard. These dangers can be prevented if they are properly handled or contained. When it comes to housing the batteries, the goal should be to provide a clean, dry, ventilated, semi conditioned space that prevents unqualified people from coming into contact with the battery bank.

3.1.6 Sensors

Sensors are a very important part of this project. Without sensors, the charge controller would not be able determine voltage levels of the battery, making an entire system pointless. Sensors give data on the status of the system, and without them, vital information about the system would not be known. This would be a problem, because without knowing vital information of the system, identifying when the system is malfunctioning would be almost impossible.

3.1.6.1 Voltage / Current Sensors

Part of the design for the project will be to be monitor the amount of voltage and current that is being outputted by the solar panel. This information will be sent to the microcontroller and displayed on the monitoring system.

The voltage of the solar panel can range from around 0 to 33 volts. This voltage range must match the maximum input voltage range of the microprocessor chip which is between zero and five volts. To measure the voltage coming from the panels, a sensor is not needed, but a voltage sensing circuit will be implemented.

By connecting a voltage divider in parallel with the solar panel the maximum output from the solar panel can be dropped to match the maximum voltage of the microprocessor. The following equation:

Equation 1

$$V_{out} = V_{in}\left(\frac{R_2}{R_1 + R_2}\right)$$

Where V_{out} is the maximum voltage of the microprocessor, and V_{in} is the maximum voltage of the solar panel, the values of R_1 and R_2 can be found.
A Zener diode can be connected in parallel with the microcontroller which would help regulate the voltage such that it does not exceed the microcontrollers threshold voltage level. A spike in voltage can damage the microcontroller. A voltage spike due to overcurrent may be caused by lightning strikes, electrostatic discharge or solar panels operating above the maximum voltage range. Most microcontrollers work in a range from 0V to 5V. This is why a Zener diodes are chosen to regulate the incoming voltage into the microcontroller to be no more than 5 V.

The data which will be sent from the voltage divider circuit will be sent to the microcontroller. Before this is done, Operational Amplifier will be used. The use of Op-Amps will be important to the design because they help ensure that the data being sent to the microcontroller will be accurate by decreasing the noise. When traveling long distances in cable, voltage signals tend to develop noise. This unnecessary noise can affect the data being outputted. This can lead to misleading results which is why the use of Op-Amps in this circuit are very important. There are many kinds of Operational Amplifiers, but Unity Gain Op-Amps have characteristics which fit the design requirements for this project and is a favorable design consideration. This type of Op-Amp is useful because the overall gain of the circuit will be in unity. It is important to minimize external influences to the output. The reason for this is that added gain to the output will generate incorrect values and extra circuitry would be needed to step the voltage down before the signal can be received by the microcontroller.

A current sensor will be utilized to monitor the DC current which is being outputted from the solar panels. Sensitivity for the panels is more important than for the batteries, so more precise measuring methods are used for the panel side. For the batteries, an Op-amp based system will be used, and for the PV panel side, a current shunt monitor will be used.

There are several different technologies which can serve the purpose of a current sensor. The ones available are surface mount Hall effect sensors, Hall effect current clamp sensors, the Hall effect open loop current sensor, the Hall Effect current sensor, and the Inductive current sensor. For DC currents, measurements are made using the "Hall Effect" while for AC currents, measurements are made using "Inductive" technology.

3.1.6.2 Temperature Sensors

Temperature is a very important consideration. This is because temperature affects the efficiency in both the batteries and the solar panels. To circumvent this, methods have been made to keep these components at idea temperature. The problem is that you can't moderate temperature without knowledge of the temperature. The logical conclusion is that it would be beneficial to know the temperature. To gain knowledge of the temperature, the addition of a temperature sensor is needed. To implement a temperature sensor, the sensor will need to have direct physical contact with the components that need it most. Namely, the batteries and the solar panels. The optimal sensor would be reliable, inexpensive and easy to replace. To choose one, research has been done on a few sensors that might be used in the design of he South Africa Project.

The first method that can be used to measure temperature is with the thermocouple. This temperature sensor is a junction of two different metals. When the temperature is different between them, there will be a potential difference between the two metals. One of the two metals is treated as a reference temperature. The other metal is at the location where the temperature is to be measured. Thermocouples are cheap, tough and reliable over a wide temperature range. One thing to remember when using thermocouples is that it each of the metals are connected to copper wires to integrate them in a circuit or into instrumentation. This connection will create two extra junctions. These two junctions will have a voltage difference that is temperature dependent. With this in mind, it is important to make sure that the junction connections are at some standard temperature. If they are not, then errors in the readings may happen. The problem with thermocouples is that it is sometimes difficult to keep the circuit in a condition where the standard temperature can be kept. This is especially true if the circuit was in direct contact with solar panels that were getting direct sunlight for an extended period of time.

The second method that can be used to measure temperature is with a thermistor. Thermistors are temperature sensitive resistors made up of semiconductor material. They have a resistivity that is specially designed to sense temperature. Thermistors have special characteristics due to the properties used to make them. They also come in 2 types. Thermistors that have a Negative temperature coefficient have a resistance that decreases as the temperature increases. Thermistors that have a Positive temperature coefficient have a resistance that increases as the temperature increases [23]. Thermistors are cheap, user friendly and adaptable. They are comparable in sensitivity with thermocouples. The biggest drawback to using them are that they have a relatively long equation that becomes more complex as the temperature increases that could give the microprocessor possible errors. This problem makes them impractical for use in applications that need to measure higher temperatures.

3.1.6.3 Solar Radiation Sensors

In order for determine irradiation levels it is necessary to figure out a way to sense light from the sun. The common term for solar sensors are photodiodes. Photodiodes are P-N junction diodes that are designed to harness the photoelectric effect. The photodiode is a versatile solid state device that has many applications. Photodiodes are used as light detectors, power sources, and light emitters. Photodiodes have many uses, and a use for them has been described previously, because Solar cells are another kind of photodiode, with the specific application of using the current from the photoelectric as a power source.

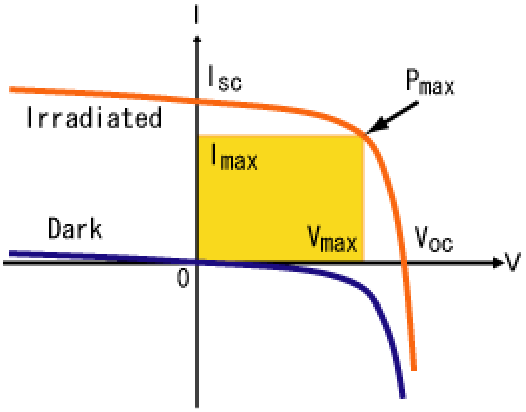
With that brief explanation of what a photodiode is and its general application, this section can now go into detail about another application for photodiodes. Other than being used for generating power, photodiodes are used to sense light intensity. The more intense the sunlight, the higher the current. This information is useful in research in solar tracking to optimize the direction in which the solar panels are angled towards the sun to maximize light exposure. This information can also be used to help determine what areas get the most sun.

3.2 Relevant Technologies

With the objectives and requirements of this project decided upon, it was necessary to spend some time researching other models and projects that implemented similar technologies to this project. Fortunately, there is a lot information about solar power generators available. There has been many different designs involving solar energy in UCF's senior design. Some have been more successful than others and other groups past experiences to make the design of the South Africa Project better. An example of this is Solar Tracking. This technology was considered to be incorporating into the system. Solar Tracking involves the movement of the solar panels mechanically by feedback from sensors [19]. The sensors detect where the sun is shining brightest and moves the panels accordingly. It was found that even though the design sounded good, it would not be beneficial in the system. The reason that it would not be beneficial is because the mechanical parts can wear out and stop functioning over time. Also, the gain of solar energy from the tracking is not worth the energy consumed to have the system run.

On the other hand, maximum power point tracking is a valuable technique that will be integrated to the project's charge controller. The benefits of MPPT will enable the charge controller to get the most of the solar panels while charging the batteries. To do this, the MPPT technique changes the voltage of the panels to keep at its maximum potential. For example, to charge a 12V battery approximately 13.5V would be needed to charge. However, most solar panels work at a higher voltage of about 20V and the Amps (current) stay the same. Since power is equal to current multiplied by voltage, it is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions [20]. In the figure below, the yellow rectangle gives the output power. The top right is the maximum power point, which is the target desired.

Figure 12 MPPT Graph **[26]**



Photovoltaic cells refer to the cells in material that generate energy from the transformation of electricity from sunlight. Photovoltaic cells have three attributes. The attributes are the absorption of light, the separation of charge carriers of opposite type, and the separate extraction of those carriers to an external circuit [21]. So what is happening is that the photons are absorbed, electrons are knocked out of the photons and separated creating a potential difference, then the electricity is captured and send through the output. The following is a chart which shows the semiconductor material of the solar cell, power conversion efficiency, and technology. As clearly seen, Crystalline cells are the most efficient, making them the most favorable choices for consideration in design.

Table 20 Solar Cell Type and Power Efficiency **[21]**

Semiconductor Material	Power Conversion Efficiency [%]	Technology
Mono-crystalline silicon	20-24	Crystalline
Poly-crystalline silicon	13-18	Thick and Thin-film
Gallium-arsenide	20-29	Crystalline
Amorphous silicon	8-13	Thin-film
Cadmium telluride	10-17	Thin-film
Cadmium indium selenide	10-19	Thin-film

Solar panel systems have different ways of being set up as well. Solar panel systems are either grid-tied, grid-tied with batteries, off-grid, or simply used as backup.

Grid-tied system are tied to the power grid that a residence gets its power from. They do not involve any batteries. The solar panels simply output whatever power they get to the residence they are supplying. This results in minimizing the power obtained from the grid.

A grid tied system with batteries is the same as the former except there are batteries, so power is stored. This method further minimizes the power that the residence being supplied obtains from the grid. Off grid systems are completely not connected to the areas power grid. They are completely standalone residences with no connection to the power grid. These systems almost always use batteries for power storage. Backup solar systems are used when there is a power outage in a grid-supplied area. When this occurs the backup system activates and provides power for the residence with power stored in the systems battery bank. In the case of the South Africa Project, the township of Pomolong is completely off the grid, therefore the system will be an off-grid system with batteries.

4.0 Project Hardware and Software Design

The purpose of this section is to describe the design process and selection process for the design of the South Africa power generation system. This section will discuss specifics regarding the main components of the project including the solar panels, the batteries, the charge controller, and the inverter. The specifics that will be discussed will be the parts and models that will be used in the design as well as the physical properties, assembly, and integration.

4.1 Solar Panels

Although there are many options for solar panel technologies, it is quite clear that the most reasonable choice for this project is the Mono-crystalline silicon photovoltaic panel. Poly-crystalline silicon panels less efficient and are not competitively cheaper than Mono-crystalline panels. The small savings in initial cost does not compensate for the savings in energy cost through the lifetime of the panel use. Thin-film modules were taken out for their lack of availability, questionable reliability, and inferior efficiency.

This project will not be using Polymer technology, because the technology has not been developed enough for a solid conclusion on whether it would be more beneficial to incorporate Polymer solar panels than to use tried and tested older technology. Other than the lack of resources and the fact that the technology is not fully developed, the entire purpose of this technology is to decrease production costs on a large scale to make widespread use of solar power feasible. The problem with this is that the resulting effect is that the cost dose not scale down well when used on a smaller scale like the South Africa project.

So, after all of this consideration, Grade A Solar Panels will be used. Grade A is another alias for Mono-crystalline silicon photovoltaic panels, and is a common term used in the industry.

4.1.1 Solar Panel Specifications

The main company considered in the solar panel market was Helios. The panel that has been chosen for use in this project is the Helios 7T2 305W Solar Panel Mono Cell. It has the second highest power output panel in the 7T2 mono-crystalline series [22]. Another advantage in choosing this specific panel is its price. Helios offers this panel in packages of 2 for 850.00. The specs of the panel are in the tables below.

.

Table 21 Solar Panel Characteristics

Dimension	1,984 mm x 984 mm (78.11” x 38.74”)
Area	1.95 m2 (20.99 Sq Ft)
Thickness	40 mm (1.58”)
Weight	26 kg (57.2 lbs)

Table 22 Electrical Data STC

Rated Power PMPP (W)	305
MPP Voltage (V)	36.70
MPP Current (A)	8.30
Open Circuit Voltage (V)	45.08
Short Circuit Current (A)	8.87

Table 23 Electrical Data NOCT

Rated Power PMPP (W)	229
MPP Voltage (V)	33.85
MPP Current (A)	6.75
Open Circuit Voltage (V)	41.60
Short Circuit Current (A)	7.20

4.2.2 Solar Panel Mounting

When mounting the solar panels, all measures to ensure safety should be made. It is also important to note that any damage incurred towards the glass of the solar panel is irreparable.

The location of mounting the solar panel is important. To choose a good location, the highest elevation with the least amount of possible shade is the best choice. In the Southern Hemispher, the sun is due north at noon. The following table gives the optimal angle of inclination for the solar panels to maximize sunlight throughout the year.

Table 24 Approximate Vertical Mounting Angle for Solar Panels in Harrismith, South Africa **[28]**

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
45°	53°	61°	69°	77°	84°	77°	69°	61°	53°	45°	38°

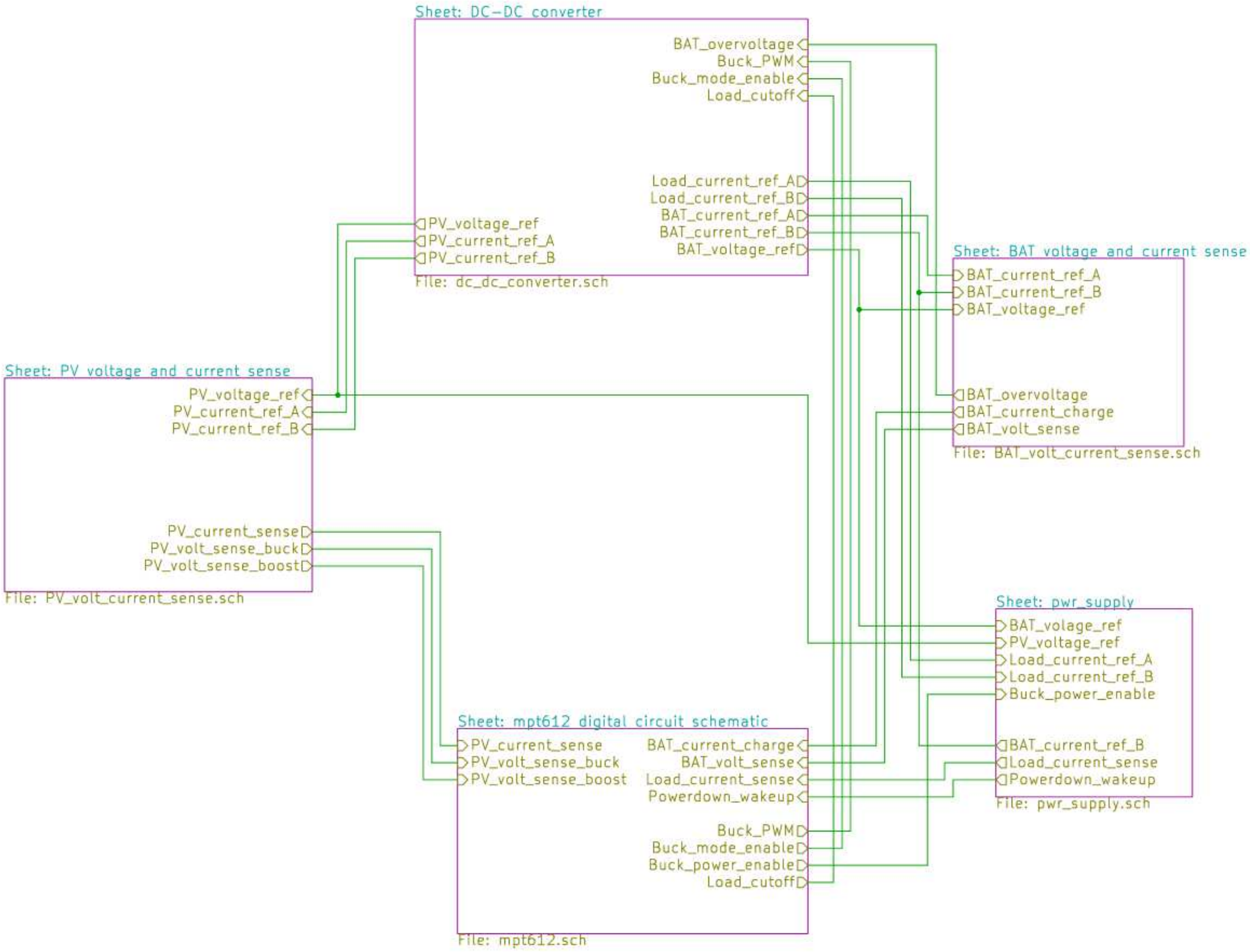
4.2 Charge Controller

This section details the charge controller circuit diagram and implementation. All diagrams were created using the KiCad EDA Software Suite. Circuits are based on Application Note AN10936 from NXP Semiconductors, which is a reference design manual for the MPT612 MPPT microcontroller used in the charge controller.

4.2.1. High level overview

The high level overview is KiCad's root sheet in its hierarchical sheet layout. It shows all of the modules in the system and the digital signals that interconnect them. These modules can be built separately and joined with ribbon cable, as it is easier to debug and prototype or they can all be built on a single board to optimize cost on the final product.

Figure 13 Charge Controller Root Sheet

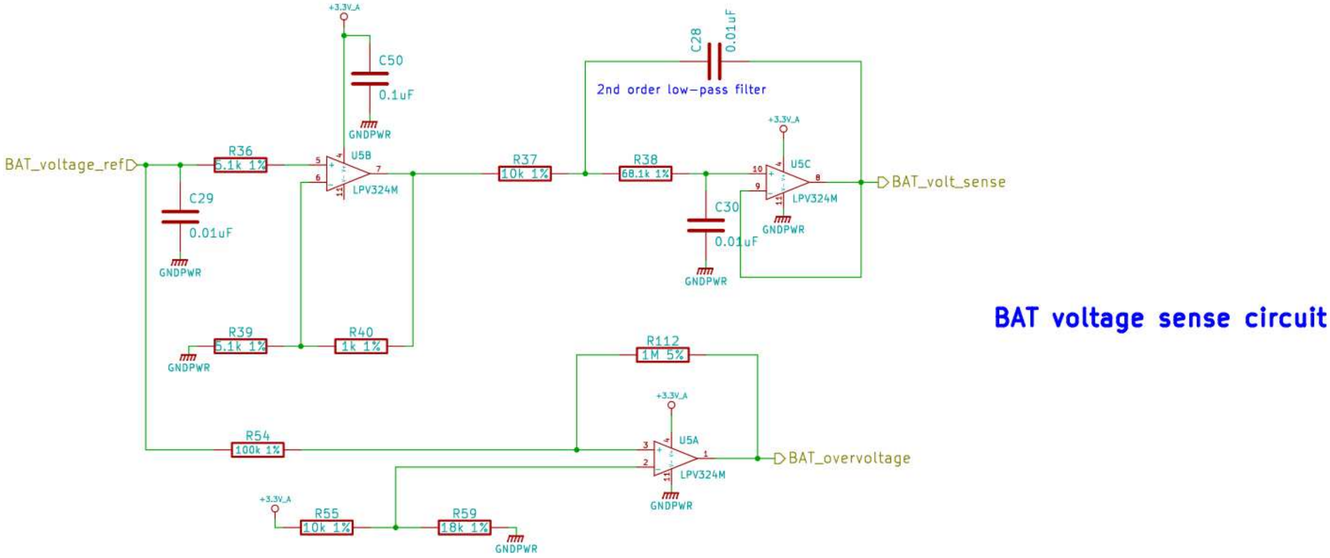


The charge controller is composed of five main modules: DC-DC converter, power supply, microcontroller, PV voltage/current sensors, battery voltage/current sensors, and an optional serial/UART module. Each of these modules is described in greater detail in the subsections below.

4.2.2. Battery Voltage and Current Sensors

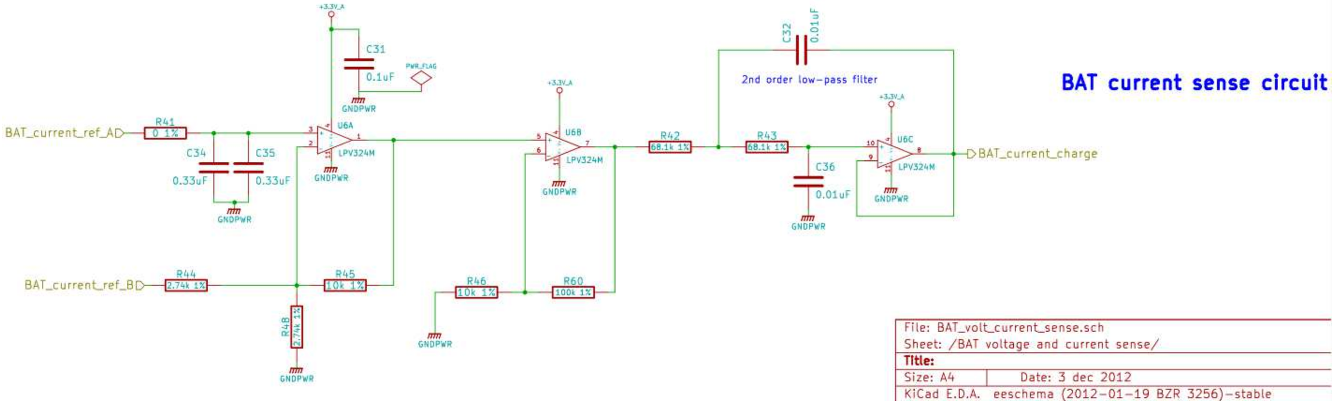
This module consists of two separate circuits, a voltage sensor and a current sensor for the battery bank. Both of these sensors take in an analog input signal from the DC-DC converter and output an amplified signal for input to the microcontroller. The operational amplifiers are used for both circuit protection and amplification purposes.

Figure 14 Battery Voltage Sense Circuit



For the battery voltage sense, the input signal comes from a voltage divider on the secondary side of the DC-DC converter. The signal enters on the left. U5A operates as a battery overvoltage indicator. If the overvoltage level is reached, PWM to the battery is cut off. Op-amps U5B and U5C comprise the main voltage sense circuit. U5B amplifies the signal with a gain of 1.1, and U5C is a low pass filter to remove noise from the signal.

Figure 15 Battery Current Sense Circuit

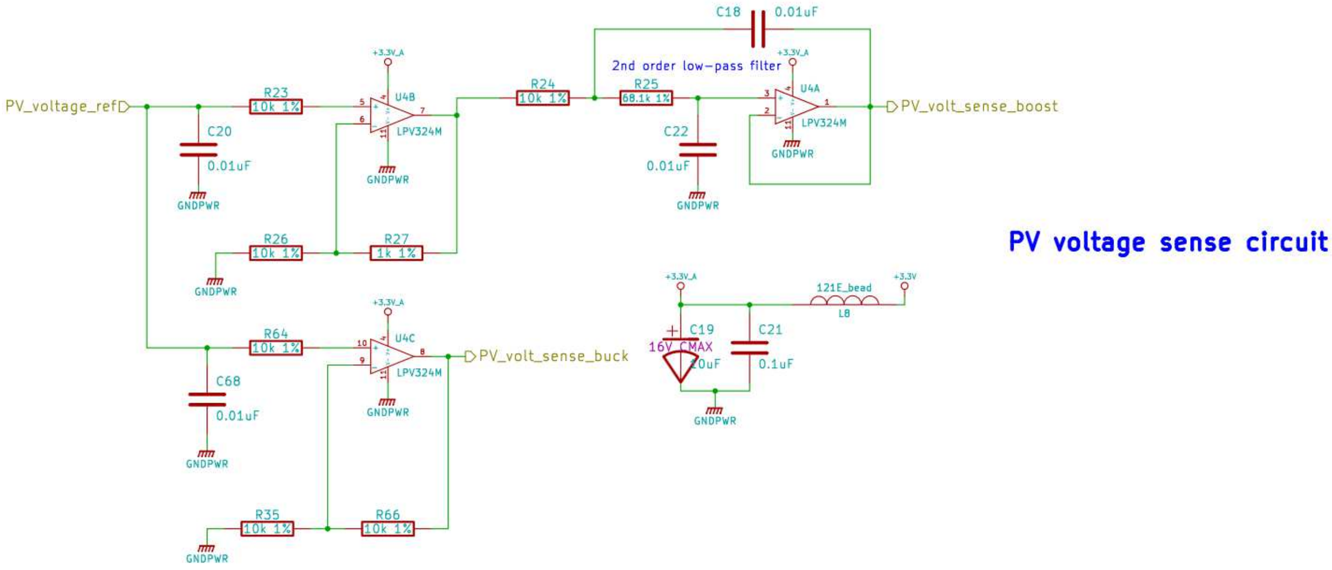


For the battery current sense, the input signals enter the circuit on the left. They come from a sense resistor located on the high current path of the secondary side of the DC-DC converter. Op-amps U6A and U6B comprise a two stage amplifier to enhance the signal. The first stage operates with a gain of 5, and the second stage has a gain of 10. Finally, Op-amp U6C is a low pass filter to remove noise from the signal.

4.2.3. PV Voltage and Current Sensors

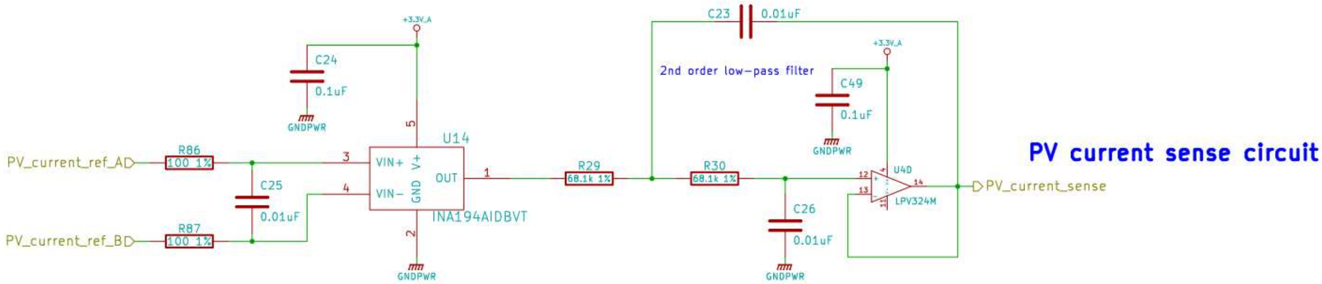
The PV sense module is similar to the battery sense module, in the context that it is also composed of two separate circuits: one for PV voltage sensing and the other for PV current sensing. Again, these modules take an analog signal from the DC-DC converter and using op-amps, output an enhanced signal for the microcontroller.

Figure 16 Solar Panel Voltage Sense Circuit



The PV voltage sensor is somewhat different in design than the battery voltage sensor because two separate sense circuits are used: buck mode and boost mode voltage sense. The signal enters on the left from a resistor divider in the secondary side of the DC-DC converter. Op-amps U4A and U4B and their associated components operate the boost mode voltage sensor with a gain of 1.1 Op-amp U4C operates the buck mode voltage sensor with a gain of 2. The RLC network to the right of the voltage sensors is a passive filter for the 3.3V_A analog voltage rail.

Figure 17 Solar Panel Current Sense Circuit



The current sensor is also constructed differently on for the PV side of the converter than the battery side. Accuracy is far more important when measuring PV current, since this parameter is needed for calculating the maximum power point. Therefore, a simple op-amp as was used in the battery current sensor is not sufficient. Instead, a Texas Instruments INA194AIDBVT current shunt monitor is used (U14 in diagram) to provide accurate measurement. The IC operates with a gain of 50. Op-amp U4D forms a low pass filter to remove noise from the signal.

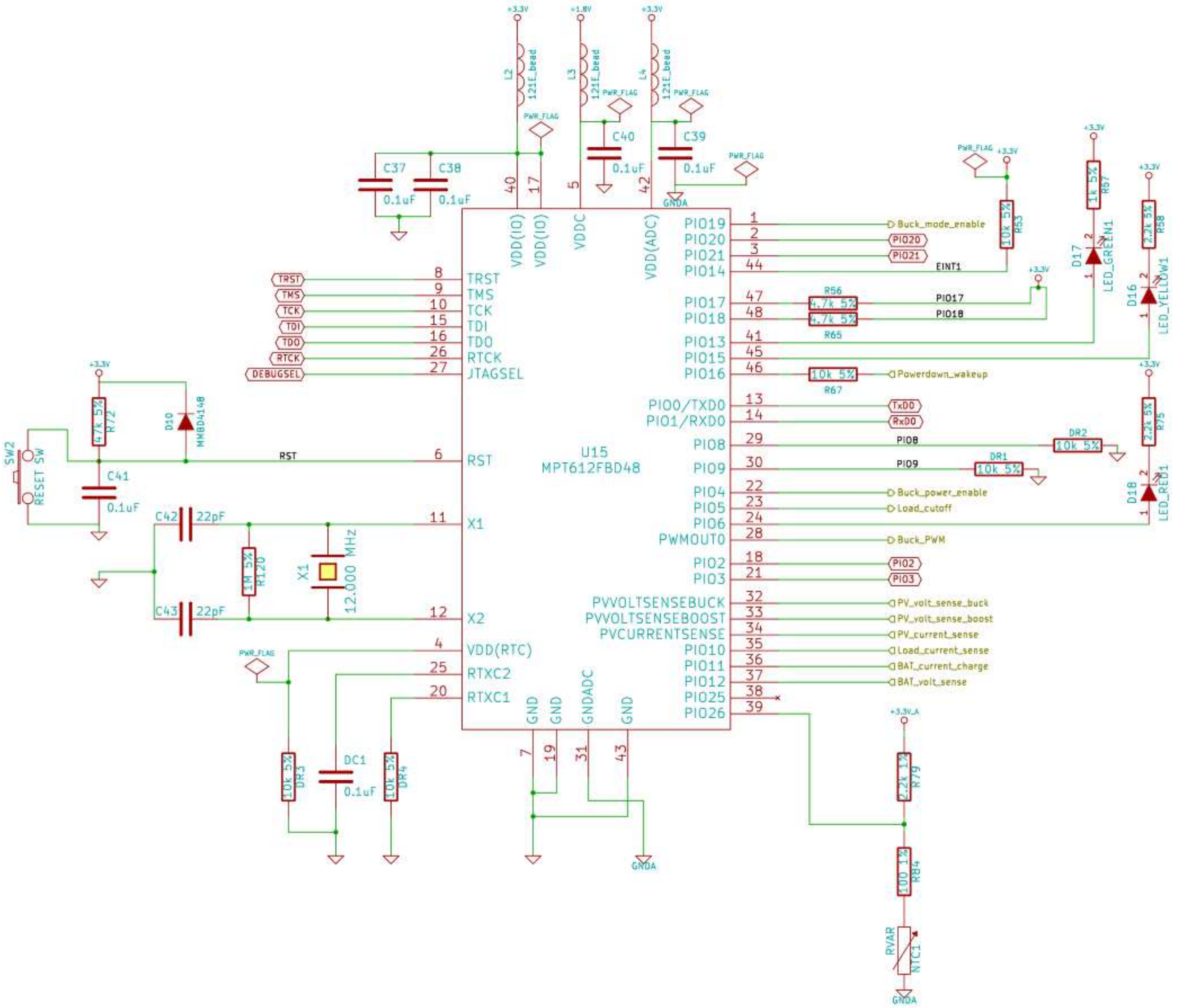
4.2.4. MPT612 Microcontroller

This subsection consists of the main logic and control portion of the charge controller, where the MPT612 controller IC is located. The IC handles the sensor inputs, temperature inputs, UART and JTAG communication, as well as outputting PWM gate drive signals to operate the DC-DC converter, and digital outputs for sending charge information to a logging or monitoring interface.

Figure 18 JTAG/UART Connector and GPIO Connector

The connector J6 on the left is the JTAG/UART connector. This connects to the serial communications module for reprogramming the MPT612. It takes a 3.3v power signal, and 11 communication lines for RS232. The connector J15 on the right is the General Purpose Input Output (GPIO) connector, which can be used for custom input and output signals.

Figure 19 MPT612



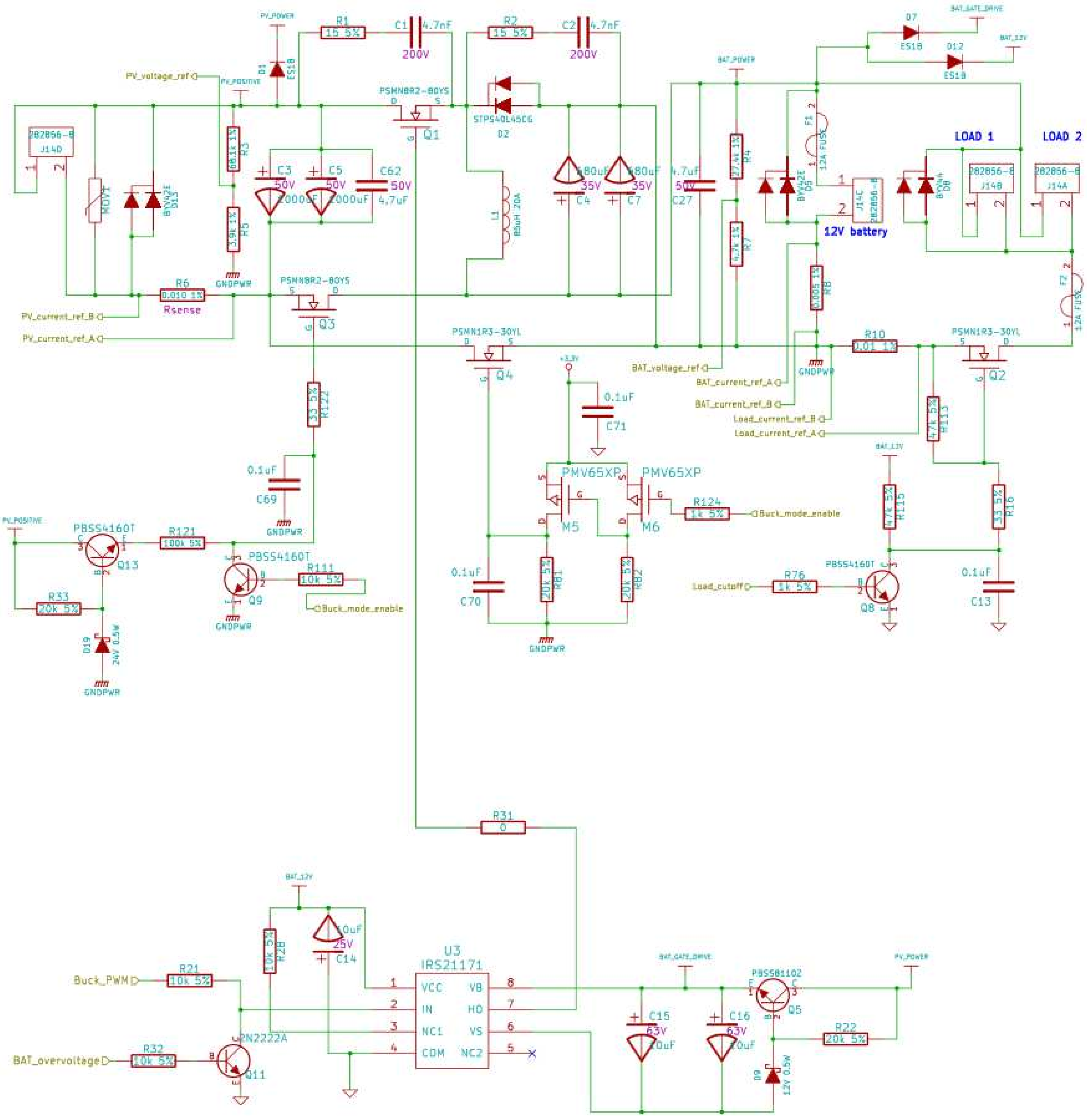
Starting from the top left of the MPT612 and moving clockwise, first there are the power supply rails, two 3.3V rails and one 1.8V rail. Pins 1, 2, 3, 44, 47, and 48 are for GPIO, power input, and buck/boost control. Pins 41 and 45 are digital outputs which connect to green and yellow LEDs to indicate charge status. Pins 46, 13, 14, 29, and 30 are for power control, serial communication, and ground. Finishing the right side of the diagram, pins 22 all the way down to 38 are all for sensor input, PWM output, GPIO, and buck/boost control. Pin 39 is for temperature input from the NTC which measures the ambient temperature. All of the pins along the bottom row are grounds. Pins from 20 to 11 form the oscillator and clock generator circuit, while pin 6 forms the reset circuit. Lastly, pins 27 up to 8 are for UART/JTAG communication.

Architecturally, the MPT612 features an ARM 32 bit processor and 32kB on-chip flash memory and 8kB static RAM. Pins that are not connected to a specific peripheral function are controlled by GPIO registers. They can be dynamically configured as inputs or outputs. The MPT612 also contains one 10-bit Analog-to-Digital Converter (ADC), capable of performing more than 400,000 samples per second. The chip also has two UARTs, two I2C bus controllers and two serial I/O controllers.

4.2.5. DC-DC Converter

The DC-DC converter is the muscle behind the charge controller. It is responsible for taking energy from the PV panels and via PWM pulsing it through the inductor which allows the energy to be converted to a different voltage and current in a theoretically lossless manner. The converter is using a buck-boost topology, and can operate in buck-boost mode or buck only mode. In buck only mode, the PV voltage must always be higher than the battery voltage. In buck-boost mode, both the PV voltage and battery voltage can be variable values with the system switching between buck and boost based on the relative voltages. The power electronics circuit is shown below.

Figure 20 DC-DC Converter



The main components in the DC-DC converter are MOSFETs Q1, Q2, Q3, and Q4, rectifier diode D2, and inductor L1. When the converter is operating in boost mode, MOSFET Q3 is closed and MOSFET Q4 is open. Similarly, when operating in buck mode, Q3 is open and Q4 is closed. Filter capacitors C4 and C7 are placed across the output to smoothen the signal. Bulk capacitors C3 and C5 are used to temporarily store energy while the main switching transistor Q1 is in the off state. Q1 is responsible for the pulse effect which excites the inductor. It is driven by a high side gate driver circuit U3 at the bottom of the figure. U3 is an International Rectifier IRS21171 single channel high side gate driver. It takes in the Buck_PWM signal from the microcontroller and outputs it to the gate of Q1.

The DC-DC converter also includes protection circuitry to reduce the risk of battery or PV panel damage. Diode D13 on the left protects the system if the PV panels are connected backwards. Similarly, diode D5 and fuse F1 on the right protects the system if the battery bank is connected backwards. MOSFET Q2 controls the load. If the load cutoff signal is sent high from the MPT612, Q2 will turn off and disconnect the load from the battery. Fuse F2 protects the load from short circuit damage.

The sense resistors used in the PV and battery sensor modules are found in the primary and secondary sides of the converter. They are a low ohmic type (0.01 ohms). R6 is used to measure PV current. R8 is for measuring battery current, and R10 measures load current. Resistor divider R4 and R7 measures battery bank voltage and divider R3 and R5 measure PV panel voltage.

The switching frequency of the converter is fixed at 20kHz to optimize both the switching loss and the inductor size. The inductor equation is given by:

Equation 2

$$I_{L(AV)} = I_O/(1-\delta)$$

Where I_O is the output current and δ is the duty cycle. In buck-boost mode, the maximum duty cycle is 60%.

The input bulk capacitor calculation is below. The parameter to keep in mind for this application is the Effective Series Resistance or ESR and RMS current rating. Low ESR is desired to minimize input voltage ripple and high current changes on the output. Placing two capacitors in parallel will also further reduce the ESR.

Equation 3

$$C_{I(min)} = (I_I \times t_{on})/\Delta V_I$$

Equation 4

$$ESR = \Delta V_I/(I_I/\delta)$$

The efficiency of the converter in buck-boost mode depends on the diode forward voltage drop V_f, so a diode with low V_f is desired. Schottky diode STPS40L45CG has a forward voltage drop V_f = 0.45V. With the V_f parameter calculated, the output filter capacitors can now also be calculated:

Equation 5

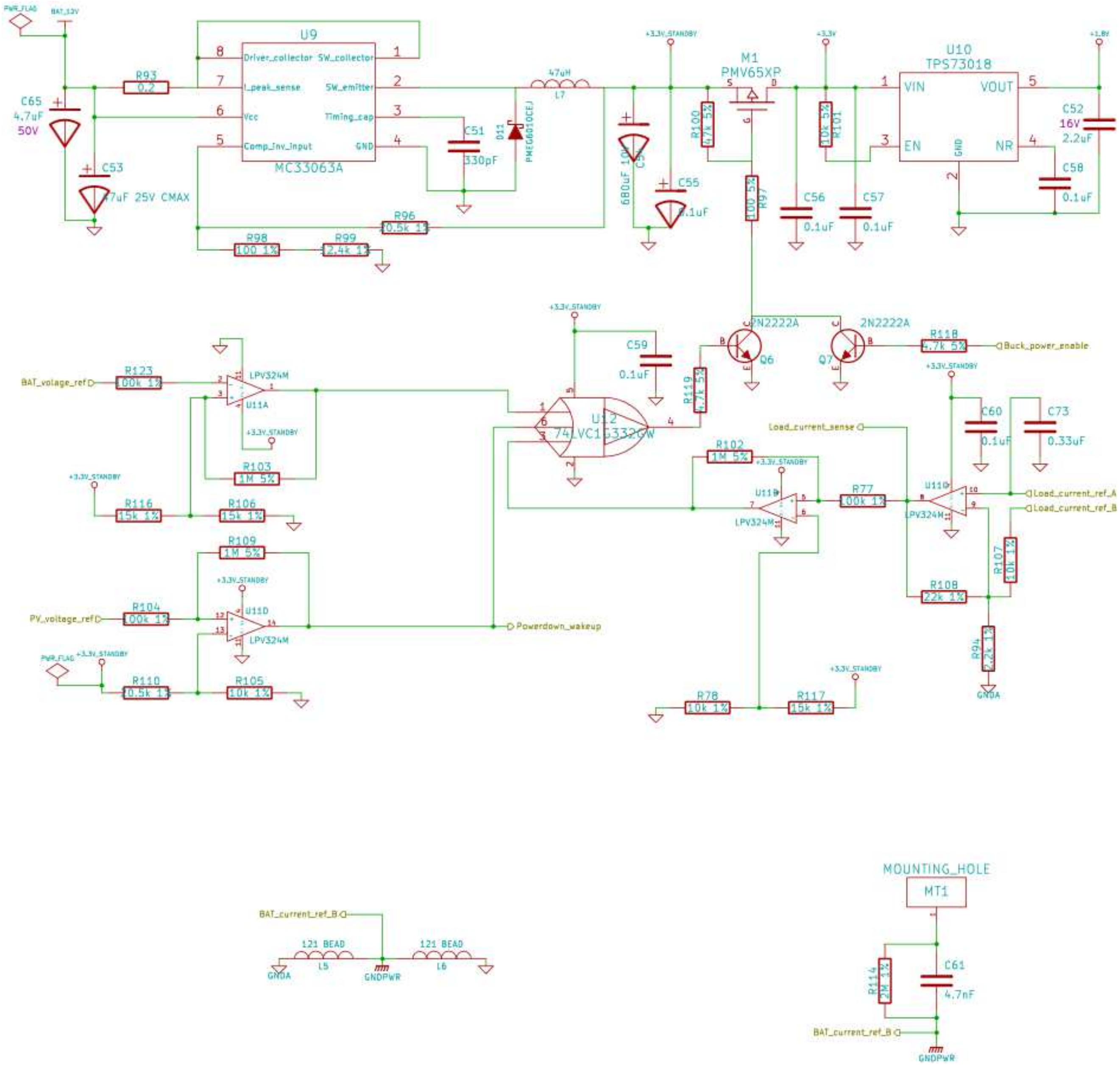
$$\frac{C_O \geq I_{O(max)} \times \Big(\big(V_O + V_f\big) \div \Big(\big(V_{I(min)} - V_{sw}\big) + \big(V_O + V_f\big)\Big)\Big)}{f_{osc} \times \Delta V_{OC}}$$

Where f_{osc} is the switching frequency (20kHz), $\Delta V_{OC} = 200mV$, and $V_{sw} = 0.4V$.

4.2.6 Power Supply

The power supply module is responsible for creating the 3.3v and 1.8v power rails which are used to power all of the integrated circuits and other externally powered components in the charging system. The power supply circuit consists of two voltage regulators and three standby switches for energy savings and circuit protection.

Figure 21 Power Supply



The circuit can be divided into three regions. At the top, everything to the left of MOSFET M1 is the standby circuit containing 3.3 volts. This circuit is always on as long as the battery is connected. Everything to the right of M1 is the active 3.3v rail and 1.8v rail. Everything on the bottom is related to controlling the gate pin of MOSFET M1 for entering and exiting standby mode.

Switching regulator U9 takes the battery voltage as the input and outputs a regulated 3.3V supply. The low dropout regulator U10 takes the 3.3v input and outputs a regulated 1.8 volts. These rails are only on when M1 is on. The standby control circuit is composed of three op-amps operating as comparators. U11A is the battery voltage comparator. If the battery voltage rises above a specified level, this comparator triggers the system to enter standby mode to stop charging. Similarly, if the PV voltage dips too low or the load is too high, op-amps U11D and U11C will respectively send the power supply into standby mode and stop the charging process. The outputs of the comparators are ORed together at the multi input OR gate U12.

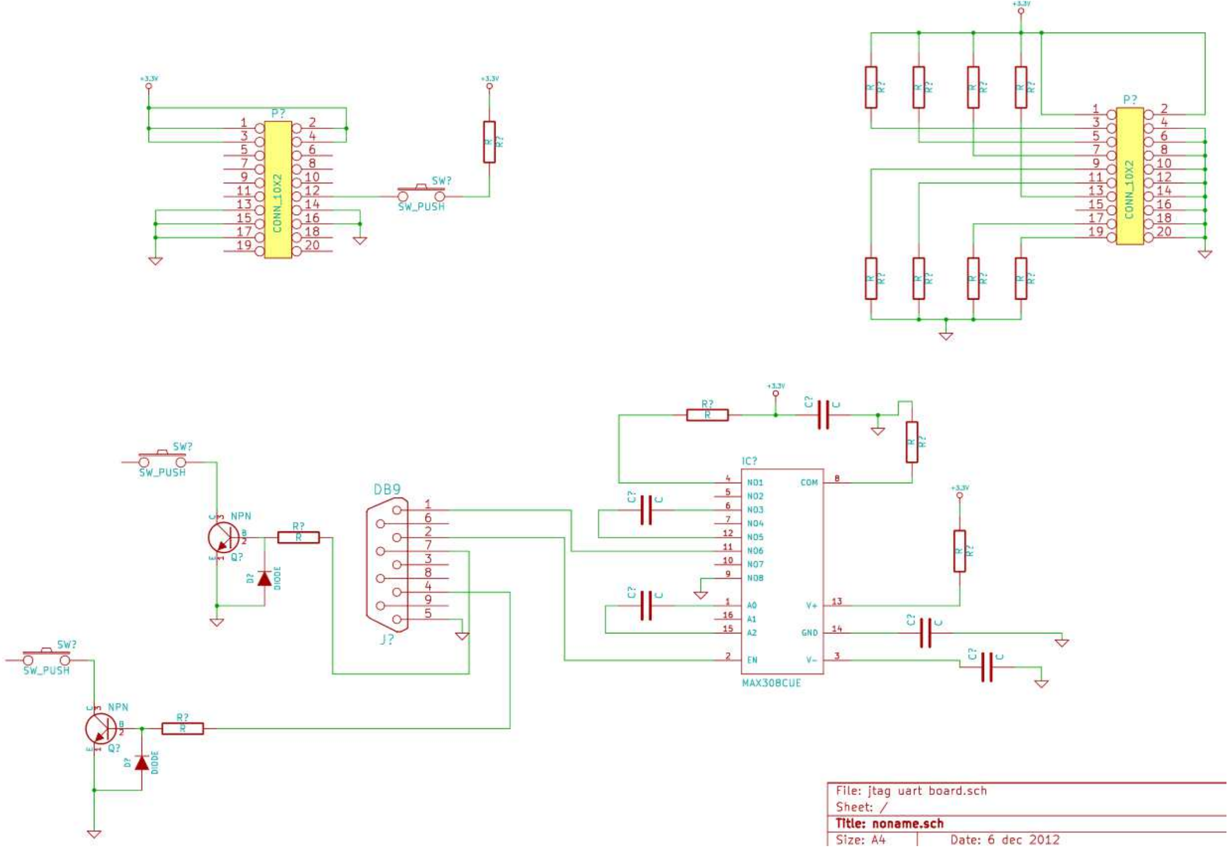
When the MPT612 is in standby mode and needs to be woken up again, a signal is sent from the output of the PV voltage comparator to the chip. The Powerdown_wakeup signal is used as an interrupt signal to wake up the MPT612 when the PV voltage rises back up to a nominal level for charging, provided that all of the other parameters (battery voltage, load current) are also nominal.

Finally, at the very bottom of the diagram, the ground connections are shown. The digital ground and analog ground planes are tied together via inductors L5 and L6. The low side of the battery current reference taps into here. The mounting hole is grounded and tied to earth ground. The battery current reference taps into here as well.

4.3.7 JTAG/UART Add-on Board

The JTAG/UART add-on board is described by NXP as an “optional” circuit which is used to program the charge controller board. For testing, it can also be used to monitor its performance.

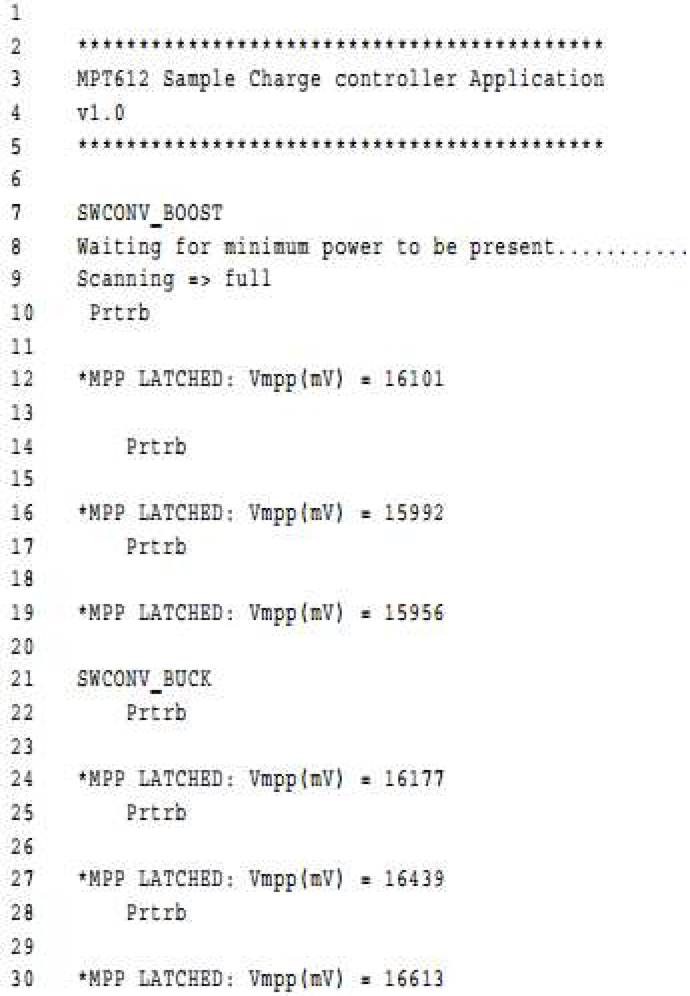
Figure 22 JTAG/UART Add-on Board



The top left is the JTAG connector. This is used for flashing new software to the MPT612 IC. The button on pin 12 is for enabling JTAG. The connector J7 on the right is what interfaces to the charge controller. It is a 20 pin header. The circuit on the bottom is the serial interface. U13 is the MAX3221 RS232-level connector IC.

In windows, using the HyperTerminal, one can connect to the charge controller over the serial interface to monitor charge performance. First, connect the JTAG/UART board to the charge controller. Then connect the D-SUB connector on the JTAG/UART board to a serial (COM) port on the PC. Open HyperTerminal or TeraTerm and set baud rate to 38400. Connect the external load on the charge controller. Connect the 12V battery to the charge controller as well as the PV panels. Press any key in the console to display a menu for open-loop efficiency testing. The functionality is executed once the menu key is pressed. The LED status indicators will show the current system function. Green fully on means the battery is charging. When the green LED is blinking, the battery is fully charged. Yellow means battery is low. Red means battery is low cut off or overload cut off. If none of the LEDs are on, the system is in standby. Before running the test, measure the PV voltage, PV current, battery voltage and battery current using a multimeter. Once sufficient PV power is available, the output of the application program is displayed on the PC terminal window. Sample application output is shown below:

Figure 23 Charge Controller Application



```

*******************************************
MPT612 Sample Charge controller Application
v1.0
*******************************************

SWCONV_BOOST
Waiting for minimum power to be present...........
Scanning => full
 Prtrb

*MPP LATCHED: Vmpp(mV) = 16101

    Prtrb

*MPP LATCHED: Vmpp(mV) = 15992
    Prtrb

*MPP LATCHED: Vmpp(mV) = 15956

SWCONV_BUCK
    Prtrb

*MPP LATCHED: Vmpp(mV) = 16177
    Prtrb

*MPP LATCHED: Vmpp(mV) = 16439
    Prtrb

*MPP LATCHED: Vmpp(mV) = 16613
```

4.3 Batteries

This section describes the design and implementation of the Battery Bank.

4.3.1 Size Codes and Common Names

Although each manufacturer has their own model numbering system, standard sizes exist for commercial batteries. Battery Council International (BCI) is a trade organization that sets some battery standards, including sizing codes. Some batteries have acquired their names from their intended use. For instance, GC2S were named from being used as golf cart batteries. Batteries with the same code or name will have approximately the same dimensions, but their capacities may differ significantly. This is especially true between flooded and sealed units. The table below show some of the more common size seen.

Table 25 Common Battery Specifications

Size	Volts (V)	Length (In)	Width (In)	Height (In)	Capacity c/20 (Ah)	Weight (Lbs)
Group24	12	10.00	7.00	9.00	70 - 85	50
Group 27	12	12.00	7.00	9.00	85 - 105	60
Group31	12	13.00	7.00	9.50	95 - 125	70
4D	12	20.75	8.75	10.00	180 - 215	130
8D	12	20.75	11.00	10.00	225 - 260	160
Gc2	6	10.50	7.00	11.00	180 - 225	70
L-16	6	11.50	7.00	16.75	325 - 415	120

4.3.2 Climate and Temperature

Always take into consideration the climate factor when trying to decide which battery will be suitable for the renewable energy source application. Most battery specifications are based on the ideal battery temperature of 77 degrees Fahrenheit. That is the attainable temperature for conditioned spaces. If the batteries are out in the cold some adjustments will be necessary. Flooded and sealed batteries behave a little differently under various temperature ranges, so be sure to check manufacturers' specifications.

Sizing correction Factors

Temp. (F)	Flooded	AGM	Gel
77	1.00	1.00	1.00
50	1.19	1.06	1.11
32	1.39	1.20	1.25
14	1.70	1.35	1.42

For a system requiring 1000 Ah of capacity using flooded batteries in sterling, VA, with common 40 F winter temperatures, by extrapolation of the above table we will get a correction factor of 1.29.

Therefore 1,000 Ah x 1.29 = 1,290 Ah battery bank size for winter temperatures Below- freezing temperatures, the electrolyte becomes very weak in discharged flooded batteries. The electrolyte can freeze solid, which will ruin the battery and the case can crack from the expanded ice. Internal connections may be damaged. For these extreme climate conditions, sealed batteries are a better choice because their electrolyte solution has a much lower freezing point. On the other hand the flooded batteries are more adapted for the hot climate.

4.3.3 Location and Safety

Make sure to have adequate and appropriate space to put the battery bank. Batteries need to be near the inverter. They should be within 10ft. of the inverter. Batteries need to be protected from unauthorized access. They need to be properly enclosed and vented to keep corrosive and flammable gasses outside of occupied spaces. High temperatures will shorten a battery’s life, especially for sealed batteries, so keep them out of direct sun and provide air circulation if needed. Good access is critical for inspection, cleaning, replacement and watering especially for flooded batteries. Therefore, it will be hard to maintain them if they are hard to get to. That is why it is very important to choose a good and safe cite for the battery bank. For remote systems, take into consideration the ease of transporting and installing the batteries.

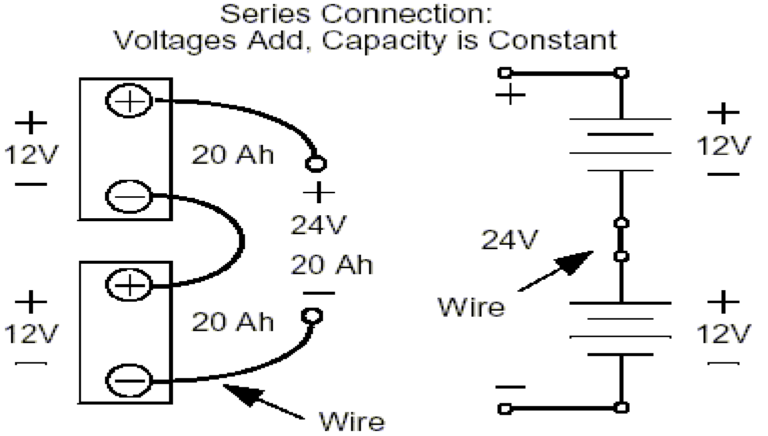
In sum, the proper temperature, ventilation, and spill containment are important for a safe and long-lasting battery bank.

4.3.4 Installation of the Batteries

Just having good batteries with high amp-hours are not a guaranty that they will not fail. This is why it is very important to connect them properly. The standard technique for installation of a battery bank is series/parallel wiring. The series/parallel wiring is a best way of combining batteries to get the desired voltage and storage capacities to match the rest of the components in the system.

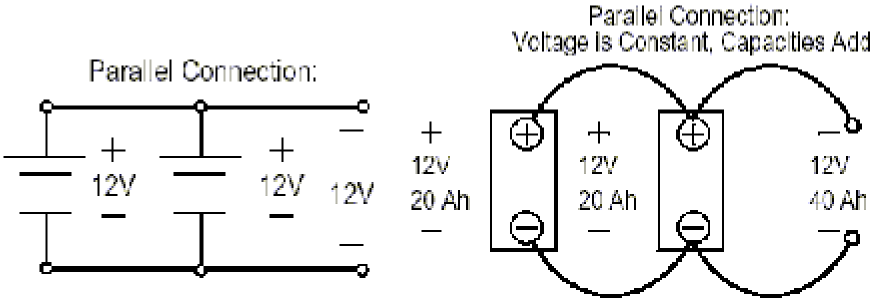
Series wiring means to connect the positive terminal of one battery to the negative terminal of the next battery. By doing so it multiply the voltage of the individual battery by the number of batteries interconnected until it reaches the desired voltage.

Figure 24 Series Wiring
Permission Pending



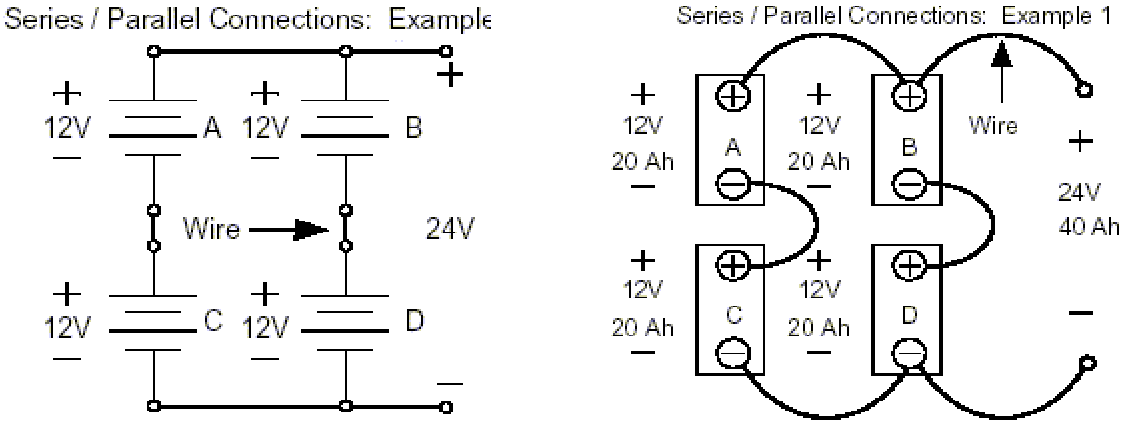
Parallel wiring multiplies the capacity in amp-hours of the battery while the voltages stay the same. In parallel we wire the positive terminal of one battery or string to the positive terminal of the other battery or string.

Figure 25 Parallel Wiring
Permission Pending



Series/parallel wiring is the combination of the series and parallel wiring. It is the technique of wiring used commonly for wiring battery banks in renewable energy systems.

Figure 26 Series/Parallel Example
Permission Pending



To promote equal charging and discharging within a battery bank, it is important to limit the number of parallel connections. There is one, two and three series string that are usually used to connect batteries. However the one series string is best for equal charging and discharging of the battery bank. But some designers prefer the two series string for redundancy in case one of the battery or cell fails, there will still be one functional series string at the correct voltage to rely on until the failed battery can be replaced. The three series strings are considered marginally acceptable, but more parallel connection introduces too many paths for the electron to choose from when entering or leaving the battery strings. Some cells can be chronically undercharged due to minute variations in cells and inter interconnection resistance which will decrease the life of the battery bank. In sum a good designer uses batteries with higher amp-hour capacities and limits the number of parallel connections.

It can be tempting to design a battery bank with plans to add capacity in the future, but this is not a good practice because of the batteries sensitivity to unequal charging and discharging whiting the bank. The batteries should all be the same make and model, and ideally manufactured in the same company. You should always size for the future from the beginning because adding new batteries, even with the same make and model, to a battery bank that is more than a year old is inviting problems the system. This is because the old batteries will already have higher internal resistances.

We decided to use CSB-HRL12280WFR 12V Deep Cycle Flooded 75Ah batteries as seen below.

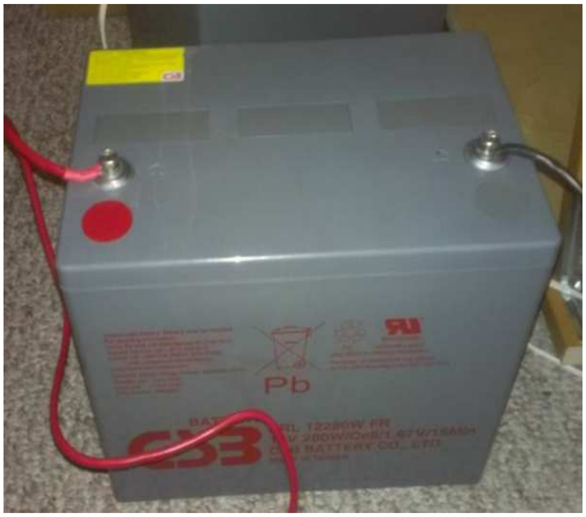


Figure 27 CSB-HRL12280WFR

4.4 Inverter

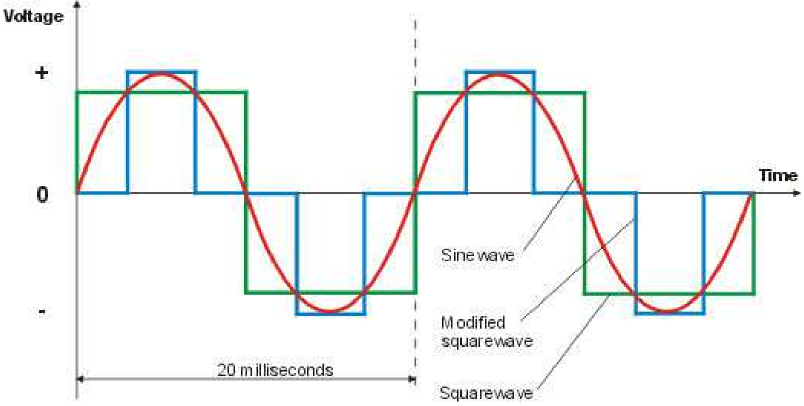
The last part of the project or the final stage of the system is the inverter. The inverter is a very important part of the project because it is through this device that the user will have the opportunity to access the power stored in the batteries that was originally obtained from the solar panel and managed by the charge controller.

The main function of the inverter in layman terms is to take the DC voltage stored in the batteries and transform it into AC voltage that can be used by the township of Pomolong to power their electronics. A good inverter will have different socket shapes for EU and NA to cover all electronic appliances out there such as cell phones, projectors, and laptops. Another feature the inverter should have is that it should be able to deliver a good amount of power evenly to its sockets that way it can power more than one device at a time instead of only one at a time. Additionally, it is crucial for the inverter to have a simple to use interface with little to no knowledge in electrical components to operate safely. Lastly, the inverter should be power efficient which means a pure sine wave output which uses the maximum amount of AC voltage available for the electronic component being powered.

It takes two steps for an inverter to change low voltage DC to high voltage AC. First, low voltage DC power is converted to high voltage DC source. Next, the high voltage DC source is converted to an AC waveform using pulse width modulation. A different way to build an inverter is to take the low voltage DC power convert it to low voltage AC power. Next, use a transformer to raise the voltage to our desired of 220-240V AC for South Africa. It was decided that the first method to produce the inverter was more applicable to our project design and it should be implemented to our project [29].

As stated before, the group is looking to make a pure sine wave inverter as oppose to modified sine wave inverter. Modified sine waves are closer to square waves than curvy sine waves; it passes the high voltage DC for a period of time so that the average power and rms voltage are closer to a pure sine wave. These modified sine wave inverters are generally cheaper than pure sine wave inverters, however, the group has decided to build a pure sine wave inverter. A pure sine wave inverter is the best output for AC voltage, it is the same as a households power outlet. Some electronic devices will only run on pure sine wave AC voltage and even go so far as to get damaged. These devices include laptops, printers, and TVs. Electronic noise is also at its lowest when using pure sine wave AC voltage. The following is picture displays modified and pure sine waves.

Figure 28 Modified/Pure Sine Wave
Permission Pending



As we can see a modified sine wave is closer to a sine wave then a square wave. This modified square wave is easy to produce because it simply is 3 different constant values at different points in time.

The differences between AC(Alternating Current) and DC(Direct Current) is that DC is a constant voltage through a circuit which results in a constant current. Batteries and digital circuitry use DC power because of logic purposes (1 and 0) since voltage will be constant high or low for either logic. AC oscillates between two voltage values at a frequency. In addition, transmission power loss is proportional to current squared, however, DC is unable of being transformed for long distance transmission while AC is capable.

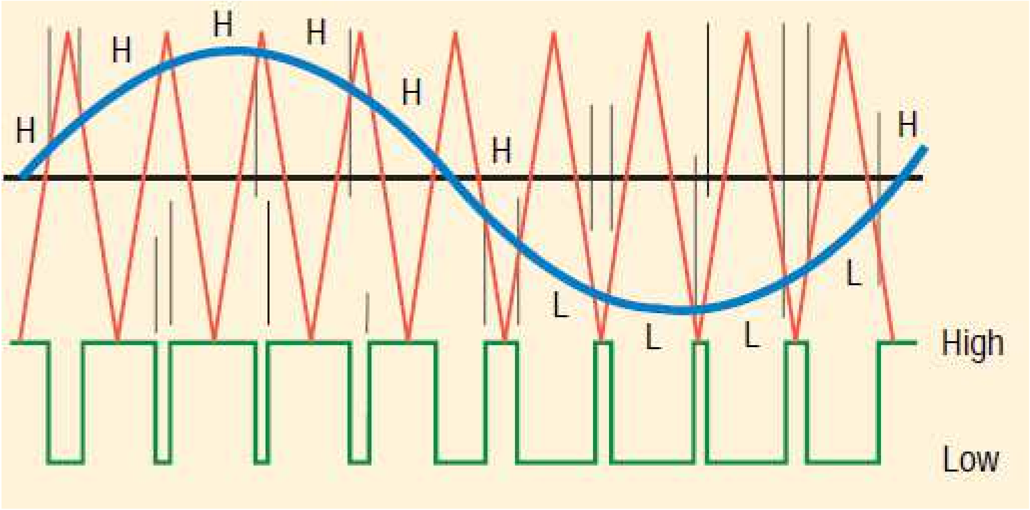
Inverters come in all shape and sizes, from lower power functions such as powering a clock to being part of a backup system for a building. A DC/AC power inverter which is the type our group will be using. The following is a picture of what a small power inverter typically looks like.

Figure 29 Commercial Power Inverter
Permission Pending

Usually these type of power inverters are used today for many tasks like powering appliances in a car such as cell phones, radios and televisions, as we can see they come in handy when performing outdoor activities such as camping, hiking, or fishing.

Pulse width modulation is a technique used often to power AC devices that have a DC power source. In this technique there is a variation of duty cycle in the signal which provides a DC voltage across the load which is in a pattern that appears to be AC signal for the load. To create this pattern electronic analog components and a digital microcontroller are used [30]. Analog PWM requires both a modulating and a carrier signal that inputs into a comparator which outputs a signal based on the difference between the input signals [31]. The modulating signal is sinusoidal and operates at the desired output frequency and the carrier signal is a triangular wave which runs at a much higher frequency. When the voltage of the carrier signal is higher than the modulating signal the output is at one state. When the opposite happens then the output is in its second state. The process is shown in the following figure with carrier signal in red and the modulating signal in blue and output signal in green.

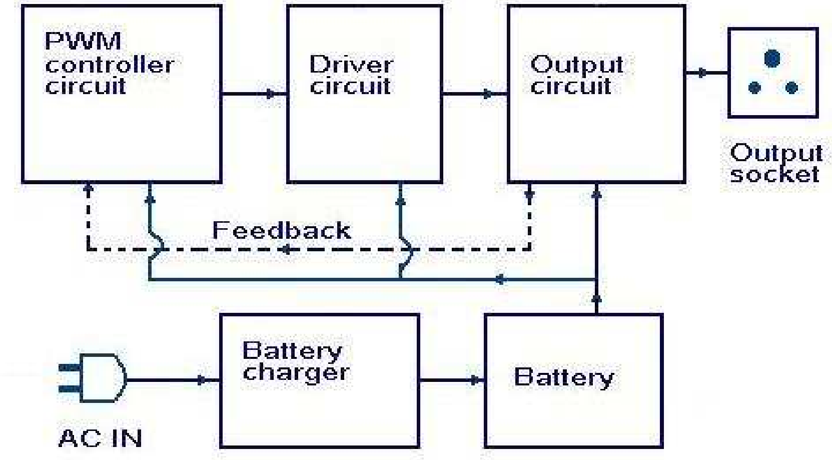
Figure 30 Pulse Width Modulation
Permission Pending



Finally, the output source is connected to the load through transistors or similar electronic components which work corresponding to whether the output signal is high or low. PWM inverters also keep the desired output regardless of the load. In other inverters, the output changes with changes in the load. To do this, a PWM inverter changes the output voltage according to the load connected. The width of the switching frequency in the oscillator is changed which controls the AC voltage at the output. As we can see, this process involved feedback from the output part of the inverter to the PWM controller section, thus making the pulse width changes. The pulse width change of the switching pulse will cancel whatever changes occur in the output voltage. Therefore, the inverter output will stay constant regardless of different loads.

In order to construct a pure sine wave inverter, it is simpler to split the project into parts. Thus the following illustrates a simple block diagram of a PWM inverter which is split into parts for easier understanding and constructing.

Figure 31 Block Diagram for PWM Inverter
Permission Pending

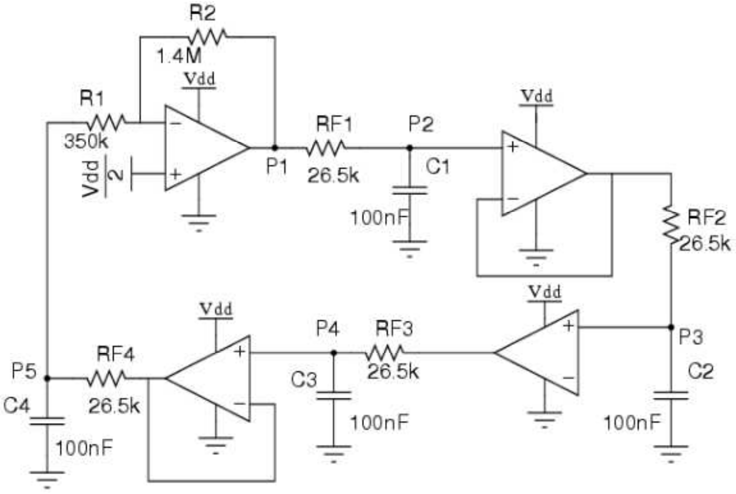


Block diagram of a basic PWM inverter www.circuitstoday.com

First, we start with the AC IN which is the AC voltage coming from the solar panels which is managed by the charge controller. Thus, the batteries are charged and output DC voltage. Next is the PWM controller circuit which is where the regulation of the output voltage takes place. Additionally, the oscillator circuit which is where the switching frequency is generated is here.

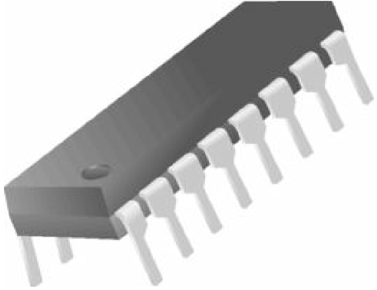
For the oscillator circuit, a Bubba Oscillator circuit is used to create a PWM signal using analog devices. The sine wave to be created is to operate at a frequency of 60 Hz which is the standard frequency for AC voltage from a power outlet. A Bubba Oscillator produces a stable sine wave signal with little to no distortion which is perfect for this project. The following is a schematic for a Bubba Oscillator, as we can see a quad op-amp will be used for this part of the inverter.

Figure 32 Bubba Oscillator Diagram
Permission Pending



Most of the time a single PWM integrated circuit takes care of this task. Examples of the PWM IC are the KA3525 or TL494CN(shown below).

Figure 33 TI TL494CN
Permission Pending



Next, the driver circuit adjusts the signal according to the switching frequency. To do this, transistors or driving integrated circuits are used for the driver circuit. The driver circuit is similar to an amplifier. Last, the output circuit, handles the load it consists of a step up transformer for stepping up the battery voltage to the new voltage in its first stage. To do this MOSFET devices are primarily used for the step up transformer. The final output voltage is then available in the second stage of the step up transformer.

We decided to design a modified sine wave inverter. We originally planned to design and build a pure sine wave inverter but due to difficulty we designed a modified sine wave inverter with the schematic for the signal generation and the PCB ordered from Hackvana seen below.

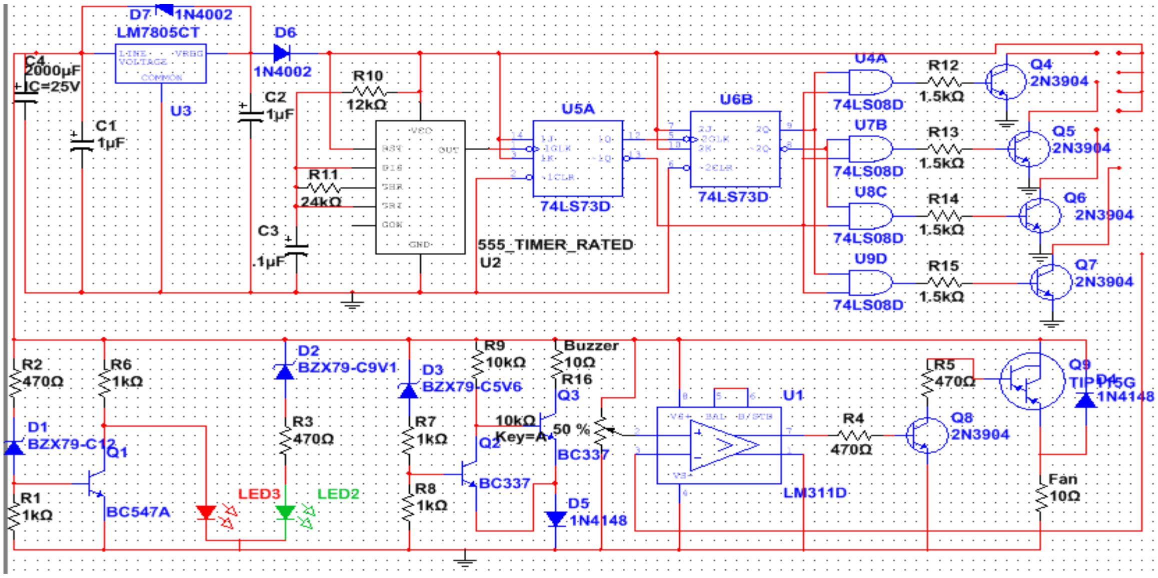


Figure 34 Signal Generation

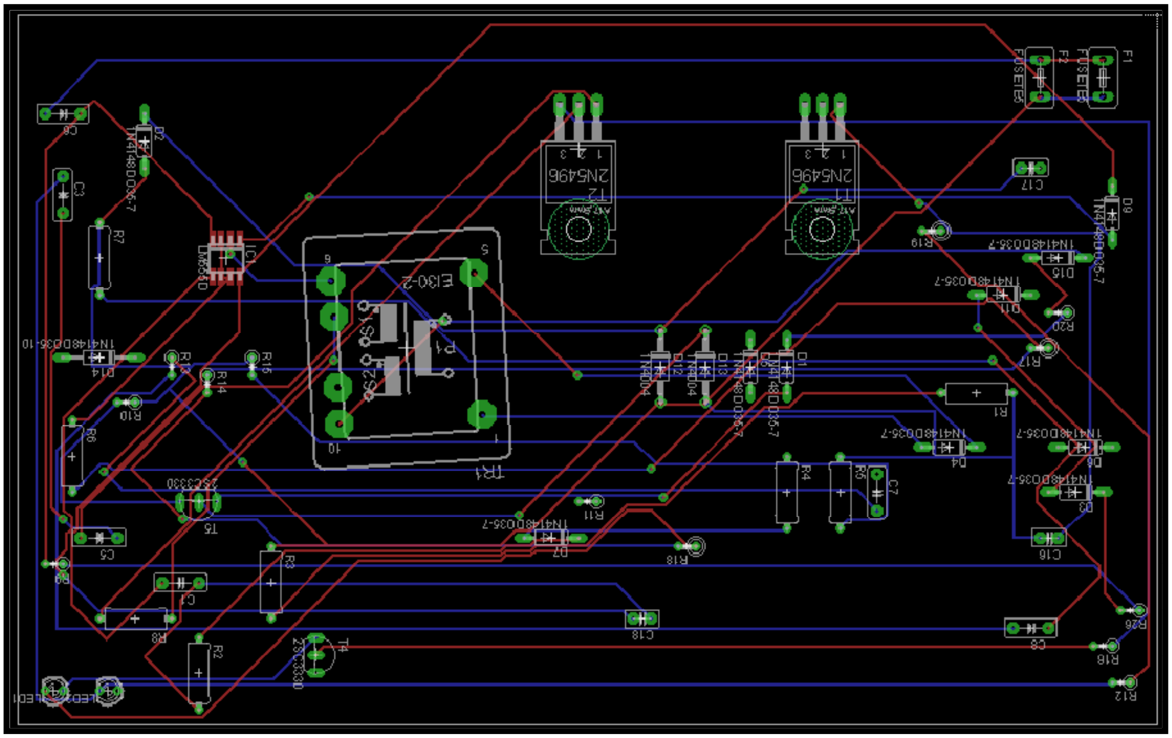


Figure 35 PCB Design

4.5 Monitoring System

The monitoring system are sets of systems that are being implemented to observe the status the entire power generation system. Some components are instruments that give readouts from the sensors, while others give readouts based on calculations of other sensors.

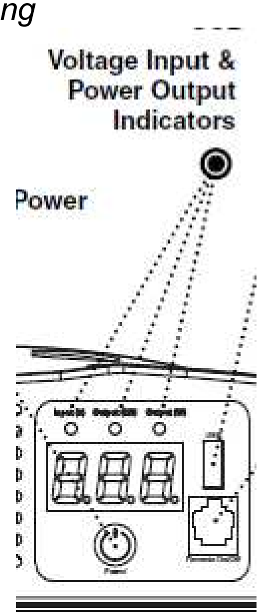
4.5.1 Charge Controller Monitoring System

The charge control monitoring system is simply the sensors that give information to the charge controller. The sensors will also have their reading displayed in small analog displays. This will allow any user to know what state in the charging process the charge controller is in. The charge controller also has lights that will tell the user if it is charging or not.

4.5.2 Inverter Monitoring System

There are high end commercial inverter which have a digital monitoring display as well as LED lights in the front panel. These monitoring parts are to indicate to the user power status of inverter(on/off), voltage input, power output, overload warning, low input voltage, and high input voltage. A power inverter is a sensitive piece of equipment and it is the groups wish to have a similar monitoring system to the one in some commercial inverters to make it easier for users to deal with the inverter. The following is a picture commercial inverter's monitoring display.

Figure 36 Example of Inverter Monitoring Display
Permission Pending



The group made a similar monitoring system to the one displayed above. There will are three LEDS of different color; they indicate power, input mode, and output mode. The power LED simply indicates whether the inverter is on or off. The input mode LED will let the user know that the number display is giving values of inverter input in Volts. In our case the input are the batteries, which we want to keep around 12 V. So if the battery output is less than 10V or higher than 15V the inverter flashes the LED to warn the user and powers down. The output mode LED lets the user know that the number display is giving values of inverter output in Watts. So depending on the devices that are connected to the outlets of the inverter the output Watts change. However, note that the inverter is rated up to 400W which means that it cannot exceed this limit. If it does the LED will flash indicating inverter overload and shutdown. In case of shutdown, the user should address the issue which caused the shutdown and then simply turn off and back on the inverter.

4.6 Encasing

The enclosure design is very important for the G7-SAP project. The approach to the product's Casing component was a progressive debate amongst the group members, continually evolving and building upon itself throughout the whole of the design process. The group all had justifiably envisioned the product In their individual ways when they came into this, and had to gradually compromise and merge all different visions to reach a consensus, yielding a product of increased functionality by summing the best of all parts. We break up the casing design of the G7-SAP into two enclosure due to the high danger that the batteries can cause. We have a casing for the battery bank and another one for all the other small component such as the inverter and charge controller.

We have seen a variety of materials used successfully such as plastic storage totes and coolers, fiberglass reinforced plastic, sheet PVC, and even old refrigerators. We ended up using an old computer chassis and modified it for use for our project. It's familiar, attractive, versatile, dimensionally stable, and strong. Most owner-builders and building crews can make a good box, and it is adaptable to specific sites and needs. For insulation, we used plywood. The best plywood material we have used is called "Baltic Birch," available through wholesale lumber and hardwood suppliers. We obtained ours from Home Depot. It is 1/2-inch thick with nine plies, and comes in various sheet sizes, including our preferred 60- by 60-inch.Besides being attractive, it is dimensionally stable and easy to work with.

To prevent maintenance issues from occurring, we made sure that the battery container was well ventilated and had a snug fit on the frame. This is about the depth of three rows of L16s or two rows of larger industrial-type cells. The length of the box was around 50 inches. If space is factored in between each battery for ventilation, this translates into a box length of about 60 inches. Two or three sheets of 60-inch plywood is enough for most battery enclosures, with little of the waste if the panels had been cut from conventional 4-by-8-foot plywood. Even if a box can be less than 48 inches long, a larger enclosure may be justified. A small system that uses golf-cart batteries may someday be upgraded to L16s or industrial 2 V cells. A golf-cart battery is about 10 1/2 inches long; an L16 is about 12 1/4 inches. So upsizing the box initially to fit future battery possibilities may save money in the long run. To plan a successful battery box layout, we drew out the batteries on paper and made cardboard templates. We left room around battery cases for ventilation, to hide rope handles, to maneuver a distilled water jug, and to get fingers and tools into the box for service. We left 5 inches above the battery tops for cables and interconnects. Plan the placement and lengths of your interconnects so that all fill caps are readily accessible and battery cables do not lay over the cell tops.

The inside of the box was carefully caulked and treated with a penetrating sealer to resist minor spills or corrosive vapors. For best results, a liner of 40-mil EPDM rubber or pond liner (available at many nurseries or home improvement stores) was placed in the bottom and about 6-8 inches up the sides, folding instead of cutting for the corners. This liner protects the wood and forms a leak proof layer. See the Figure below.

Figure 37 Enclosure Design

4.7 Wiring

To keep the performance of the project in creating a power source out of solar energy, it is important to have good wiring throughout the system. Wire failure can not only lead to system failure but also to more dangerous cases such as a fire. Therefore, top of the line wiring with good insulation was used throughout the system.

Throughout the system, the most important part as far as wiring is concerned is at the battery and inverter level. To maintain good performance of the inverter and efficient power flow, the group plans to use 4-AWG copper cable with at least a 90°C insulation rating. These type of cables are designed to withstand up to 135 A of current. These are very thick wires that provide low resistance and transfer energy in a safely manner. The following is a picture of the power cables that will be used for the battery and inverter part of the system [32].

Figure 38 Power Cables
Permission Pending

Next, we take a look at the specifications for the power cables used.

- 4-AWG cable with at least 90°C insulation rating.
- Should be as short as possible in order to reduce the voltage drop between the batteries and inverter.
- The ends of the power cables should be a metal terminal which allow secure connection to the battery and terminal. Additionally, the connection will be covered with rubber.

- Red power cables will be reserved for positive(+) terminals.

- Black power cables will be reserved for negative(-) terminals.

For the terminals, they were soldered to metal terminals. To do this the ends of the power cables were stripped, then solder will be heated and poured into the terminals and then the wire will be inserted to ensure a strong solder. As stated above once connected they will be covered with rubber covers to prevent contact. Note, it was important to correctly wire up the polarities of the inverter with the batteries, if this is failed the inverter colld fail and could possibly get damaged.

4.8 Design Summary

The purpose of this section is to give a general overview on what is planned to be designed for this project. The South Africa project to help generate power to the community center for the impoverished African village of the Pomolong Township is divided into four distinct parts. All the research and design of each of the parts have been explained in detail. What remains in this section is just a cursory overview for the purpose of getting a general idea on what design plans will be implemented. The four major parts to this project are the Solar panels, the Charge Controller, the Battery Bank, and the Inverter.

The Solar Panel is the portion of the project that generates the power. It is being implemented because of the two forms of renewable energy, it was the most practical for the limited budget at hand. The kind of solar panel was chosen based on price, availability, durability, and efficiency. Solar panels are the most expensive part of the project, so a lot of research was done in comparing the prices to see what panels were the most price competitive while retaining a high efficiency. The result of the research showed that grade-A Mono-crystalline silicon photovoltaic panels were the most efficient cost effective solar panels that could be obtained. For approximately 1,000.00 US dollars, two 700W panels could be bought, costing a little over a dollar per watt.

Batteries are the second most expensive part of the project, and like solar panels, a lot of time was used to determine if more expensive batteries were worth the slight increase in efficiency and safety. Although safety is at the top of the design consideration, having a working design that could be used by the villagers was almost as important. It was found through research that the best batteries were Lithium-ion batteries, because of their efficiency and ideal characteristics. It was found that among, Lead-Acid Batteries, that AGM was superior in almost every way. The final sway in the decision to go with flooded Deep-Cycle Lead-Acid Batteries was there cost and availability. It was considered that the part of the system most likely to be damaged or be in need of replacement would be the Batteries, so it would be ideal to choose batteries that could be easily obtained in almost any place in the world. With the price for the battery being lower, it allows for more room in the budget to make irreplaceable parts in the project more robust and stable.

The charge controller was introduced as the component in the solar system that sits in between the PV panels and the battery bank, and provides protection and monitoring capabilities aside from increasing the efficiency of the charging process using the MPPT algorithm. Several different charge controller implementations were looked at, varying from the simplicity of a 555 timer or an Arduino, but these were too simplistic in the sense that they did not employ the use of a DC-DC converter for increasing efficiency. In the case of Arduino, it freed up the computer engineer from doing any real computer engineering. The more sophisticated charge controller ICs all required some form of DC-DC converter and thus were more complex however also far more efficient. They were specifically geared toward renewable energy applications, so all featured an MPPT algorithm. The ICs from Texas Instruments and NXP have sophisticated features such as full bridges and ADCs, compared to a simple 555 timer.

The NXP Semiconductor MPT612 Maximum power point tracking IC was selected for its flexibility, power, and high level of documentation. It has plenty of protection features which prevent catastrophic failure in the event that the panels or battery are connected backwards. It has load cutoff if the load gets too high or the battery voltage goes too low. The MPT612 can automatically switch between buck-boost and buck-only mode depending on the relative voltages of the PV panel and battery, and uses operational amplifiers and current shunt monitors to accurately and precisely monitor the voltage and current of both the PV panels and the battery. Accurate measurement of the PV current is vital for the microcontroller's ability to latch onto the maximum power point.

To summarize the inverter design, many ideas have been gathered from previous inverter technology. To begin with, the enclosure will be metal with air vents on the sides of the inverter to help with cooling, if possible fins will also be incorporated. During testing, we will measure temperatures while in different levels of operation. If it is required, then fans will be incorporated to the enclosure on the back panel of the inverter. The enclosure will also have a warning label on the top part of the inverter. On the front panel of the inverter, there will be two power outlets, a power switch, 3 LEDS(input mode, output mode, Power on/off), and a 3 digit monitor display.

Next, for the circuitry, we will first assemble it in a breadboard and make sure the circuitry outputs the desired output. The reason for this is that to achieve a pure sine wave a lot of tweaking will need to be done along with an oscilloscope until the final circuitry is achieved. Then with a schematic on hand, the pcb board will be ordered with the components integrated. At this point, the enclosure and the board will be connected. This includes the power switch connection, the monitor display, and anything else that is attached with the enclosure. The inverter will take in 24V DC and output 210V AC in a pure sine wave form.

the conclusion of this design summary will end on a solemn note. The best and most expensive parts were unfeasible to use and implement in the design due to budget constraints. With the tools that were available, robust design in a MPPT charge controller as well as a Perfect Sine inverter are implemented to give the people of Pomolong the best that could be given It was fully wished and desired to use the most expensive parts, but as they were not available, what can be given is something that will work as well or better.

5.0 Project Prototype Construction

The purpose of this section of the documentation is to highlight how construction of a working prototype can be accomplished. This includes a plan on acquiring parts, listing the bill of materials, and developing a plan to have the PCB ready for final project.

5.1 Parts Acquisition

Our project was entirely sponsored by Progress Energy. The group turned in a proposal with a budget of $1995 estimated for all the parts required for the project and the budget was approved. We had to order parts and give the receipts to a coordinator who later reimbursed the money in the form of a check. The group could not be reimbursed for any parts purchased online and shipped to their residence, so anything purchased from the internet had to be addressed to UCF.

Before the acquisition of any part, all group members had to approve the purchase. The reason behind this is if any other group member may know where to get it cheaper, if they already have that part or a replaceable part, or if they already acquired the part. The last thing the group wanted to do was to waste money and if there is anything that we already had that could be used, then so be it. Additionally, there was an inventory of all parts used in the project indicating how it was obtained, how it was used, and how much it cost. If for any reason, we did not get the Progress Energy sponsorship or the group did not get the full amount asked in the proposal, the cost of parts would be be split between group members.

5.2 Bill of Materials

The following is the component list and price that is required for construction of the South Africa Project. This project is roughly divided into the photovoltaic panels, the battery bank, the charge controller and the Inverter. A budget for the project was proposed and mentioned earlier in this paper, but this section goes into detail on the specification and price of each part that will be purchased.

Table 26 Charge Controller Bill of Materials

ref	value	footprint	part number	vendor	cost
C1	4.7nF	SM0805	C0805C472K2RACTU	Kemet	$0.22
C2	4.7nF	SM0805	C0805C472K2RACTU	Kemet	$0.22
C3	1000uF	C2V10	UHD1H102MHD	Nichicon	$1.95
C4	680uF	C2V10	UHD1V681MHD	Nichicon	$1.59
C5	1000uF	C2V10	UHD1H102MHD	Nichicon	$1.95
C7	680uF	C2V10	UHD1V681MHD	Nichicon	$1.59
C13	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C14	10uF	C1V8	UVZ1E100MDD	Nichicon	$0.20
C15	10uF	C1V8	UVZ1J100MDD	Nichicon	$0.20
C16	10uF	C1V8	UVZ1J100MDD	Nichicon	$0.20
C18	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C19	10uF	C1V8	UVZ1C100MDD	Nichicon	$0.15
C20	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C21	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C22	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C23	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C24	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C25	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C26	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C27	4.7uF	SM1206	C1206C475K5PACTU	Kemet	$0.45
C28	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C29	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C30	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C31	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C32	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C34	0.33uF	SM0805	08055C334MAT2A	AVX	$0.79
C35	0.33uF	SM0805	08055C334MAT2A	AVX	$0.79
C36	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C37	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C38	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06

C39	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C40	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C41	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C42	22pF	SM0805	08055A220KAT2P	AVX	$0.17
C43	22pF	SM0805	08055A220KAT2P	AVX	$0.17
C49	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C50	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C51	330pF	SM0805	08055C331KAT2A	AVX	$0.22
C52	2.2uF	SM0805	08055C104MAT2A	AVX	$0.06
C53	47uF 25V CMAX	C1V8	UVZ1E470MDD	Nichicon	$0.18
C54	680uF 10V	C1V8	EEUFM1A681L	Panasonic Corp	$0.84
C55	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C56	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C57	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C58	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C59	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C60	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C61	4.7nF	SM1206	C1206C472KDRACTU	Kemet	$0.15
C62	4.7uF	SM1206	C1206C475K5PACTU	Kemet	$0.45
C65	4.7uF	SM1206	C1206C475K5PACTU	Kemet	$0.45
C68	0.01uF	SM0805	08055C103MAT2A	AVX	$0.10
C69	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C70	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C71	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
C73	0.33uF	SM0805	08055C334MAT2A	AVX	$0.79
D1	ES1B	DO214	ES1B	Fairchild Semiconductor	$0.46
D2	STPS40L45CG	DPAK2	STPS40L45CG	STMicroelectronics	$1.52
D5	BYV42E	TO220	BYV42E-150	NXP Semiconductors	$1.44
D7	ES1B	DO214	ES1B	Fairchild Semiconductor	$0.46
D8	BYV44	TO220	BYV44-500	NXP Semiconductors	
D9	12V 0.5W	diode-1-SOD123	BZT52H-C12	NXP Semiconductors	$0.30
D10	MMBD4148	SOT23	MMBD4148	NXP Semiconductors	$0.05

D11	PMEG6010CEJ	diode-1-SOD323-W	PMEG6010CEJ	NXP Semiconductors	$0.34
D12	ES1B	DO214	ES1B	Fairchild Semiconductor	$0.46
D13	BYV42E	TO220	BYV42E-150	NXP Semiconductors	$1.44
D16	LED_YELLOW1	LED-3MM	HLMP-1719	Everlight	$0.25
D17	LED_GREEN1	LED-3MM	HLMP-1790	Everlight	$0.24
D18	LED_RED1	LED-3MM	HLMP-K150	Everlight	$0.22
D19	24V 0.5W	diode-1-SOD123	BZT52H-C24	NXP Semiconductors	$0.30
DC1	0.1uF	SM0805	08055C104MAT2A	AVX	$0.06
DR1	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
DR2	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
DR3	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
DR4	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
F1	50A FUSE	6.3x32mm	BK/AGC-50	Cooper Bussmann	$0.72
F2	50A FUSE	6.3x32mm	BK/AGC-50	Cooper Bussmann	$0.72
F1	FUSE HOLDER	keystone-FH_5X20	751.0056	Schurter	$0.50
F2	FUSE HOLDER	keystone-FH_5X20	751.0056	Schurter	$0.50
J6	JTAG/UART	con-headers-jp-HDR-100-2X10	SSW-110-01-T-D	Samtec Inc	$2.24
J15	GPIO_CON	con-headers-jp-SIP-100-10	TSW-110-07-T-S	Samtec Inc	$0.75
J141	282856-2	mors_2p	282856-2	TE Connectivity / AMP	$0.87
J142	282856-2	mors_2p	282856-2	TE Connectivity / AMP	$0.87
J143	282856-2	mors_2p	282856-2	TE Connectivity / AMP	$0.87
J144	282856-2	mors_2p	282856-2	TE Connectivity / AMP	$0.87
L1	85uH 20A	617 / 22	RB6132-50-0M2	Schaffner	$26.49
L2	121E_bead	SM0603	EXC-3BP121H	Panasonic Corp	$0.30
L3	121E_bea	SM0603	EXC-3BP121H	Panasonic Corp	$0.30

	d				
L4	121E_bead	SM0603	EXC-3BP121H	Panasonic Corp	$0.30
L5	121 BEAD	SM0603	EXC-3BP121H	Panasonic Corp	$0.30
L6	121 BEAD	SM0603	EXC-3BP121H	Panasonic Corp	$0.30
L7	47uH	-140CLH-1010	B82464G4473M	EPCOS	$2.09
L8	121E_bead	SM0603	EXC-3BP121H	Panasonic Corp	$0.30
M1	PMV65XP	SOT23	PMV65XP	NXP Semiconductors	$0.42
M5	PMV65XP	SOT23	PMV65XP	NXP Semiconductors	$0.42
M6	PMV65XP	SOT23	PMV65XP	NXP Semiconductors	$0.42
MOV1	VR	R3-LARGE_PADS	SIOV-CN2220K25G	EPCOS	
NTC1	RVAR	R3-LARGE_PADS	2381 640 63152	Vishay/BC Components	$0.39
Q1	PSMN8R2-80YS	transistor-power-SOT669	PSMN8R2-80YS	NXP Semiconductors	$1.30
Q2	PSMN1R3-30YL	transistor-power-SOT669	PSMN1R3-30YL	NXP Semiconductors	$1.30
Q3	PSMN8R2-80YS	transistor-power-SOT669	PSMN8R2-80YS	NXP Semiconductors	$1.30
Q4	PSMN1R3-30YL	transistor-power-SOT669	PSMN1R3-30YL	NXP Semiconductors	$1.30
Q5	PBSS8110Z	SOT223	PBSS8110Z	NXP Semiconductors	$0.43
Q6	2N2222A	SOT23	PMBT2222A	NXP Semiconductors	$0.12
Q7	2N2222A	SOT23	PMBT2222A	NXP Semiconductors	$0.12
Q8	PBSS4160T	SOT23	PBSS4160T	NXP Semiconductors	$0.17
Q9	PBSS4160T	SOT23	PBSS4160T	NXP Semiconductors	$0.17
Q11	2N2222A	SOT23	PMBT2222A	NXP Semiconductors	$0.12
Q13	PBSS416	SOT23	PBSS4160T	NXP	$0.17

	0T			Semiconductors	
R1	15 5%	SM0805	ESR10EZPJ150	ROHM Semiconductor	$0.17
R2	15 5%	SM0805	ESR10EZPJ150	ROHM Semiconductor	$0.17
R3	68.1k 1%	SM0805	MCR10EZHF6812	ROHM Semiconductor	$0.10
R4	27.4k 1%	SM0805	MCR10EZHF2742	ROHM Semiconductor	$0.05
R5	3.9k 1%	SM0805	MCR10EZHF3901	ROHM Semiconductor	$0.05
R6	0.010 1%	R2512	MCS3264R010FER	Ohmite	$0.40
R7	4.7k 1%	SM0805	MCR10EZHF4701	ROHM Semiconductor	$0.05
R8	0.005 1%	R2512	MCS3264R005FER	Ohmite	$0.40
R10	0.01 1%	R2512	MCS3264R010FER	Ohmite	$0.40
R16	33 5%	SM0805	ERJ-6GEYJ330V	Panasonic Corp	$0.07
R21	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
R22	20k 5%	SM0805	RK73B2ATTD203J	KOA Speer	$0.08
R23	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R24	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R25	68.1k 1%	SM0805	MCR10EZHF6812	ROHM Semiconductor	$0.10
R26	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R27	1k 1%	SM0805	MCR10EZHF1001	ROHM Semiconductor	$0.05
R28	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
R29	68.1k 1%	SM0805	MCR10EZHF6812	ROHM Semiconductor	$0.10
R30	68.1k 1%	SM0805	MCR10EZHF6812	ROHM Semiconductor	$0.10
R31	0	SM0805	MCR10EZHJ000	ROHM Semiconductor	$0.05
R32	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
R33	20k 5%	SM0805	RK73B2ATTD203J	KOA Speer	$0.08
R35	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R36	5.1k 1%	SM0805	MCR10EZHF5101	ROHM Semiconductor	$0.05
R37	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R38	68.1k 1%	SM0805	MCR10EZHF6812	ROHM	$0.10

				Semiconductor	
R39	5.1k 1%	SM0805	MCR10EZHF5101	ROHM Semiconductor	$0.05
R40	1k 1%	SM0805	MCR10EZHF1001	ROHM Semiconductor	$0.05
R41	0 1%	SM0805	MCR10EZHJ000	ROHM Semiconductor	$0.05
R42	68.1k 1%	SM0805	MCR10EZHF6812	ROHM Semiconductor	$0.10
R43	68.1k 1%	SM0805	MCR10EZHF6812	ROHM Semiconductor	$0.10
R44	2.74k 1%	SM0805	MCR10EZPF2741	ROHM Semiconductor	$0.10
R45	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R46	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R48	2.74k 1%	SM0805	MCR10EZPF2741	ROHM Semiconductor	$0.10
R53	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
R54	100k 1%	SM0805	MCR10EZPF1003	ROHM Semiconductor	$0.05
R55	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R56	4.7k 5%	SM0805	RK73B2ATTDD472J	KOA Speer	$0.08
R57	1k 5%	SM0805	RK73B2ATTDD102J	KOA Speer	$0.08
R58	2.2k 5%	SM0805	MCR10EZPJ222	ROHM Semiconductor	$0.10
R59	18k 1%	SM0805	MCR10EZPF1802	ROHM Semiconductor	$0.10
R60	100k 1%	SM0805	MCR10EZPF1003	ROHM Semiconductor	$0.05
R64	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R65	4.7k 5%	SM0805	RK73B2ATTDD472J	KOA Speer	$0.08
R66	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R67	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
R72	47k 5%	SM0805	MCR10EZPJ473	ROHM Semiconductor	$0.05
R75	2.2k 5%	SM0805	MCR10EZPJ222	ROHM Semiconductor	$0.10
R76	1k 5%	SM0805	RK73B2ATTDD102J	KOA Speer	$0.08
R77	100k 1%	SM0805	MCR10EZPF1003	ROHM Semiconductor	$0.05
R78	10k 1%	SM0805	MCR10EZPF1002	ROHM	$0.05

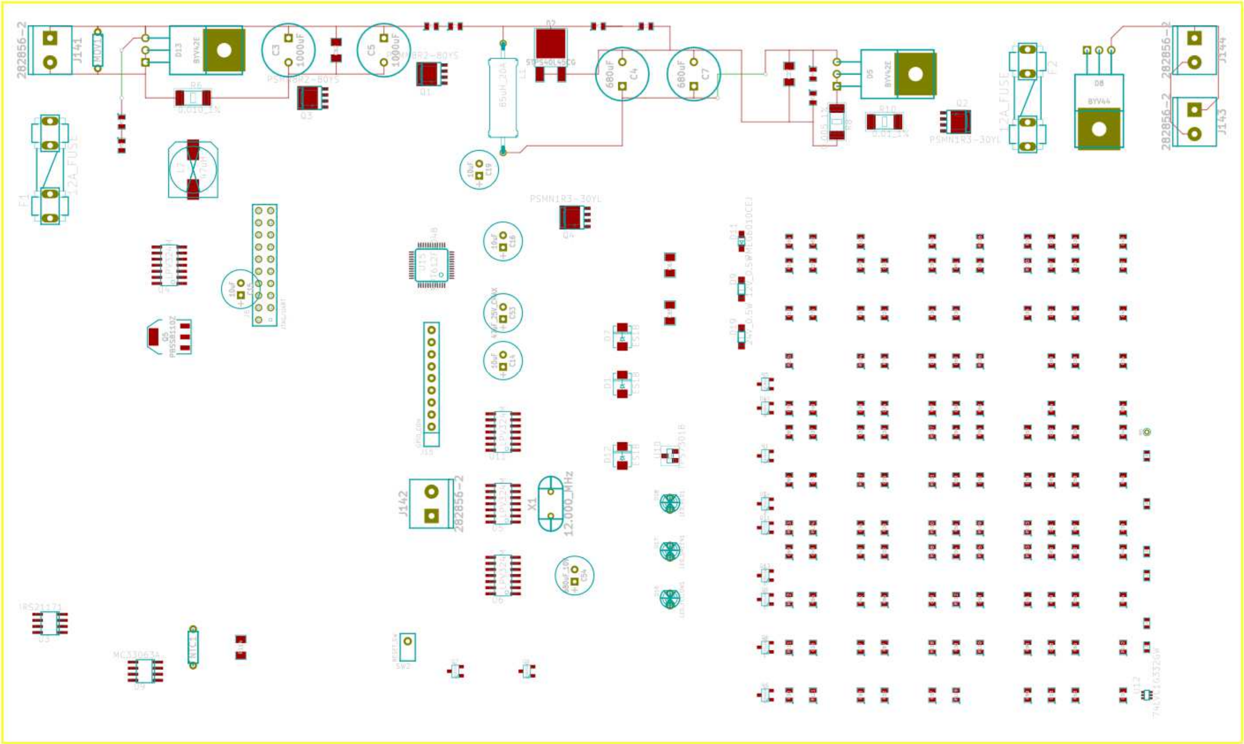
				Semiconductor	
R79	2.2k 1%	SM0805	MCR10EZPF2201	ROHM Semiconductor	
R81	20k 5%	SM0805	RK73B2ATTD203J	KOA Speer	$0.08
R82	20k 5%	SM0805	RK73B2ATTD203J	KOA Speer	$0.08
R84	100 1%	SM0805	MCR10EZHF1000	ROHM Semiconductor	$0.05
R86	100 1%	SM0805	MCR10EZHF1000	ROHM Semiconductor	$0.05
R87	100 1%	SM0805	MCR10EZHF1000	ROHM Semiconductor	$0.05
R93	0.2	SM0805	MCR10EZHFLR200	ROHM Semiconductor	$0.37
R94	2.2k 1%	SM0805	MCR10EZPF2201	ROHM Semiconductor	
R96	20.5k 1%	SM0805	MCR10EZHF2052	ROHM Semiconductor	
R97	100 5%	SM0805	MCR10EZPJ101	ROHM Semiconductor	$0.10
R98	100 1%	SM0805	MCR10EZHF1000	ROHM Semiconductor	$0.05
R99	12.4k 1%	SM0805	MCR10EZHF1242	ROHM Semiconductor	$0.05
R100	47k 5%	SM0805	MCR10EZPJ473	ROHM Semiconductor	$0.05
R101	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
R102	1M 5%	SM0805	MCR10EZPJ105	ROHM Semiconductor	$0.05
R103	1M 5%	SM0805	MCR10EZPJ105	ROHM Semiconductor	$0.05
R104	100k 1%	SM0805	MCR10EZPF1003	ROHM Semiconductor	$0.05
R105	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R106	15k 1%	SM0805	MCR10EZHF1502	ROHM Semiconductor	$0.05
R107	10k 1%	SM0805	MCR10EZPF1002	ROHM Semiconductor	$0.05
R108	22k 1%	SM0805	MCR10EZHF2202	ROHM Semiconductor	$0.05
R109	1M 5%	SM0805	MCR10EZPJ105	ROHM Semiconductor	$0.05
R110	20.5k 1%	SM0805	MCR10EZHF2052	ROHM Semiconductor	
R111	10k 5%	SM0805	RK73B2ATTD103J	KOA Speer	$0.08
R112	1M 5%	SM0805	MCR10EZPJ105	ROHM	$0.05

				Semiconductor	
R113	47k 5%	SM0805	MCR10EZPJ473	ROHM Semiconductor	$0.05
R114	2M 1%	SM1206	MCR18EZPF2004	ROHM Semiconductor	$0.14
R115	47k 5%	SM0805	MCR10EZPJ473	ROHM Semiconductor	$0.05
R116	15k 1%	SM0805	MCR10EZHF1502	ROHM Semiconductor	$0.05
R117	15k 1%	SM0805	MCR10EZHF1502	ROHM Semiconductor	$0.05
R118	4.7k 5%	SM0805	RK73B2ATTDD472J	KOA Speer	$0.08
R119	4.7k 5%	SM0805	RK73B2ATTDD472J	KOA Speer	$0.08
R120	1M 5%	SM0805	MCR10EZPJ105	ROHM Semiconductor	$0.05
R121	100k 5%	SM0805	RK73B2ATTED104J	KOA Speer	$0.08
R122	33 5%	SM0805	ERJ-6GEYJ330V	Panasonic Corp	$0.07
R123	100k 1%	SM0805	MCR10EZPF1003	ROHM Semiconductor	$0.05
R124	1k 5%	SM0805	RK73B2ATTDD102J	KOA Speer	$0.08
SW2	RESET SW	con-headers-jp-SIP-100-02	1825027-5	TE Connectivity	$0.11
U3	IRS21171	SOIC8	IRS21171STRPBF	International Rectifier	$3.15
U4	LPV324M	avr-4-SOIC14	LPV324M/NOPB	Texas Instruments	$1.19
U5	LPV324M	avr-4-SOIC14	LPV324M/NOPB	Texas Instruments	$1.19
U6	LPV324M	avr-4-SOIC14	LPV324M/NOPB	Texas Instruments	$1.19
U9	MC33063A	SOIC8	MC33063ADR2G	ON Semiconductor	$0.79
U10	TPS73018	SOT23	TPS73018DBV	Texas Instruments	$0.63
U11	LPV324M	avr-4-SOIC14	LPV324M/NOPB	Texas Instruments	$1.19
U12	74LVC1G332GW	SOT363_PHILIPS	74LVC1G332GW	NXP Semiconductors	$0.32
U14	INA194AIDBVT	SOT23	INA194AIDBVT	Texas Instruments	$2.14
U15	MPT612FBD48	LQFP48	MPT612FBD48,151	NXP Semiconductors	$7.98
X1	12.000 MHz	HC-49V	ECS-120-20-4XDN	ECS	$1.09
Total					$99.71

5.3 PCB Vender and Assembly

The PCB layout for the charge controller is shown below. The board in its current state features 209 components, mostly of surface mount packaging. The final design was mainly done on perf boards divided into modules as outlined in the schematics. Building the system in a modularized fashion allowed for more effective testing and debugging. Also, moving to a purely through-hole component selection was desired for easier assembly and prototyping.

Figure 39 PCB



As outlined in the bill of materials, many of the parts were available at Mouser electronics. Components which were not found in the Mouser catalog were either found in DigiKey's catalog or Future Electronics. All of the electrolytic capacitors were chosen from Nichicon. All of the ceramic capacitors are AVX branded surface mount 0805 components. Some of them are size 1206 and Kemet branded. Nearly all of the resistors are size 0805 and from ROHM Semiconductor or KOA Speer. The current sense resistors are size 1225.

Most of the diodes and transistors are NXP Semiconductor branded. These components and their respective tracks on the circuit board were revised to support higher currents (about 50A maximum) in order to sustain at least 500W of solar energy without fault. The other active components such as quad op amps, current shunt monitor, and switching voltage regulator were cataloged from ON Semiconductor, Texas Instruments, and International Rectifier. These components were also changed because the design moved to a through-hole topology.

The system is estimated to cost around $300 USD, including the cost of the circuit boards. The most expensive component found during selection was the inductor, coming in at over 25% of the total cost at $26.49. This is likely due to the cost of materials associated with winding copper wire to create the inductor. Second to the inductor was the MPT612 chip itself. Though not nearly as expensive, it comes in at $7.98.

Three different options were considered during research for fabrication of the printed circuit board: Home fabrication, Hackvana PCBs, and 4PCB. Home fabrication of the PCB is most desirable, as it shows a high level of skill in the general prototyping and design field. It is also cost effective, as a homemade circuit board can be fabricated for a fraction of the cost compared to sending it out to a vendor. The drawbacks for homemade circuit boards are that they are not as professional looking, absent expensive machinery such as a CNC or drill press. Furthermore, etching small tracks at very close tolerances for surface mount components such as the LQFP48 may prove to be somewhat difficult. Etching a double sided board may also be more difficult than it seems. Shorts and opens may exist and not be discovered until later, requiring a partial or full rework of the whole board.

Hackvana is a PCB and electronic components vendor based out of Shenzhen China. Hackvana (nirvana for hackers), has supplied nearly 4,000 PCBs in just the last year alone. Since they are based in China, shipping time may be longer however manufacturing costs are greatly reduced. Hackvana is able to manufacture professional high quality circuit boards of any shape and size. Different color options are also available, as well as silk screen text.

Lastly, there is 4PCB. 4PCB is an American based circuit board manufacturer located in Aurora Colorado, Tempe Arizona, and Maple Grove Minneapolis. 4PCB is going to be the vendor of last resort for this project, considering the higher costs associated. They may also be considered if a PCB needs to be made and delivered ASAP, since they are in the USA. Being that 4PCB is a much larger and more established company than Hackvana, they are clearly reputable and reliable. Ultimately, the available funds and time will determine who wins the bid for circuit board vendor.

6.0 Project Prototype Testing

The purpose of this section of the project report is to give a detailed explanation on how testing of each of the project components as well as the project as a whole will be conducted.

6.1 Solar Panel Testing

Testing solar panels are not an easy task and setting up the appropriate testing environment was the first order of business when it comes to testing solar panels. The first thing that needed to be set up was to have a sturdy apparatus constructed for the solar panel to sit on. The elevation around 6 feet at 30 degrees. The power system was tested on the ground for safety reasons, although the final design is meant for the panels to be mounted on a roof. Before testing the panels, proper safety precautions were made. The safety procedure included the following:

- Checking if wires are grounded,
- Making sure rubber grips are used
- Using Multimeters that are capable of handling the current and voltage load from the solar panel

All of the Rating specifications are often found on the back of any solar panel. As part of the safety measures, all labeling will be read before testing.

To get an accurate read, the testing occurred in a “full sun” time of the day which was easy to do in April in Florida. This means that the sun needed to be fully exposed. This was conducted during the middle of the day.

The first test that was conducted was a Voltage test. To do this you need to get the voltage of an open circuit. In order to test voltage, a multimeter’s leads needs to be attached at the positive terminal and the negative terminal. This is where a warning needs to be made, because photovoltaic panels are live when exposed to sunlight, and it would result in serious injury if improper contact was made with the potential difference. Live voltage will be flowing through the terminals of the output. When this happens arc flashes, sparking or shocking could happen.

The next step in measuring the voltage is to double check that the multimeter is set to DC Voltage at the 200 V marking and on voltage. The rated open circuit voltage is on the back of the panel, and the voltmeter should read approximately the same value as the rated open circuit voltage.

The next measurement that will be tested will be the short circuit current. The rating for the short circuit current should also be on the panel, and that is the value that will be compared. To test the closed circuit current, the photovoltaic panel must be completely covered. A solution to this problem is to turn the panel away from the sun to that it is not absorbing direct photons. This is another safety precaution that will be put in effect to prevent sparking when hooking the photovoltaic cell to the Multimeter. As stated before, Photovoltaics in daylight are live.

When checking the current, the leads from the Multimeter must be pushed firmly into the input and output of the panel, and set to DC Amperes on the 10 Amperes range. Once connected the panel will be \turned to face the sun again. Once directly facing the sun, the solar panel were tilted so that they were facing the sun perpendicularly. The recorded current was then measured against the specifications on the back of the panel to test for actual output. Efficiency of the system was determined after testing was complete.

These two tests can be performed before purchasing a Solar Panel so that the system is confirmed to work as rated or better, but we could not do it since we purchased our panels online. To find how much power is being produced, this simple equation for DC power was applied:

Equation 6

$$\text{DC Watts} = \text{Voltage} \times \text{Current}$$

The power is measured in Watts (W), the voltage is measured in Volts (V), and current is measured in Amperes (I). The power generated in full sunlight depends upon the resistance of the electrical load connected to it. Ohm's law states that V = I x R, meaning that a simple method of measuring power output of a solar panel is to connect different values of resistors of to the panel and measure the voltage.

The measurements were used to plot the power output, and a performance graph for the individual panel. The manufacturer of the photovoltaic cell panel usually has this chart already prepared, results from individual testing can check the actual against the theoretical.

The only way to test if a solar panel is charging correctly is to test it with a battery. The photovoltaic cells will be producing DC voltage and current, so there is no problem in applying it directly to the battery using the appropriately gauged wire.

A multimeter were then connected, through short circuit, to find how much current is flowing through to the battery. This test also reveals the internal resistance of the battery. Once this was completed, using the same equations as before, an accurate assessment of how well the solar panels are actually charging the battery was made and actual power estimates were produced. The single most important factor when performing these tests was to perform them in the middle of a clear shining sun. This is because only direct sunlight will give correct readings as to what the peak performance of the panels truly are.

Above all, when working with high voltages and current, safety must be the highest priority. Utmost caution must be used in connecting the solar panel to anything while in direct sunlight. Under sunlight, the photovoltaic cell is producing DC voltage and current and can cause sparking r arc flashes when connecting.

Solar Panel Testing Checklist:

- Set multimeter to DC Voltage
- tests performed in the clear sunny sky
- Turn panel away from sun
- Perform Open Circuit Voltage test with multimeter
- Rotate the photovoltaic cell both away from the sun
- Turn the panel away from the sun
- Disconnect multimeter
- Set multimeter to DC Amperes
- Perform short circuit current test with multimeter
- Turn the photovoltaic panel towards the sun
- Rotate the photovoltaic cells perpendicular to the sun to measure the full DC current
- Turn the photovoltaic cell away from sunlight
- Disconnect multimeter
- Connect the Solar Panel directly to the Battery using appropriate gauged wiring
- Connect the multimeter

- Set multimeter to DC Amperes to measure the amount of DC current flowing into the battery.

- Rotate the photovoltaic cells away from the sun

- Record highest amount of current drawn.

- Turn the photovoltaic cells away from the sun

- Disconnect the battery.

6.2 Battery Testing

When testing a flooded battery it is very important to visually inspect it for obvious problems. Check to see if there is anything loose or broken. Verify also that the terminal clams are not corroded, dirty or wet. Get a digital voltmeter with 0.5% or better accuracy to test the state of the battery. The table below helped tp estimate the state of the battery.

Table 27 Voltage vs. State of Charge

Digital Voltmeter	Approximate State Of Charge
12.65	100%
12.45	75%
12.24	50%
12.06	25%
11.89	0%

After that we tested a battery charge time and discharge time in order to gauge the time of charge needed for the battery to be fully charged or discharged. The time of battery charge mainly depends on solar panels output power, which in turn depends on the irradiance level. The battery discharge time determine the maximum charge supplied to the inverter. See the tables below

Table 28 Battery Charge Time

Steps	Procedure	Expected Results
1	Connect the battery to the system with no load	Battery should start to Charge
2	Connect Multi-meter to battery to check for voltage	The Multi-meter should read a voltage that coincides with the charging stage
3	Connect Multi-meter to battery to check for current	The Multi-meter should read a current that coincides with the charging stage
4	Monitor the time it takes for the battery to reach the Float charging state	According to the battery and charge controller ratings, it should take 8 hrs

Table 29 Battery Discharge Time

Steps	Procedure	Expected Results
1	Connect the battery to the inverter with a predetermined load	Battery should start to discharge
2	Connect Multi-meter to battery to check for voltage	The Multi-meter should read battery-full voltage that will gradually decrease
3	Connect Multi-meter to battery to check for current	The Multi-meter should read a current that is being drawn
4	Monitor the time it takes for the battery to reach the Float charging state	According to the battery and load ratings, it should take 8 Hrs. at a 5Ah load rate

6.3 Inverter Testing

First, we tested if the inverter outputs an AC voltage of 120V from a 24V DC power source. The output waveform should be a modified sine wave with no distortion. The maximum power should be 500W and the surge power should be 600W. If any of the specifications above were not accomplished then the group had to go back to designing and building because without these specifications than the inverter could not be able to accomplish its goal of powering AC loads at the groups specifications.

When testing new equipment it is important to note what the equipment is meant to do, thus having an idea of what kind of testing to perform not only to check if it is in proper working condition but also meets safety standards and will not endanger its users. So if one looks at the purpose of the projects inverter, the device is used to convert DC power to AC power. Therefore, this device works with high voltage and current which will cause high temperatures coming from the device. The high temperatures can potentially cause a fire if there are no cooling properties for the device.

So for the first part of testing, we wanted to make sure that the inverter is safe to use for long periods of times without anything catching fire. Also, we had to take note that the system would be used in a non air-conditioned room. So to take this into account, we did temperature testing outside. As far as stress tests for the inverter, the group plans on running the inverter for 8 hours straight powering a low demanding AC load which is no more than 150 W and monitor the temperatures. Next, we will run the inverter at its max AC load for as long as the batteries can hold and monitor the temperatures. Depending on the results of these tests the inverter may require some idle time after being run at its max AC load. According to commercial inverter's user manuals and information considers the electrical components of the inverter, the surrounding air temperature should be between -20 C and 40 C. To help dissipate the temperatures from the inverter, the group plans to make the enclosure of the inverter of metal as well with small slits to provide ventilation [33].

Next, we address the warning/caution labels. The group plans to have a label on the inverter that addresses all the safety procedures that are involved when using the inverter. These also include the appliances which our solar panel powered energy source can be used safely. These warning label contents include but are not limited to the following:

- Danger of shock or electrocution - Please treat the inverter outlets the same as you would treat a standard power outlet.

- Do not use the inverter near flammable materials or any location that can contain flammable gases. Note that when disconnecting or connecting a device from/to the inverter a brief spark may occur.

- Do connect any appliance to the inverter that are wet or damaged.

- Do not let minors handle the inverter.

- Do not allow any liquids to contact the inverter.

- Do not leave the inverter in direct sunlight.

- Do not cover the inverter. Keep the inverter in a clear area that has good air circulation.

- Do not input anything different than a 24V DC power source. The inverter is made to work with 24V DC power source, anything else can damage the inverter.

- Make sure to connect the 24V DC power source correctly positive to the red terminal and black to the negative terminal. If not connected right, the inverter will be damaged.

- Do not connect the inverter to any appliance that uses over 700W of power to operate. It will not operate due to surge power requirements.

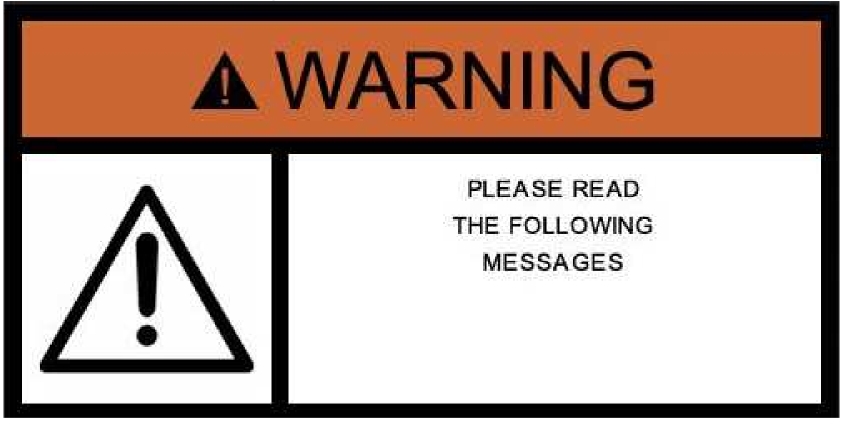
- Do not use this inverter with medical equipment.

- Do not use this inverter while in motion.

- In the event of anything irregular with the system IMMEDIATELY turn the inverter off and disconnect any appliances from the inverter.

The group plans on having the above warning label contents in a warning label on the surface of the inverter, where it is clear to see and read by the users. The following is a sample of how the warning label will look like. Note that the above guidelines are not on the label, however they will be in the finished product.

Figure 40 Warning Label Sample
Permission Pending



Next, we address surge power for the appliances being used with the inverter. The surge power also called peak power or load is the initial power input an appliance needs to start. Once started the appliance needs less power to operate. In the case of this inverter, the surge power is 600W. Any appliance with a higher surge power will not start or operate with this inverter. This operating power of an appliance is called continuous load in terms of power requirements. Most appliances will not mention how much power it needs to start and operate. So the user has to determine these two values. If it is looks for values in Watts(W) in a stick or label of the appliance or its charger or user's manual. If not, then we can calculate from Amperes(A) by multiplying the Amperes * 120V which equals the continuous load in Watts(W). For most appliances, one can multiply the continuous load in Watts(W) by two to find the surge power requirements also in Watts(W). Note, that this is just an approximations and some appliances including refrigerators have a much higher surge power requirement.

6.4 Sensor Testing

A testing plan, shown in the following tables has been made in order to make sure that all of the sensors that are going to be incorporated work the way they are supposed to work. This also helped to eliminate the possibility of any factory defects existing before they were implemented into the final design. The following tables contain each sensor to be tested with the test plan that was put in place for each sensor followed by the results.

Table 30 Voltage Sensor

Step #	Procedure	Results
1	Devise a voltage divider configuration.	Standard.
2	Calculate appropriate resistor values based on the Solar panel and microcontroller specs.	R_1= Large R value R_2= Small value V_{out} < 5 volts min
3	Simulate Voltage Divider using a circuit simulation software.	Circuit simulation should reflect previous expected results.
4	Build a voltage follower connected to a low pass filter.	V_{out} was equal at the designated points.
5	Construct circuit and test it	Results reflected the simulation results.

Table 31 Current Sensor

Step #	Procedure	Results
1	Implement the shunt resistor monitor in the a circuit design.	Shunt resistor was in series with voltage source.
2	The current value is going be verified in both the Microcontroller and the Voltmeter	Current was the same on both devices.

Table 32 Temperature Sensor

Step #	Procedure	Results
1	Temperature sensor is connected to the Microcontroller.	A value was outputted by the sensor.
2	Sensor is tested in room temperature and compared with a thermometer.	Both temperature results were close to equal.
3	Extra heat is applied to both thermometer and temperature sensor.	Increase in Temperature reading in the thermometer matched the sensor's readings.

Table 33 Solar Radiation Sensor

Step #	Procedure	Results
1	The Sensor is connected to the Microcontroller board	Data was received from the output of the Microcontroller.
2	Ambient light will be increased and decreased.	Noticeable changes in the raw data were observed.
3	Sensor will be placed in direct sunlight and in shade.	Similar results as the previous test were obtained.
4	The algorithm to translate the reading to lumens will be implemented.	Direct sunlight: 100,000 lux. Cloudy sky: 5,000 - 10,000 lux Moonlight: Less than 0.25 lux.

6.5 Wiring Testing and Precautions

When connecting the wiring between the different parts of the system, we first powered off all parts including the charge controller and inverter. We made sure the power cable was not connected to the inverter as well.

The first step began by connecting the solar panels to the charge controller. The length and elevation of the wire was very important. Minimizing these factors allowed a decrease in the voltage drop. Now, since the solar panels will be mounted on the roof of the Pomolong community center and the charge controller will be placed inside the center, it was estimated to be about 20 feet of wire distance between the two. Also, it was taken into account that the solar panels run at 8.5 A at maximum capture. Multiplying this by two to factor in two panels was 17 A. Finally, the solar panel connection were 48V. These specifications required a 10 AWG wire for the this connection.

Next, we connected the charge controller to the batteries. The same size wires were used because these wires did not carry any more current than the solar panel to the charge controller connection.

Next, the connection between the batteries were addressed. Since we are using two batteries in parallel the connection was very simple and straightforward. The positive of one battery was connected to the positive of another battery. The other terminals were connected to other devices. 4 AWG wire were used to do the connection of the batteries.

Finally, it was important to identify the polarity of the power cables and its terminals; red is for positive and black for negative. This was really important because if a device is connected with the wrong polarity the internals of the device can blow up and become damaged. Thus, we connected the power cables from the batteries to the inverter using 8 AWG cables. A spark may occur which was fine because the batteries contain power thus giving a chance of spark. It was important to be far away from any flammable materials or liquids when doing the connections. As an extra precaution, there will be a fuse between the batteries and inverter to prevent overload of the inverter The fuse has an ampere rating of 30 which will cover all operations up to 600W which is less than the surge power of the inverter. So if any wiring short occurs the fuse will burn out before the inverter.

To conclude, after all the wires were connected it was important to trace all the wiring and make sure they were all secure and safe. A regular check can be beneficial due to the fact that over time wire connections can become loose. Also, it is important to stress that all devices must be powered off when performing connections to prevent any damage to the system.

7.0 User Manual

The Purpose of this section is to give the user detailed instructions on how to operate the power system

7.1 Setup

Connecting the photovoltaic (PV) panels

The photovoltaic panels are polarized and must be connected properly. The charge controller has terminal studs labeled “PV” and “Battery”. The PV panels must be connected at the studs labeled “PV”. The positive lead of the PV panel array must connect to the stud labeled “+”, and the negative lead connects to the stud adjacent to it. PV inputs are rated for a maximum of 20A. **Warning**: failure to connect the PV panels with the proper polarity may result in damage to the charge controller.

Connecting the batteries

The battery bank is also polarized and likewise must be connected properly. The charge controller has two terminal studs underneath the PV terminals. The positive lead of the battery bank must connect to the stud labeled “+”, and the negative lead connects to the stud adjacent to it. Maximum battery current is fused and rated at 20A. Warning: failure to connect the PV panels with the proper polarity may result in damage to the charge controller.

Connecting the loads

Loads can be connected via the wall outlet located on the charge controller next to the PV and battery terminals. The load will be powered by a 115-120V, 60Hz modified sine wave. Any load up to 500 watts will function normally. If there is a surge in current, or the load is too high, an alarm will sound and the load will be cut off from the power source. In this event, the power switch will require resetting. Maximum load current is fused and rated at 20A. Warning: the voltage at the load terminals is dangerous and potentially life threatening. Do not connect any load with exposed wiring, or around children or animals, without proper supervision.

7.2 Operation

Once the PV panels, battery bank, and loads are connected, the system can be turned on via the power switch. The power switch is responsible for giving battery power to the charge controller. Once the switch has been closed, the load should begin receiving power. If there is sufficient solar energy available, the status LEDs should also light up. Without sufficient solar energy (PV voltage >= 11V), the controller will remain in standby mode with all LEDs off. The load will still work in this state. The status LED indicators are as follows:

i. Green ON: Battery is charging.
ii. Green blinking: Battery is fully charged.
iii. Yellow blinking: Battery is low.
iv. Red ON: Battery is low and/or load is too high (cut-off).
v. All LEDs OFF: System is in standby.

7.3 Monitoring and Logging

The charge controller can be monitored via a serial connection to a PC/laptop. Using hyperterminal or any similar serial connection application, the output can be viewed by creating a connection on COM1 with the following parameters:

i. Baud rate: 57600 bps
ii. Data bits: 8
iii. Stop bits: 1
iv. Parity: None

Once the connection is opened, real time data will begin scrolling on screen. The columns shown are described respectively:

PV voltage (mV)
PV current (mA)
PV power (μW)
battery voltage (mV)
battery current (mA)
ambient temperature (Celsius)
Load current (mA)
PWM duty cycle

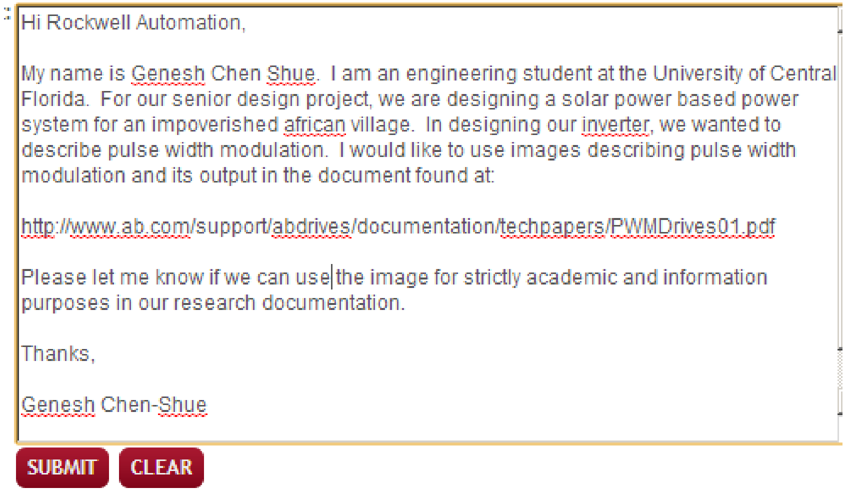
The controller output will say **TRACKING** when it is tracking for the maximum power point (MPP). Once the MPP has been found, the following will be displayed in the terminal:

```
*MPP LATCHED: Vmpp(mV) = 17067 | Wmpp (uW) = 18483561 | PW = 261
```

This means the maximum power point has been achieved and the battery is being charged at optimum efficiency. In the event that the controller output freezes or stops responding, the software can be reset by momentarily pushing the red reset button located on the side of the charge controller. This will restart the system and should begin tracking for MPP again.

Appendices

Appendix A - Copyright Permissions



Hi Rockwell Automation,

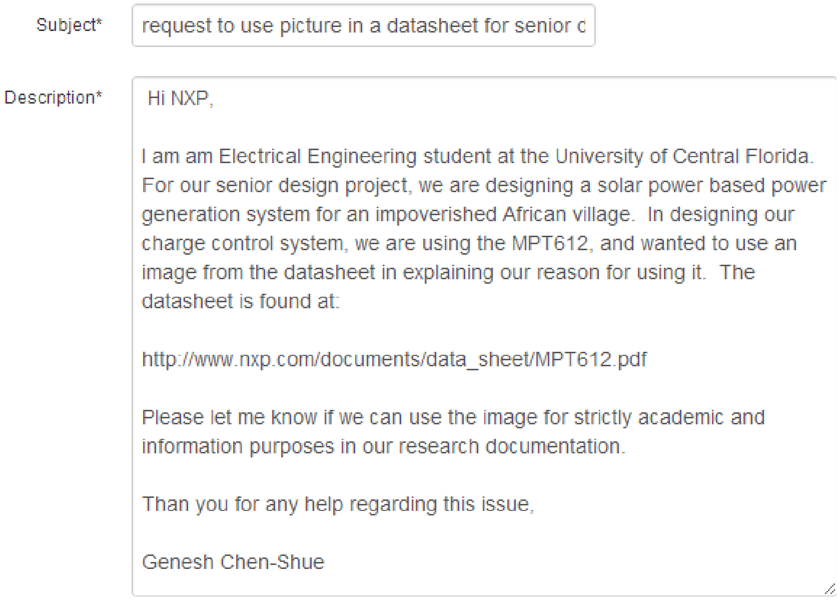
My name is Genesh Chen Shue. I am an engineering student at the University of Central Florida. For our senior design project, we are designing a solar power based power system for an impoverished african village. In designing our inverter, we wanted to describe pulse width modulation. I would like to use images describing pulse width modulation and its output in the document found at:

http://www.ab.com/support/abdrives/documentation/techpapers/PWMDrives01.pdf

Please let me know if we can use the image for strictly academic and information purposes in our research documentation.

Thanks,

Genesh Chen-Shue



Subject* request to use picture in a datasheet for senior c

Description*

Hi NXP,

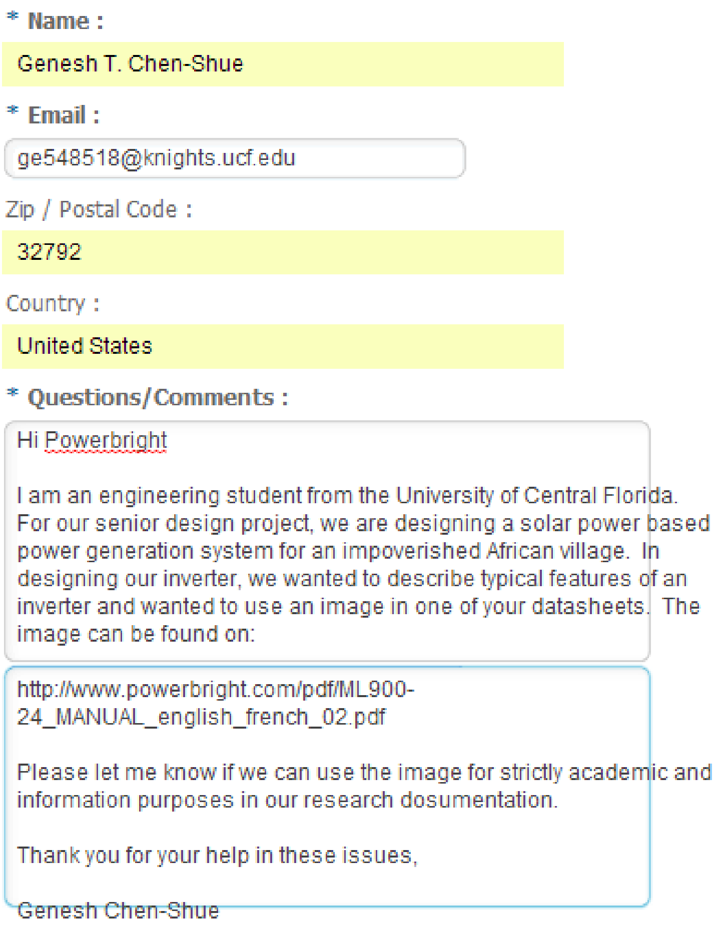
I am am Electrical Engineering student at the University of Central Florida. For our senior design project, we are designing a solar power based power generation system for an impoverished African village. In designing our charge control system, we are using the MPT612, and wanted to use an image from the datasheet in explaining our reason for using it. The datasheet is found at:

http://www.nxp.com/documents/data_sheet/MPT612.pdf

Please let me know if we can use the image for strictly academic and information purposes in our research documentation.

Than you for any help regarding this issue,

Genesh Chen-Shue



* **Name :** Genesh T. Chen-Shue

* **Email :** ge548518@knights.ucf.edu

Zip / Postal Code : 32792

Country : United States

* **Questions/Comments :**

Hi Powerbright

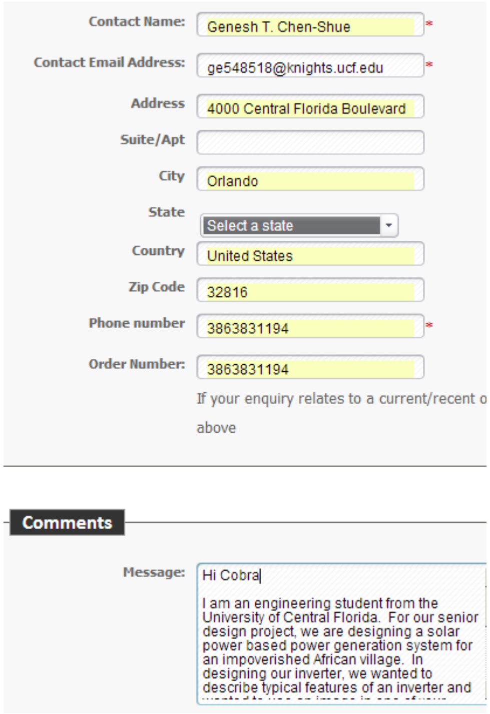
I am an engineering student from the University of Central Florida. For our senior design project, we are designing a solar power based power generation system for an impoverished African village. In designing our inverter, we wanted to describe typical features of an inverter and wanted to use an image in one of your datasheets. The image can be found on:

http://www.powerbright.com/pdf/ML900-24_MANUAL_english_french_02.pdf

Please let me know if we can use the image for strictly academic and information purposes in our research dosumentation.

Thank you for your help in these issues,

Genesh Chen-Shue



Contact Name: Genesh T. Chen-Shue *

Contact Email Address: ge548518@knights.ucf.edu *

Address 4000 Central Florida Boulevard

Suite/Apt

City Orlando

State Select a state

Country United States

Zip Code 32816

Phone number 3863831194 *

Order Number: 3863831194

If your enquiry relates to a current/recent o

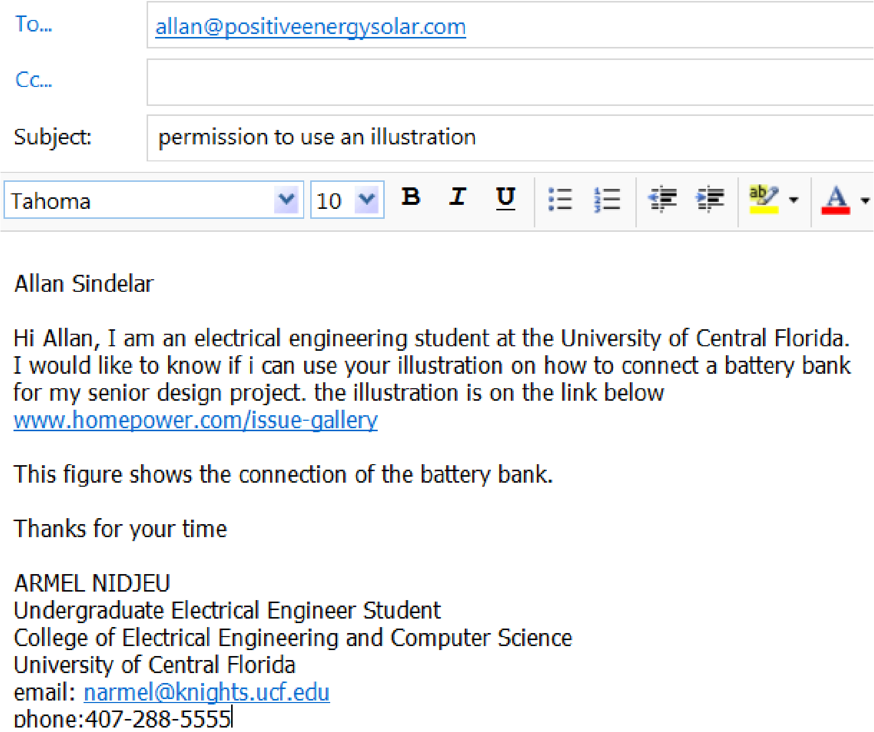
above

Comments

Message:

Hi Cobra

I am an engineering student from the University of Central Florida. For our senior design project, we are designing a solar power based power generation system for an impoverished African village. In designing our inverter, we wanted to describe typical features of an inverter and



To... allan@positiveenergysolar.com

Cc...

Subject: permission to use an illustration

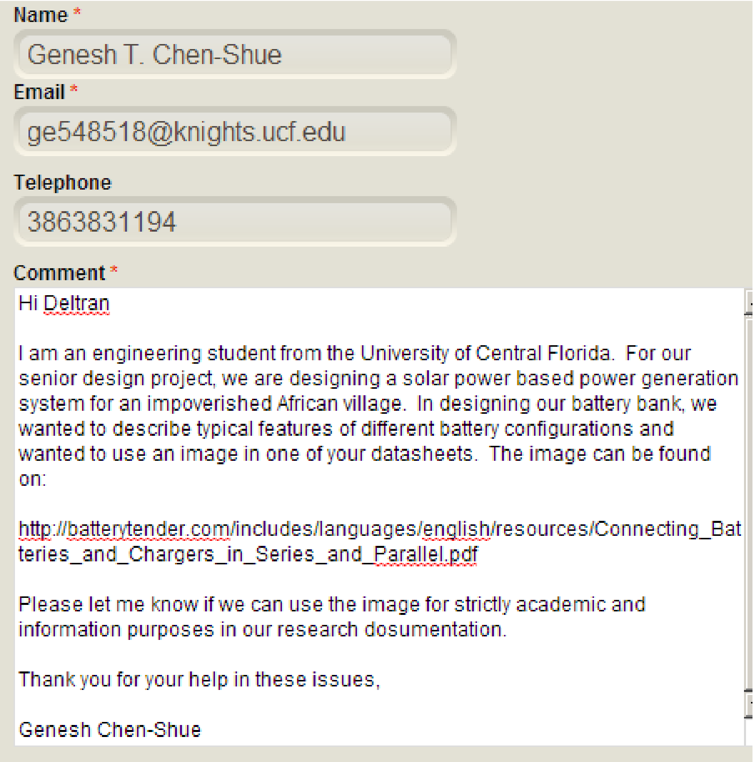
Allan Sindelar

Hi Allan, I am an electrical engineering student at the University of Central Florida. I would like to know if i can use your illustration on how to connect a battery bank for my senior design project. the illustration is on the link below
www.homepower.com/issue-gallery

This figure shows the connection of the battery bank.

Thanks for your time

ARMEL NIDJEU
Undergraduate Electrical Engineer Student
College of Electrical Engineering and Computer Science
University of Central Florida
email: narmel@knights.ucf.edu
phone:407-288-5555



Name *
Genesh T. Chen-Shue

Email *
ge548518@knights.ucf.edu

Telephone
3863831194

Comment *

Hi Deltran

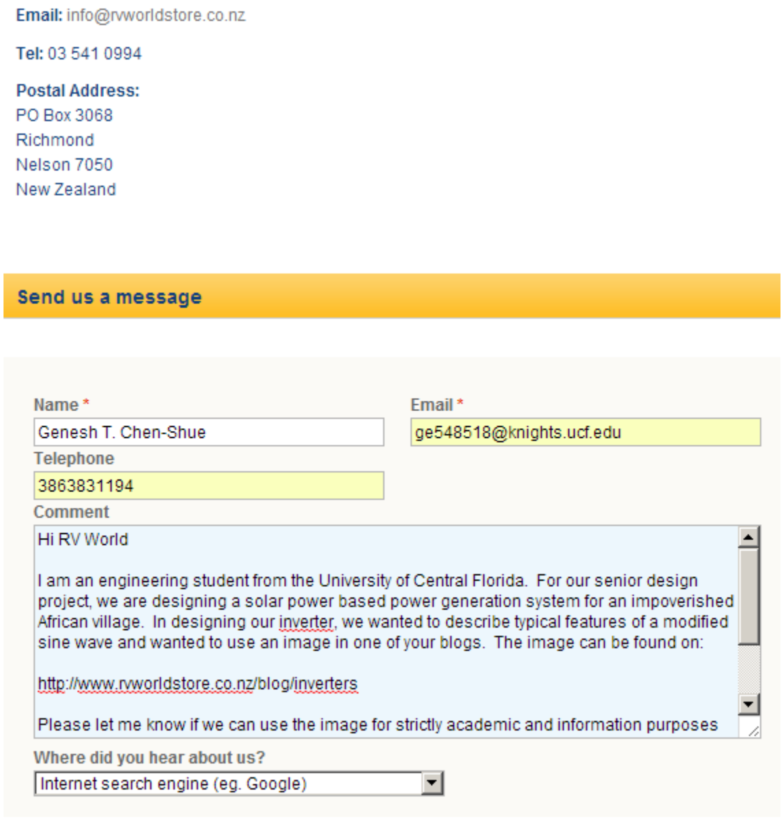
I am an engineering student from the University of Central Florida. For our senior design project, we are designing a solar power based power generation system for an impoverished African village. In designing our battery bank, we wanted to describe typical features of different battery configurations and wanted to use an image in one of your datasheets. The image can be found on:

http://batterytender.com/includes/languages/english/resources/Connecting_Batteries_and_Chargers_in_Series_and_Parallel.pdf

Please let me know if we can use the image for strictly academic and information purposes in our research dosumentation.

Thank you for your help in these issues,

Genesh Chen-Shue



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Postal Address:
PO Box 3068
Richmond
Nelson 7050
New Zealand

Name * Genesh T. Chen-Shue

Email * ge548518@knights.ucf.edu

Telephone 3863831194

Comment

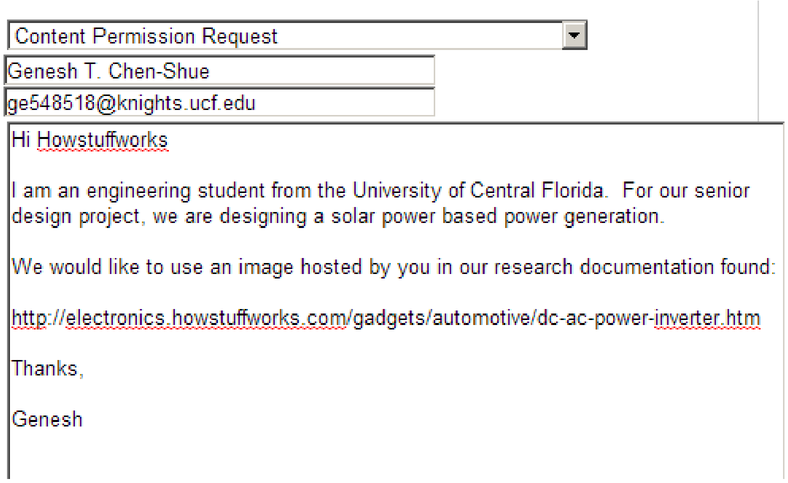
Hi RV World

I am an engineering student from the University of Central Florida. For our senior design project, we are designing a solar power based power generation system for an impoverished African village. In designing our inverter, we wanted to describe typical features of a modified sine wave and wanted to use an image in one of your blogs. The image can be found on:

http://www.rvworldstore.co.nz/blog/inverters

Please let me know if we can use the image for strictly academic and information purposes

Where did you hear about us? Internet search engine (eg. Google)



Content Permission Request

Genesh T. Chen-Shue

ge548518@knights.ucf.edu

Hi Howstuffworks

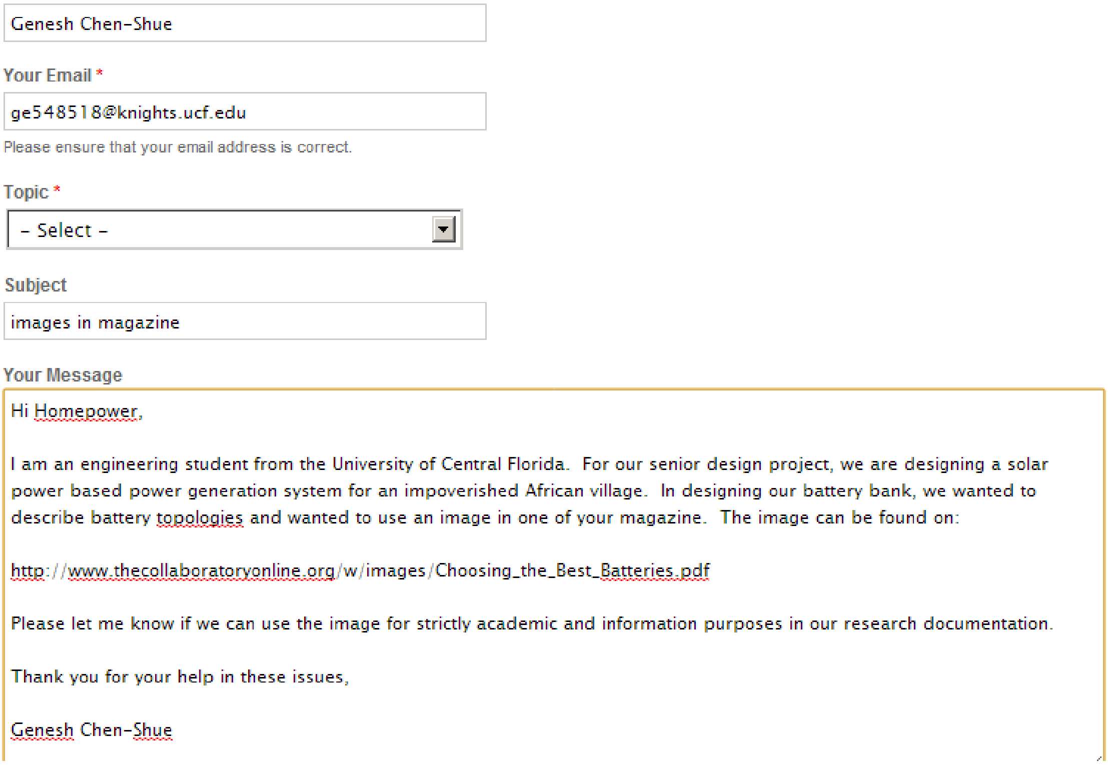
I am an engineering student from the University of Central Florida. For our senior design project, we are designing a solar power based power generation.

We would like to use an image hosted by you in our research documentation found:

http://electronics.howstuffworks.com/gadgets/automotive/dc-ac-power-inverter.htm

Thanks,

Genesh



Genesh Chen-Shue

Your Email *

ge548518@knights.ucf.edu

Please ensure that your email address is correct.

Topic *

- Select -

Subject

images in magazine

Your Message

Hi Homepower,

I am an engineering student from the University of Central Florida. For our senior design project, we are designing a solar power based power generation system for an impoverished African village. In designing our battery bank, we wanted to describe battery topologies and wanted to use an image in one of your magazine. The image can be found on:

http://www.thecollaboratoryonline.org/w/images/Choosing_the_Best_Batteries.pdf

Please let me know if we can use the image for strictly academic and information purposes in our research documentation.

Thank you for your help in these issues,

Genesh Chen-Shue

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Appendix C - List of Figures

Appendix D - List of Tables

Appendix E - List of Equations