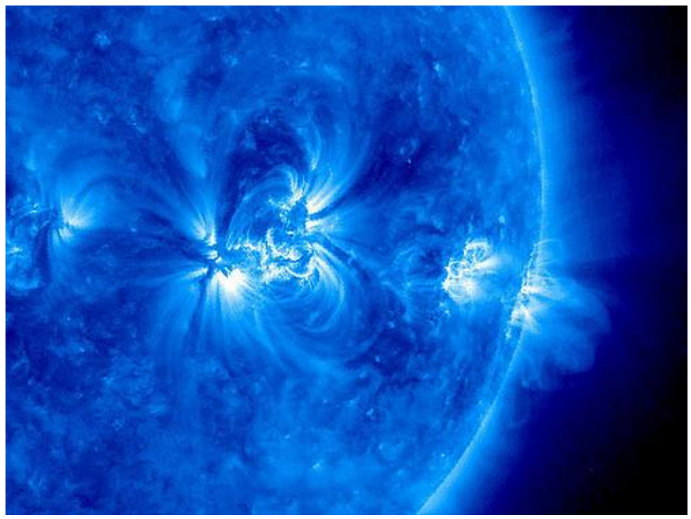
Highly Integrated Grid-Tied Power Module for PV and Storage (iPV++)



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1.0 Executive Summary

According to SEIA, “Solar energy is the cleanest and most abundant renewable energy source available, and the U.S. has some of the richest solar resources in the world”. As we know, the sun is virtually an unlimited energy resource, and there are various ways to harvest this energy. Methods of harvesting consist of using photovoltaic cells, solar thermal collectors, solar concentration centers with mirrors, and passive solar designs.

Starting with photovoltaic cells, they are able to convert solar rays into energy. “When sunlight hits a cell, the energy knocks electrons free of their atoms, allowing them to flow through the material. The resulting DC (direct current) electricity is then sent to a power inverter for conversion to AC (alternating current), which is the form in which electric power is delivered to homes and businesses”.

Our senior design project takes the average solar panel system and converts it into a single package, a modern photovoltaic system. A photovoltaic panel, battery, and inverter all three combined into one product that is intertwined within the power grid. “The main goal of this proposed effort is to investigate, design and develop an advanced integrated and cost-effective technology consisting of PV, smart inverter, and battery management”.

iPV++ is a multidisciplinary project, including mechanical and electrical engineers. This report will focus on the electrical design of power electronics and battery integration. Starting with the design of the dual-input isolated DC/DC converter, we will create an efficient 1.2 kW dual input converter. Extensive analysis and testing will be needed to reduce the cost and improve reliability. Next, the bi-directional single-phase inverter will be constructed. This will be designed and tested with the input DC link voltage of 200 V. Finally we will design and investigate the battery size. Ensuring that the proper battery size is obtained for the power that will be supplied from the PV panel. This battery design and inverter will also need to be implemented within the thermal packaging to ensure minimum energy losses. Collaboration with the mechanical engineers will be required in order to complete this task and provide adequate airflow to cool the system.

2.0 Project Specifications

In this section, we discuss the motivation, goals and objectives, design requirements, block diagrams of responsibilities, roles and responsibilities of both the electrical and mechanical teams, timelines, budget and financing goals, and the house of quality for the highly integrated grid-tied power module for PV and storage.

2.1 Motivation

Our group, Group 17, is composed of members who are very passionate about the power industry in general. Throughout our education at the University of Central Florida, we have carefully chosen classes which would make us much more attractive to potential employers within the power industry. Although our passion for this began beforehand, through our individual research into the power industry, we became further enamored by taking the fundamentals of power systems course offered within our coursework. This class enlightened us on the multiple disciplines that we as newly graduated students could find employment within the power industry, the collective issues that exist within it, and the troubleshooting techniques and software that are popular within the industry.

This project, specifically, allows us to work with professionals who are deeply embedded within the power industry and have contributed ample amounts of progress to it. Through it, although we are sure it will be an arduous experience throughout our two semesters of senior design, we hope to gain valuable knowledge that will undoubtedly help us join the industry with experience that will help us stand out from our peers. We also hope that our final design will be robust and substantial enough to grant us a spot in some of the top projects at the end of our journey -- which will in turn cause more visiting industry professionals and faculty to be aware of the beauty within the power industry. Further, during the span of this project, tariffs were placed on the export of solar panels. We hope that projects like ours will help contribute to the overall opinion of clean energy within the country so that more industry professionals, politicians, and civilians alike will make the push for a more clean energy approach to energy distribution.

2.2 Goals and Objectives

The main goals for this project are to design and build an interesting and unique inclusion to the power industry. The design should be aesthetically pleasing and meet the design requirements proposed by our sponsor. The project will be technologically complex and shall be integrated in a timely manner, so as to meet our design schedule by the end our two semesters of senior design. As such, both the technical and non-technical parts of the project shall be integrated closely to reinforce synergy and the ability to easily troubleshoot individual components and the overall system requirements.

The main goals for this project are to create an integrated power module for solar panels that include the microinverter, DC/DC converter, microcontroller and battery pack. This new power module will have to be small enough to fit behind individual solar panels and have a detachable battery to accommodate different battery size requirements. This new module will also have to be easy to install that way people can buy them and install it themselves. When designing the DC/DC converter, we have make sure it's at least 95% efficient to be able to compete with other DC/DC converters already in market.

Another goal is to create an algorithm to program into the microcontroller that will be able to control the different states of the converter such as solar panels charging the batteries, solar panels feeding power into the grids, and solar panels and batteries feeding power into the grid.

2.2.1 Efficiency

The efficiency of the system will have to be high enough to compete with the unintegrated systems that already exist.

2.2.2 Small Scalability

The system will be a small scale prototype to illustrate the idea of a fully integrated solar panel system that can be bought and installed by the user without having to hire a contractor.

2.2.3 Low Maintainability and User Friendliness

The system will be built to fit under a solar panel. It will have a racking system built by the mechanical engineering team that can slide out and will contain the iPV++ integrated power module and an interchangeable battery pack that size will vary depending on how much solar power can be generated where you live. This will allow user to buy and install the system. This system will also have to be low maintenance. The components used will have to be able to withstand a big temperature range -20°C to 70°C (-4°F to 158°F) and need to be in a weatherproof sealed box to withstand rain, snow, dust storms. The connection between the battery and the iPV++ power module will have to be a sealed quick connect to allow for fast installation or replacement of the battery.

2.2.4 Primary Input – Solar Panels

One of the inputs into the iPV++ power module will be the power produced from the solar panels. According to solar power rocks the average power of solar panels installed in the United States was 265 W in 2015. We will be using a 300 to 330 W solar panel. The power produced from this solar panel will go into the iPV++ power module. From there, the power module will select if it will use this energy to charge the battery or feed it into the grid.

2.2.5 Secondary Input – Batteries
The second input into the iPV++ module will be the battery. The battery will be used to store the energy locally on each solar panel instead of a battery bank inside of the house. This battery will also provide energy into the grid dependent on how much power the iPV++ module has decided to send into the grid from the battery. The battery used for the project will have to be weatherproof to withstand the rain and snow. There will also have to be way to keep the batteries from overheating.

2.2.6 DC/DC Converter
The DC/DC converter is the main part of this project. The goal is to create a dual input DC/DC converter that will have a battery connected on one side as an input and output and the solar panel on the other side as only an input. This converter will also have different modes that it must choose from by controlling the duty cycle on the power mosfet. Lastly, this converter must incorporate a boost converter to be able to boost the voltage from the solar panels and have enough current to charge the battery.

2.2.7 DC/AC Inverter
The goals and objectives of the DC/AC inverter are to create a bidirectional inverter that is connected to the utility grid as an input and output. This inverter must be able to synchronize with the utility grid when it is in output mode.

2.2.8 Power Management
In order to ensure the power that is being delivered to the customers is consistent, we will be developing software that will determine if power will be supplied from the solar panel or the battery. Using four different switches in our circuit board design, we will use a microcontroller to develop constraints to control this.

2.2.9 Output
The main goal of the output is to deliver 300 watts of power to the grid, with a frequency of 60 Hz. In addition to this, our design will meet the various constraints as described in the section below.

2.3 Design Requirements
In this section, we will discuss the requirements set upon our group by our sponsor for our final design. Our group will base all our research and design procedures towards the following list so that our final design meets the full capabilities that our sponsor had in mind when he proposed the project.

- The solar panels will provide the main source of energy to the batteries and if full, provided to the grid.

- The integrated microcontroller will keep power flow steady using energy from the batteries if any disturbances occur when the solar panel is interrupted by clouds, residue, etc.

- Low voltage generated by the solar panel will be stepped up via the DC/DC converter to aid in faster charging of the batteries.

- The bi-directional single-phase inverter will allow the solar panels or batteries to power the grid with AC power or allow the grid to charge the battery when the demand is low and sun coverage is poor.

2.4 Roles and Responsibilities

This is a multidisciplinary project that will require effort from all group members. The roles and responsibilities are divided as the following:

2.4.1 The Electrical Team

Angelica Becker

- Network diagram, battery phase and type research, and soldering, copper wire specifications, and any other specifications dealing with connecting components. Research of DC/DC controller.

Jeffrey Claudio

- Network diagram, battery phase and type research, and soldering, copper wire specifications, and any other specifications dealing with connecting components. Research of DC/DC controller.

Emmanuel Ortiz

- Assisting with circuit board design, researching capacitors, circuit board characteristics, and any other parts related to the circuit board. Also, edit and combine information for final report.

2.4.2 The Mechanical Team

Daniel Croatti

- Assisting with circuit board design, researching capacitors, circuit board characteristics, and any other parts related to the circuit board. Also, edit and combine information for final report.

Teron Lewis

- Assisting with circuit board design, researching capacitors, circuit board characteristics, and any other parts related to the circuit board. Also, edit and combine information for final report.

Eric Ross

- Assisting with circuit board design, researching capacitors, circuit board characteristics, and any other parts related to the circuit board. Also, edit and combine information for final report.

Chun Yip Yung

- Solidwork Cad design, Simulation, Data Analysis. Budgeting, purchasing, tracking, and coordinating pick up and drop off.

2.5 Project Block Diagrams

For this project, the main component will be the integrated micro-inverter module which will govern how the solar panel and battery will work in unison to increase PV penetration into the grid. Figure 1. shows the hardware configuration of the proposed system and Figure 2. shows what the microcontroller will control.

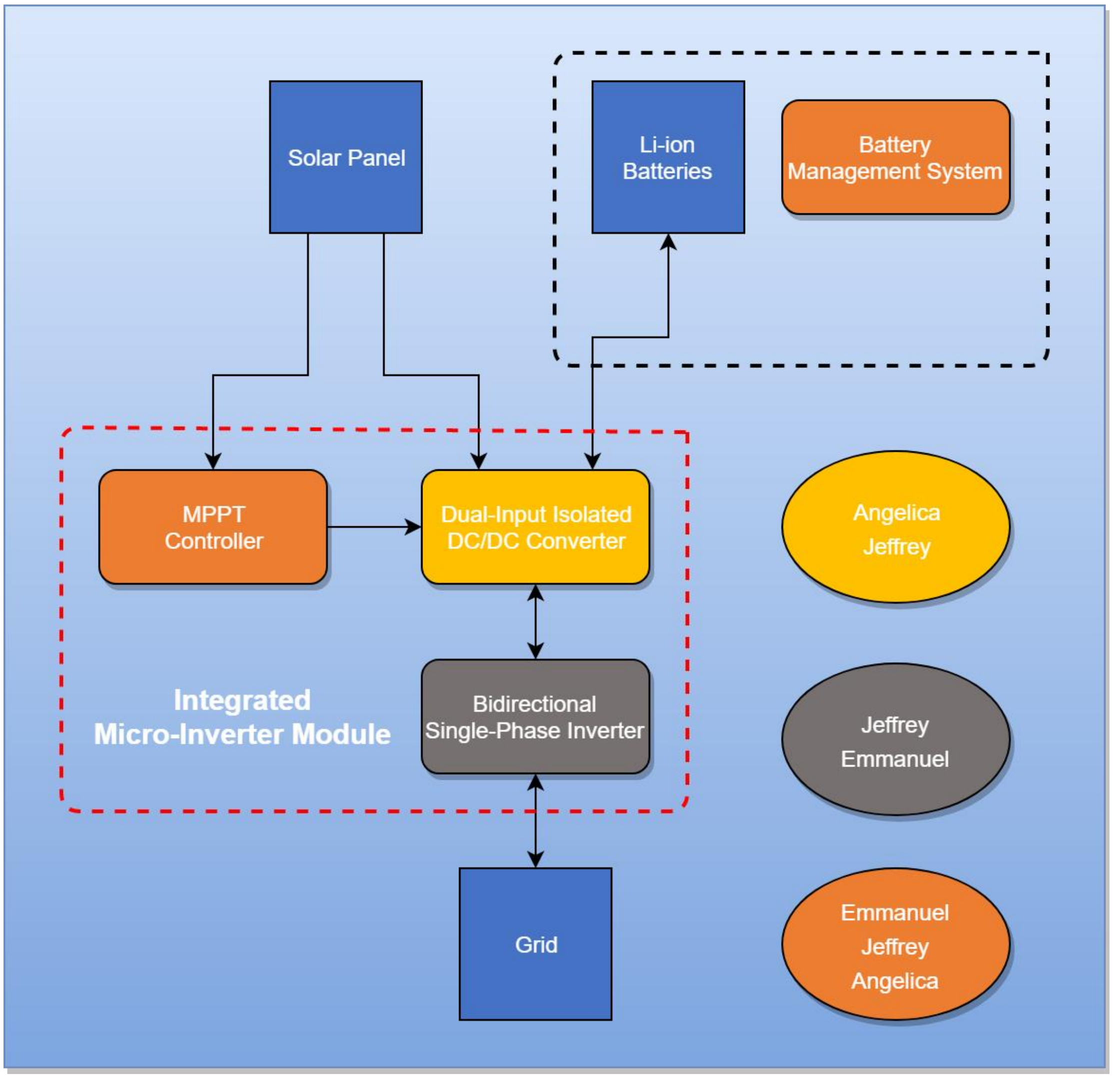


Figure 1. Hardware Block Diagram

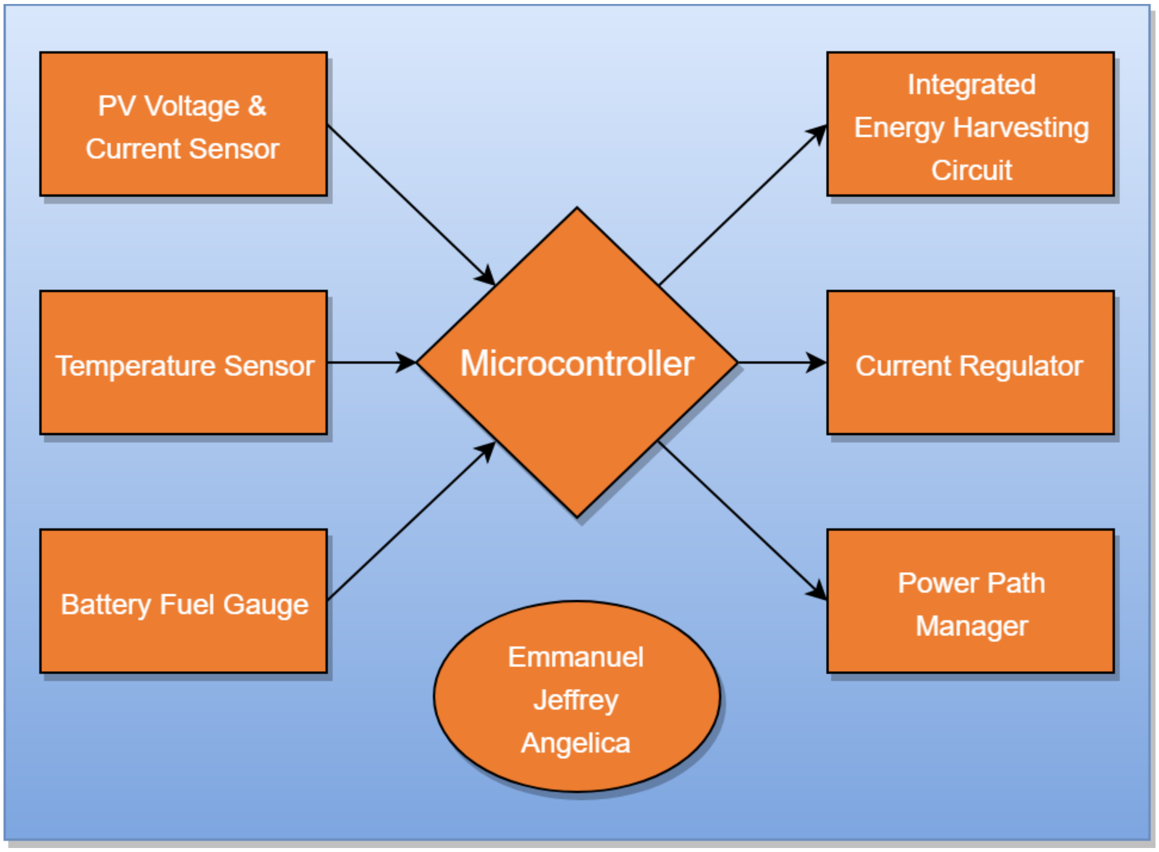


Figure 2. Software Block Diagram

2.6 Timeline

In order to ensure tasks would be completed within a certain time period, we created multiple goals to reach and tracked them in the following tables.

2.6.1 Senior Design I Spring 2018 Project Milestones

Shown in Table 1. are the due dates of each task that we created in Senior Design I, spring 2018. With the various issues we faced at the beginning of our project and the issues with communication, finishing the following tasks were very strenuous and time consuming.

Task	Start	End	Status
Project Topic Selection	1/15/2018	1/18/2018	Completed
Divide and Conquer (Rough Draft)	1/22/2018	1/28/2018	Completed
Hardware Research	1/28/2018	5/2018	Completed
Rough Draft of Report (45 Pages)	1/28/2018	4/9/2018	Completed
Selection of needed Components	1/28/2018	5/2018	Postponed
Software Research	1/28/2018	5/2018	Postponed
Meeting with Mechanical Engineers	2/20/2018	3/2018	Completed
Final Draft of Report (90 Pages)	1/28/2018	4/27/2018	Completed

Table 1. Spring 2018 Project Schedule

2.6.2 Senior Design II Summer 2018 Project Milestones

Shown in Table 2. are the due dates of each task that we created in Senior Design 2, summer 2018 class. These are tentative dates and are subject to change throughout the semester.

Task	Start	End	Status
Assembling the prototype	05/2018	06/2018	Completed
Develop software for microcontroller	05/2018	07/2018	Completed
Troubleshooting	05/2018	07/2018	Completed
Design and buy PCB	05/2018	06/2018	Completed
Test and fine tune the PCB	05/2018	06/2018	Completed
Finalize Device with Mech. Engineers	06/2018	07/2018	Completed

Table 2. Summer 2018 Project Schedule

2.7 Budget and Financing Goals

For the design of the iPV++ module or for any design, money is a constraint that affects the quality and efficiency of the product. The goal is to minimize cost and optimize efficiency thus leading to a robust design. The battery will be provided by AllCell and is not considered a financial hindrance; however, despite this being a sponsored project, there will be no funding from the sponsor. Table 3. shows the estimated cost for the entire module to be designed.

Item Description	Price / Unit	Quantity	Subtotal
Solar Panel	Rental	1	N/A
Li-ion Batteries	Free	N/A	N/A
DC/DC Converter	$174.75	1	$174.75
Single Phase Inverter	$112.28	2	$224.57
PCB	$2.80	20	$56.00
Total Cost			$455.33

Table 3. Budget and Financing

2.8 House of Quality

The house of quality is a systematic graphical representation of product design information organized as a matrix, which provides an illustrative summary of useful product information. Usually there are two dimensions in the house of quality one representing customer requirements and the other engineering requirements. The customer requirements came first since anything being designed needs to meet their requirements. The engineering requirements depict how those requirements are going to get met. Table 4. represents the house of quality that our group devised for this project:

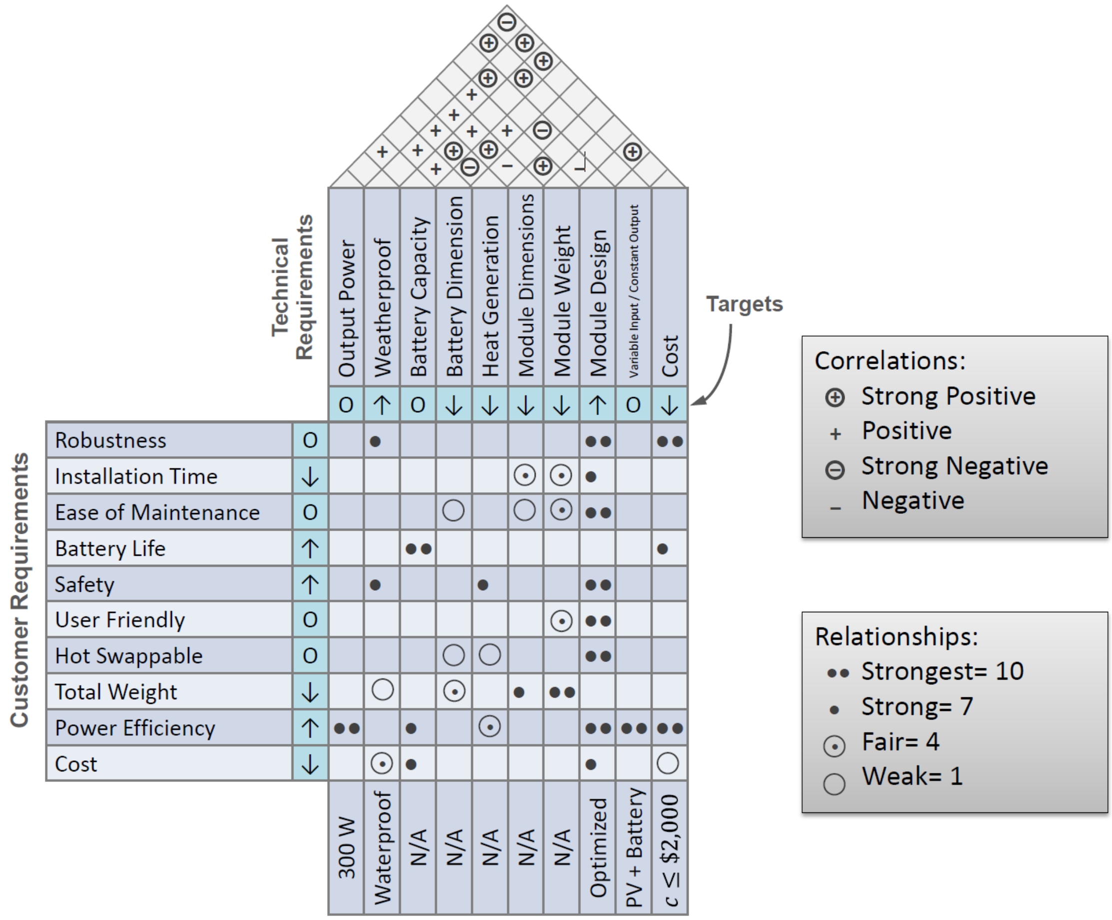


Table 4. House of Quality

As shown, these parameters are qualitative and focus on the elements of the project which provide the largest influence in determining the marketability of the product. Our group feels that the device should be very interactive, have ease of use and integration, feel intuitive, and be well documented from a non-technical standpoint.

The engineering parameters within this table provide information on the structural integrity of the product, and should follow the dimensions set by the design parameters and requirements proposed by our sponsor. Ideally, our device would have a low amount of heat dissipation and would store adequate amounts of energy.

3.0 Research and General Knowledge

In this section, we discuss the general knowledge of the different parts of the project. With a primary focus of the following topics: Existing similar projects and products, solar panels, batteries, transformers, AC/DC rectifiers, DC/DC converters, DC/AC inverters, load management, MPPT algorithms, PCB boards, microcontrollers, power management system and finally the mechanical research.

3.1 Existing Similar Projects and Products

As the project depicts, the goal is to design a PV module that increases PV penetration into the grid. This approach is not anything new and other companies have either developed a product or are currently in the process of developing such implementations.

3.1.1 SolPad

Currently SolPad has a product called SolPad Mobile which includes many features including power generation, inversion, and battery storage. This module is meant to be portable and is primarily designed as a means of portable power. It is capable of outputting at 115/230 VAC sinusoidal at 60/50 Hz being able to output 1,000 WAC continuously. Besides this product, according to the SolPad's website, SolPad Home is coming this year. This variant is designed to supply power to entire homes and like many PV systems built into homes, is capable of supplying power to the grid.

3.1.2 Integrated Renewable Power System Controller

A charge controller or charge regulator is basically a voltage and/or current regulator to keep batteries from overcharging. It regulates the voltage and current coming from the solar panels going to the battery. Most of the solar panels have more voltage than batteries. If the voltage left unregulated batteries will be damaged from overcharging.

3.1.3 Standard Controller

Often work with high voltage panels with maximum input voltage of the charge controller being within limit. However, from 20 to 60% of power will be lost. Charge controls take the output of the panels and feed current to the battery until the battery is fully charged. A solar panel can only output certain amps. When the voltage is reduced, the power is lost in the processes since the power function is I^2R.

3.1.4 Simple 1 or 2 Stage Control

This is a very old system. It relies of relays or shunt transistors to control voltage in a one or two steps. Essentially this control short or disconnect the solar panel when desired voltage is reached. They are very cheap control system and have very little components.

3.1.5 Three-Stage and Pulse Width Modulation (PWM)

Often used as method of float charging, it sends out a series of short charging pulses to battery instead of a steady output from the controller. The controller constantly checks the state of the battery to determine how fast to send pulses, and how long (wide) the pulses will be. In a fully charged battery with no load, it may just "tick" every few seconds and send a short pulse to the battery. In a discharged battery, the pulses would be very long and almost continuous, or the controller may go into "full on" mode. The controller checks the state of charge on the battery between pulses and adjusts itself each time [45].

3.1.6 Maximum Power Point Tracking (MPPT)

Most advanced systems have efficiencies of 94 to 98% range. They provide somewhere between 10 to 30% more power to the battery. However, they are most expensive. They are often used in a larger system. MPPT is an algorithm in controllers that program to extract maximum available power from PV module under certain conditions. MPPT checks the output of the PV module and compares it to optimal voltage and then fixes it to the best power that the PV module can produce to charge the battery. It converts the optimal voltage to get maximum current into the battery [46].

3.2 Solar Panels

As the foundation of the project, photovoltaic cells convert solar energy into electrical energy through the photoelectric effect. The photoelectric effect essentially states that when photons strike the surface of certain materials, electrons would use this energy to break free [5]. This is a useful property and when implemented onto a semiconductor doped with electron and holes, the electrons would flow in one direction due to the internal electric field in the semiconductor. If used in a closed circuit, this would lead to current flow along with a small voltage. Since the voltage is usually too low to serve any practical use, these photovoltaic cells (or simply solar cells) are connected in series to raise the voltage thus increasing power output.

Photovoltaic cells can be found in:

- Calculators
- Satellites
- Rooftops
- Solar Farms
- Various other Devices

Photovoltaics have been around since 1954 when Bell Labs discovered that they could harvest the solar energy by using silicon based solar cells that offered 14 mW per cell for $25 or $1,785 per watt with 2 percent efficiency [3]. Throughout the years, the innovation gradually developed, and in the mid-21st century, the government started to promote this advancement. For a residential home owner, the decision of buying solar panels comes down to how much they have to spend upfront and how much they will save. A business decision on buying solar panels will come down to government incentives and how much they will save. Marketing and political or environmental pressures will encourage potential buyers, especially when there are state or federal incentives which help relieve some of the financial burden of purchasing panels. Even with today's technology; however, there is still room for improvement and the options for buyers are only growing larger with development of technology. This is why our sponsor wants to create an all-in-one Integrated Smart PV System and create another innovation in the solar industry.

"Almost 90% of the world's photovoltaics today are based on some variation of silicon. In 2011, about 95% of all shipments by the U.S. manufactures to the residential sector were crystalline silicon solar panels. The silicon used in PV takes many forms. The main difference is the purity of the silicon. The efficiency of solar panels goes hand in hand with purity, but the processes used to enhance the purity of silicon are expensive" [8].

We will now explore the types of solar panels available in today's market and their applications. The types offered today are monocrystalline silicon, polycrystalline silicon, thin film (TFSE), amorphous silicon (a-Si), copper indium gallium selenide (CIS), building integrated (BIPV) and cadmium telluride (CdTe). A consolidated chart from the referenced website is offered in Table 5.

	Crystalline			Thin Film			
Advantages	Monocrystalline	Polycrystalline	String Ribbon	a-Si	CdTe	CIS/ CIGS	BIPV*
Efficiency %	Best (15-20%)	13-16%	13–14%	6–8%	9–11%	10–12%	N/A
Small	Yes 4x thin film	No	Worst	No	No	No	N/A
Affordability	Least	No	No	Yes	Yes	N/A	Worst
Maintainability	Lower	Lower	Lower	Higher	Higher	N/A	N/A
Life Span	Best	Good	Good	Bad	Bad	N/A	N/A
Low Light	Best	Good	Good	Bad	Bad	N/A	N/A
Product Waste	A Lot of Waste	< Mono	$\frac{1}{2}$ Mono	N/A	N/A	N/A	N/A
Manufacturing Cost	< Polycrystalline	Low	Very high	Low	Low		
Other	If dirty, entire circuit could break down	Heat brings efficiency down	Heat brings efficiency down	Flexible	Flexible, More cost efficient than any others	In testing	Pricy
Attractive	More	Less	Less	More	More	N/A	High

Table 5. Types of Solar Panels

3.2.1 Monocrystalline Solar Panels

Monocrystalline solar panels have a uniform appearance to them as they are made from high-purity silicon. This purity level also leads to higher efficiency making monocrystalline based panels the most efficient compared to the other types. When exposed to low lighting conditions, they perform better than the polycrystalline based panels. The cells are made by the Czochralsi process from pure molten silicon and then doped with impurities to form an n-type or p-type semiconductor [19].

“Solar cells made of monocrystalline silicon, are also called single-crystalline silicon, and are quite easily recognizable by an external coloring and uniform look, indicating high-purity silicon…” [8]. These solar cells are “made out of silicon ingots, which are cylindrical in shape. To optimize performance and lower costs of a single monocrystalline solar cell, four sides are cut out of the cylindrical ingots to make silicon wafers, which is what gives monocrystalline solar panels their characteristic look” [8].

According to the energy informative, monocrystalline solar panels have the following advantages [8]:

- “Monocrystalline solar panels have the highest efficiency rates since they are made out of the highest-grade silicon. The efficiency rates of monocrystalline solar panels are typically 15-20%”

- “Monocrystalline silicon solar panels are space-efficient. Since these solar panels yield the highest power outputs, they also require the least amount of space compared to any other types. Monocrystalline solar panels produce up to four times the amount of electricity as thin-film solar panels”

- “Monocrystalline solar panels live the longest. Most solar panel manufacturers put a 25-year warranty on their monocrystalline solar panels”

- “Tend to perform better than similarly rated polycrystalline solar panels at low-light conditions”

And the following disadvantages [8]:

- “Monocrystalline solar panels are the most expensive”

- “If the solar panel is partially covered with shade, dirt or snow, the entire circuit can break down”

- “The Czochralski process is used to produce monocrystalline silicon. It results in large cylindrical ingots. Four sides are cut out of the ingots to make silicon wafers. A significant amount of the original silicon ends up as waste”

- “Monocrystalline solar panels tend to be more efficient in warm weather”

3.2.2 Polycrystalline Solar Panels

Polycrystalline based panels are also based of silicon but are made of fragmented crystals orientated in many shapes and sizes. Each section in the fragmented structure is differentiated by grain sizes which control the performance of how the solar cells will perform [19]. A larger grain size leads to greater efficiency and reduced combination in the depletion region of a P-N junction. Despite this, due to the impurities in polycrystalline based panels, the efficiency is not as good compared to some monocrystalline based panels [9].

First introduced to the market in 1981, polycrystalline solar panels “do not require the Czochralski process. Raw silicon is melted and poured into a square mold, which is cooled and cut into perfectly square wafers.

The energy informative states the following advantages of polycrystalline solar panels [8]:

- "The process use to make polycrystalline silicon is simpler and cost less. The amount of waste silicon is less compared to monocrystalline"

- "Polycrystalline solar panels tend to have slightly lower heat tolerance than monocrystalline solar panels. This technically means that they perform slightly worse than monocrystalline solar panels in high temperatures. Heat can affect the performance of solar panels and shorten their lifespans"

And the following disadvantages [8]:

- "The efficiency of polycrystalline-based solar panels is typically 13-16%. Because of lower silicon purity, polycrystalline solar panels are not quite as efficient as monocrystalline solar panels"

- "Lower space-efficiency. You generally need to cover a larger surface to output the same electrical power as you would with a solar panel made of monocrystalline silicon"

- "Monocrystalline and thin-film solar panels tend to be more aesthetically pleasing since they have more uniform look compared to the speckled blue color of polycrystalline silicon"

3.2.3 Thin Film Technology Based Solar Panels

This type of technology is pretty common in small portable electronics such as calculators. Looking into a-Si (Amorphous Silicon) based cells, they are the least efficient in the chain on thin film based solar cells. When exposed to the sun, there is a degradation in power output which can be solved by thinning out the solar cells [10]. Unfortunately, this leads to less absorptions of the solar energy produced from the sun. Despite these drawbacks, this type of semiconductor is great for small-scale applications but not for large-scale applications says William.

Another variation of this technology consists of CdTe (Cadmium Telluride) or CIGS (Copper Indium Gallium Deselenide). Compared to a-Si, these have higher efficiencies and are catching up to traditional monocrystalline based solar panels. "The different types of thin-film solar cells can be categorized by which photovoltaic material is deposited onto the substrate" [8]. Such as Amorphous silicon, cadmium telluride, copper indium gallium selenide or organic photovoltaic cells.

"Depending on the technology, thin-film module prototypes have reached efficiencies between 7-13% and production modules operated at about 9%. Future module efficiencies are expected to climb close to 10-16%".

Advantages of Thin Film Technology [8]:

- “Mass-production is simple. This makes them and potentially cheaper to manufacture than crystalline-based solar cells”
- “Their homogenous appearance makes them look more appealing”
- “Can be made flexible, which opens up many new potential applications”
- “High temperatures and shading have less impact on solar panel performance”
- “In situations where space is not an issue, thin-film solar panels can make sense”

Disadvantages of Thin Film Technology [8]:

- Solar panels required a lot of space. “...Monocrystalline solar panels produce up to four times the amount of electricity as thin-film solar panels for the same amount of space”
- “Low space-efficiency also means that the costs of PV-equipment will increase”
- “Thin-film solar panels tend to degrade faster than mono- and polycrystalline solar panels”

3.2.4 Amorphous Silicon (a-Si)

Being on the market for more than 15 years, amorphous-silicon is a non-crystalline form of silicon. These type of solar cells are “formed by vapor-depositing a thin layer of silicon material, about 1 micrometer thick, on a substrate material such as glass or metal”. In order to achieve better stability, multiple thin layers need to be used. This increases the electric field strength across the material [10].

Amorphous solar cells’ efficiency is low at only 7 percent. This is partly due to the “Staebler-Wronski effect, which manifests itself in the first hours when the panels are exposed to sunlight, and results in a decrease in the energy yield of an amorphous silicon panel from 10 percent to around 7 percent” [10]. The lifetime of amorphous silicon cells are less than that of a crystalline cell. In addition, in order to increase the efficiency of the material, multiple layers need to be used. This increases the complexity of the design and in the long run increasing the cost of using this type of material.

Even with the low efficiency, there are advantages to using this type of solar cell. Having lower manufacturing costs (when less layers are used), allows these cells to become very cost competitive. This material can “be produced in a variety of shapes and sizes. This makes it an ideal technology to use in a variety of applications such as powering electronic calculators, solar wristwatches, garden lights, and to power car accessories. Small solar cells used in pocket calculators have been made with a-Si for many years" [10]. "Unlike crystalline solar cells in which cells are cut apart and the recombined, amorphous silicon cells can be connected in series at the same time the cells are formed, making it easy to create panels in a variety of voltages" [10]. In addition to these advantages, "This type of technology is greater resistance to heat. According to a four year NREL study- it was observed that amorphous silicon PV modules experience higher results as temperatures increase" [10].

3.2.5 Copper Indium Gallium Selenide (CIS/CIGS)

"CIGS-based thin-film solar cell modules represent the highest-efficiency alternative for large-scale, commercial thin-film solar cells" [11]. A three stage process is normally used, "This process enables the formation of a CIGS thin-film layer that is of the proper composition and structure to allow the photo generated charge carriers to exist long enough in the CIGS layer of the device so that they can be separated and collected at the front and back contacts. This separation and collection is critical for demonstrating high conversion efficiency" [11].

3.2.6 Cadmium Telluride (CdTe)

"Cadmium telluride is the only thin-film solar panel technology that has surpassed the cost-efficiency of crystalline silicon solar panels in a significant portion of the market. The efficiency of solar panels based on cadmium telluride usually operates in the range 9-11%" [8].

3.2.7 Building Integrated (BIPV)

Some newer technology has begun to emerge in today's society. Instead of individual solar cell technology, we have begun to integrate solar cells of different types of structures. "Building integrated photovoltaics can be facades, roofs, windows, walls and many other things that is combined with photovoltaic material" [8].

3.2.8 Solar Radiation

"Solar radiation, often called the solar resource, is a general term for the electromagnetic radiation emitted by the sun. Solar radiation can be captured and turned into useful forms of energy such as heat and electricity, using a variety of technologies. However, the technical feasibility and economical operation of these technologies at a specific location depends on the available solar resource" [13].

Many factors can affect the amount of solar radiation that reaches earth's surface. Factors such as the geographic location, time of day, season, local landscape and local weather. According to energy.gov:

“Because the Earth is round, the sun strikes the surface at different angles, ranging from 0° (just above the horizon) to 90° (directly overhead). When the sun's rays are vertical, the Earth's surface gets all the energy possible. The more slanted the sun's rays are, the longer they travel through the atmosphere, becoming more scattered and diffuse. Because the Earth is round, the frigid Polar Regions never get a high sun, and because of the tilted axis of rotation, these areas receive no sun at all during part of the year.

The Earth revolves around the sun in an elliptical orbit and is closer to the sun during part of the year. When the sun is nearer the Earth, the Earth's surface receives a little more solar energy. The Earth is nearer the sun when it is summer in the southern hemisphere and winter in the northern hemisphere. However, the presence of vast oceans moderates the hotter summers and colder winters one would expect to see in the southern hemisphere as a result of this difference.

The 23.5° tilt in the Earth's axis of rotation is a more significant factor in determining the amount of sunlight striking the Earth at a particular location. Tilting results in longer days in the northern hemisphere from the spring (vernal) equinox to the fall (autumnal) equinox and longer days in the southern hemisphere during the other 6 months. Days and nights are both exactly 12 hours long on the equinoxes, which occur each year on or around March 23 and September 22.

Countries such as the United States, which lie in the middle latitudes, receive more solar energy in the summer not only because days are longer, but also because the sun is nearly overhead. The sun's rays are far more slanted during the shorter days of the winter months. Cities such as Denver, Colorado, (near 40° latitude) receive nearly three times more solar energy in June than they do in December.

The rotation of the Earth is also responsible for hourly variations in sunlight. In the early morning and late afternoon, the sun is low in the sky. Its rays travel further through the atmosphere than at noon, when the sun is at its highest point. On a clear day, the greatest amount of solar energy reaches a solar collector around solar noon” [13].

In addition to this, we have diffuse and direct solar radiation. “As sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected by: air molecules, water vapor, clouds, dust, pollutants, forest fires and volcanoes. This is called diffuse solar radiation. The solar radiation that reaches the Earth’s surface without being diffused is called direct beam solar radiation. The sum of the diffuse and direct solar radiation is called global solar radiation. Atmospheric conditions can reduce direct beam radiation by 10% on clear, dry days and by 100% during thick, cloudy days” [13].

Photovoltaic systems use both direct and scattered sunlight. “Other technologies may be more limited. However, the amount of power generated by any solar technology at a particular site depends on how much of the sun’s energy reaches it. Thus, solar technologies function most efficiently in the southwestern United States, which receives the greatest amount of solar energy" [13]. As shown in Figure 3. is a map of the United States solar irradiance. It shows how the southwestern side of the United States has a greater potential for use of solar energy.

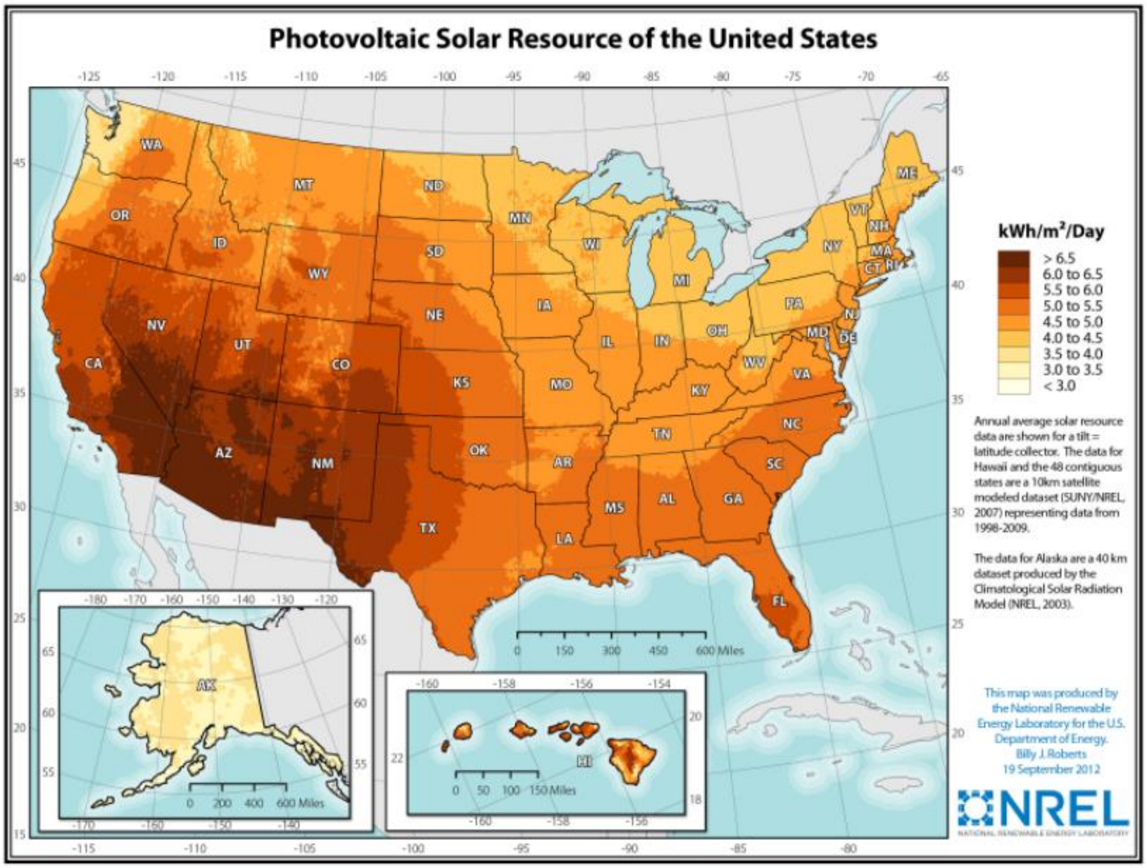


Figure 3. Photovoltaic Solar Resource of the United States
Pending permission from: National Renewable Energy Laboratory

3.2.9 Temperature Effect

"One of the key factors impacting the amount of electricity your solar panels produce is the temperature at which they operate. It is easy to presume that more sun and therefore more heat result in more electricity but this is wrong. Different solar panels react differently to the operating ambient temperature, but in all cases the efficiency of a solar panel decrease as it increases in temperature" [21]. The aforementioned information is known as the temperature coefficient.

Usually data sheets provided by solar panel manufacturers show a term known as the temperature coefficient pMax. "This value, which is normally given in the form of negative percentage, reveals the impact of temperature on the panel" [21].

Usually solar panels are power tested at 25°C, so this coefficient shows the change in efficiency.

The following gives information about the temperature coefficient [21]:

- “Both monocrystalline and polycrystalline cells have a temperature coefficient pMax of between -0.45% to -0.50%

- “Amorphous based thin film panels have a rating of between -0.20% to -0.25%

- “Hybrid solar cells currently on the market sit in the middle with a temperature coefficient pMax of between -0.32%”

Solutions are available to stop solar panels from getting too hot. “Firstly in the process of making the panels, companies use a thermally conductive substrate to help vent excess heat from the glass layer” [21]. In addition ensuring the free flow of air below the solar panels by elevating the panels off of the surface.

3.2.10 String System vs. Parallel System vs. Both

Parallel connections are mostly utilized in smaller and more basic systems. It is usually with pulse width modulation controllers. Connecting panels in parallel increases the amps but keep the voltage the same. Since the equation of power lost is I^2R, parallel system lose more power than system in series. Hence, the downside to parallel systems is that high amperage is difficult to travel long distances unless very thick wires are used.

Series connection are mostly utilized in maximum power point tracking system. Since maximum power point tracking system are able to accept high voltage input and alternate it to smaller voltage output. Connecting panels in series increase the voltage level and keep the amperage the same. From the equation power lost = I^2R, series connection loses less power. This is very distinctable in a long distance system. The downside to series systems is each panel has to work the same for the same output voltage. For example, if one panel were to be shaded, this will affect the output of all entire system.

Parallel and series connection are often combine for larger system. Since the limitation of the charge controller have to be satisfied. Charge controllers are only design to accept a certain amount of amperage and voltage. Hence, for a larger system series and parallel system are often combine to achieve desired amperage and voltage.

3.3 Batteries

In this section we researched and discuss the various types of batteries. The purpose of this section is to determine which type of battery would suit our project best.

3.3.1 Lithium-Ion Batteries

Lithium-ion batteries have a high power density which allows the batteries to be a smaller size they are used in a multitude of devices Ex. Cell Phones, calculators, pacemakers, electric cars, power storage. In the market there are six different types of lithium-ion batteries that exist.

3.3.1.1 Lithium Cobalt Oxide

Lithium-ion cobalt batteries are made from lithium carbonate and cobalt. They have very high capacity and are used in small electronics. According to investingnews.com “This type of battery has some drawbacks, including a shorter lifespan and limited specific power. That means that devices that use these batteries require relatively frequent charging — as smartphone owners can attest.” [14]

3.3.1.2 Lithium Manganese

Lithium manganese batteries have a low internal resistance and improved current handling which enables fast charging and high currents discharging. Some specifications on lithium manganese batteries from battery university are “Li-manganese can be discharged at currents of 20–30A with moderate heat buildup. It is also possible to apply one-second load pulses of up to 50A” This allow these batteries to be used in power tools, medical instruments, as well as hybrid and electric vehicles [15].

3.3.1.3 Lithium Iron Phosphate

Lithium iron phosphate “benefit from low resistance properties, which enhance their safety and thermal stability. Other benefits include durability and a long lifecycle — fully charged batteries can be stored with little change to the total lifespan of the battery’s charge. Li-phosphate batteries are often the most cost-effective option as well, when their long lifespan is taken into consideration. However, the lower voltage of the li-phosphate battery means that it has less energy than other types of lithium batteries.” [14]

3.3.1.4 Lithium Nickel Manganese Cobalt Oxide

Lithium nickel manganese cobalt oxide batteries often abbreviated as NMC “can be tailored to serve as Energy Cells or Power Cells. For example, NMC in an 18650 cell for moderate load condition has a capacity of about 2,800mAh and can deliver 4A to 5A; NMC in the same cell optimized for specific power has a capacity of only about 2,000mAh but delivers a continuous discharge current of 20A. NMC has good overall performance and excels on specific energy. This battery is the preferred candidate for the electric vehicle and has the lowest self-heating rate.” [15]

3.3.1.5 Lithium Nickel Cobalt Aluminum Oxide

“Lithium nickel cobalt aluminum oxide batteries are also called NCA batteries, and are becoming increasingly important in electric powertrains and in grid storage. NCA batteries are not common in the consumer industry, but are promising for the automotive industry. NCA batteries provide a high-energy option with a good lifespan, but they are not as safe as they could be and are quite costly.” [14]

3.3.1.6 Lithium Titanate

“LTO (commonly $Li4Ti_5O_{12}$) has advantages over the conventional cobalt-blended Li-ion with graphite anode by attaining zero-strain property, no SEI film formation and no lithium plating when fast charging and charging at low temperature. Thermal stability under high temperature is also better than other Li-ion systems; however, the battery is expensive. At only 65Wh/kg, the specific energy is low, rivalling that of NiCd. Li-titanate charges to 2.80V/cell, and the end of discharge is 1.80V/cell. Typical uses are electric powertrains, UPS and solar-powered street lighting.”[15]

3.3.2 Nickle-Cadmium Batteries

Nickel-Cadmium batteries also known as NiCd was invented in 1899 by Waldemar Jungner. It was the only other rechargeable battery at that time beside lead acid batteries “For many years, NiCd was the preferred battery choice for two-way radios, emergency medical equipment, professional video cameras and power tools. In the late 1980s, the ultra-high capacity NiCd rocked the world with capacities that were up to 60 percent higher than the standard NiCd. Packing more active material into the cell achieved this, but the gain was shadowed by higher internal resistance and reduced cycle count.” NiCd also suffer from the memory effect if not allowed to fully discharge then the battery will only discharge up to the previous value [15].

3.3.3 Nickle-Metal Hydride Batteries

Nickel Metal Hydride also known as NiMH was being researched in the late 1960s but didn't become available until 1980 when researcher were able to provide NiMH batteries that had 40 percent higher specific energy than NiCd. “NiMH has become one of the most readily available rechargeable batteries for consumer use. Battery manufacturers, such as Panasonic, Energizer, Duracell and Rayovac, have recognized the need for a durable and low-cost rechargeable battery and offer NiMH in AA, AAA and other sizes. The battery manufacturers want to lure buyers away from disposable alkaline to rechargeable batteries.” [15]

3.3.4 Battery Comparison

Table 6. in the following page compares Lithium ion, Nickel, and Lead-acid batteries and is one of the most comprehensive comparison charts available on the internet, however, it does not include price and power capacity which are two of our major factors. It does show a comparison of operating temperatures, however, life cycles, and maintenance requirements, which are also very important. As you can see, Lithium ion batteries have no maintenance

requirements, are more energy dense, and have similar operating temperatures to other types of batteries making them a good choice for our application.

Battery Technology Comparison

Specifications	Lead-Acid	NiCd	NiMH	Li-Ion		
				Cobalt	Manganese	Phosphate
Specific energy density (Wh/kg)	30 – 50	45 – 80	60 – 120	150 – 190	100 – 135	90 – 120
Internal resistance (mΩ/V)	<8.3	17 – 33	33 – 50	21 – 42	6.6 – 20	7.6 – 15.0
Cycle life (80% discharge)	200 – 300	1,000	300 – 500	500 – 1,000	500 – 1,000	1,000 – 2,000
Fast-charge time (hrs.)	8 – 16	1 typical	2 – 4	2 – 4	1 or less	1 or less
Overcharge tolerance	High	Moderate	Low	Low	Low	Low
Self-discharge/month (room temp.)	5 – 15%	20%	30%	<5%	<5%	<5%
Cell voltage	2.0	1.2	1.2	3.6	3.8	3.3
Charge cutoff voltage (V/cell)	2.40 (2.25 float)	Full charge indicated by voltage signature	Full charge indicated by voltage signature	4.2	4.2	3.6
Discharge cutoff volts (V/cell, 1C*)	1.75	1	1	2.5 – 3.0	2.5 – 3.0	2.8
Peak load current**	5C	20C	5C	> 3C	> 30C	> 30C
Peak load current* (best result)	0.2C	1C	0.5C	<1C	< 10C	< 10C
Charge temperature	-20 – 50°C	0 – 45°C	0 – 45°C	0 – 45°C	0 – 45°C	0 – 45°C
Discharge temperature	-20 – 50°C	-20 – 65°C	-20 – 65°C	-20 – 60°C	-20 – 60°C	-20 – 60°C
Maintenance requirement	3 – 6 months (equalization)	30 – 60 days (discharge)	60 – 90 days (discharge)	None	None	None
Safety requirements	Thermally stable	Thermally stable, fuses common		Protection circuit mandatory		
Time durability				>10 years	>10 years	>10 years
In use since	1881	1950	1990	1991	1996	1999
Toxicity	High	High	Low	Low	Low	Low

Source: batteryuniversity.com. The table values are generic, specific batteries may differ.
*"C" refers to battery capacity, and this unit is used when specifying charge or discharge rates. For example: 0.5C for a 100 Ah battery = 50 A.
**Peak load current = maximum possible momentary discharge current, which could permanently damage a battery.

Table 6. Battery Comparison Chart [29]

Table 7. compares lithium batteries by price, power capacity, and weight. The highest average household consumption of energy in the US is 15 MWh/mo which occurred in Louisiana which averages 21 kW/hr. If a solar panel supplies 100W, there would be 210 solar panels on this house. In the lowest average, Hawaii used 6 MWh/mo which would require 81 panels [30]. If each panel has 1 battery, then for the highest average, each battery would need to be able to store 2.31 kWh in order to have enough energy to last for 2 days. For the lowest average, each battery would need to store 4.78 kWh. This can be supplied by almost all of the batteries below. Lithium Manganese batteries would only be able to provide 45 hours which we consider sufficient. As you can see, the Lithium Cobalt batteries had the lowest price per kWh at $0.468 per kWh. Given that it has a low weight, high power density, and ample power capacity, we select this battery type for our project.

Battery	Price/kWh	Weight of 1 battery	Power Capacity (kWh)	Model number
Lithium Manganese	$1.11	<1 lb	4.5	Energizer [31]
Lithium Iron	$0.8688	3.03 lb	252	LFX 21L6-BS12 [29]
Lithium Iron Phosphate	$0.879	1.2 lb	108	Deltran [30]
Lithium Cobalt	$0.468	1.75 lb	64.8	Panasonic type L [31]

Table 7. Lithium Battery Prices

3.4 Transformers

Transformers are an important part of this project as transformers will have to be used in the DC/DC Converter and the DC/AC inverter. There are two types of transformers step up, step down. There are also different way to design these transformers such as laminated core, toroidal core and planar.

3.4.1 Step Up transformer

Step up transformers are made to take a low AC voltage and make it a larger AC voltage. By using the fact that an Alternating Current Voltage that flows through a wire that is wrap into a coil on the primary side will create a magnetic field and that magnetic field will alternate with the flow of the current. Then this alternating magnetic field will flow through a ferromagnetic iron core and induce an alternating magnetic field on secondary side coil which in turn causes an alternating current and voltage to flow through the secondary coil windings. What controls how big the voltage will get is the ratio of winding between the primary and secondary side.

3.4.2 Step Down transformer

Step up transformers are made to take a large AC voltage and make it a smaller AC voltage. By using the fact that an Alternating Current Voltage that flows through a wire that is wrap into a coil on the primary side will create a magnetic field and that magnetic field will alternate with the flow of the current. Then this alternating magnetic field will flow through a ferromagnetic iron core and induce an alternating magnetic field on secondary side coil which in turn causes an alternating current and voltage to flow through the secondary coil windings.

3.4.3 Laminated Core Transformer

Laminated core transformer is one of the oldest type of transformer design according to edisontechcenter.org the first working laminate core transformer was built in 1886 by William Stanley while he was working for Westinghouse and was used in the electrification of great Barrington, Massachusetts [16]. electronicshub.org states that “These are most commonly used transformers and are available from milliwatts to megawatts range. These types of transformers are used in electric power transmission and also in appliances to supply the low voltage. This transformer consists of a laminated core to reduce the eddy currents. A core of thin steel or CRGO or CRNGO ‘E’ and ‘I’ laminations are used for low and high power transformers which can be single or three phase transformers. These laminations are clamped together with bolts. Both primary and secondary windings are wound on a former and are placed around the central limb of the core. These transformers use split bobbin to provide high insulation between the windings for small appliances. Between the primary and secondary, shields may be used to reduce the electromagnetic interference." [17]

3.4.4 Toroidal Core Transformer

Toroidal core transformers has many "advantages over laminated core transformer that it provides quiet and efficient operation with reduced stray or external magnetic fields. Due to less weight and small size, these are easily designed for any application operating either low or high voltage. A highly efficient donut shaped core is used which is made from grain oriented silicon iron and is cut to form a ribbon of steel. This core is further wrapped by copper windings like a very tight clock spring. Compared to the EI laminated core transformer, toroidal core transformers are more expensive. However, for a given rating a smaller and lighter will be the toroidal transformer compared with EI laminated type transformer. Also, it provides less leakage of magnetic field and higher efficiency. These are available from a few tens of VA's to thousands of VA's. Mostly, they come with center single hole mounting by a bolt with washers and rubber pads." [17]

3.4.5 Planar Transformer

Planar transformer are a new type of transformer design that is built by creating the primary and secondary winding on a printed circuit board. This allow the transformer to be smaller and also allows for better integrated circuit designs because you can design the transformer on the same PCB as the rest of your power circuit.

The advantages of planar transformer:

"Advantages:

1. Low profile – the windings are flat, allowing a shorter winding window. This can also mean the core can be designed for larger cross-sectional area and greater surface area on the top and bottom to facilitate removal of heat from the transformer.

2. Excellent repeatability of construction – the PCB windings are very repeatable, which makes the parasitic effects such as leakage inductance and interwinding capacitance more predictable and repeatable.

3. High isolation – The PCB construction allows increased insulation between winding layers.

4. High-efficiency (typical 99% +), in a lightweight compact form." [18]

The tradeoffs of planer transformers:

“Tradeoffs:

1. The PCB takes up more of the winding window, limiting the total number of turns that can fit on a particular package. For this reason, planar transformers are usually chosen for high frequency transformer applications (>100 kHz) because as frequency increases, the number of turns on each winding generally decreases.

2. Higher inter-winding capacitance: because the windings are flat PCB traces, the capacitance from one layer to the next can be higher than traditional transformers.

3. Greater initial tooling investment is required to lay out all the windings on multiple PCB layers. Standard transformer package materials are readily available and custom versions can be wound easily. Planar transformers often require PCB setup charges, and so custom planar transformers are less common.” [18]

3.5 Passive Components

Passive components are necessary in every circuit design. In this section we are going to research capacitor, inductor, and resistor that can be used to design and build the LLC converter and inverter.

3.5.1 Capacitors

One of the many applications that capacitors are used for is storing electrical energy. In our design we are required to use a capacitor in the LLC circuit and must be able to handle switching frequencies form 80 kHz to 200 kHz and 40 to 60 VDC. Capacitors used in on the secondary side of the dc to dc converter after the voltage doubler it will have to be able to handle 200 to 400 volts. Capacitors used in the inverter will have to be able to handle 240 to 250 VAC. there are a million manufacture of capacitors to choose so we decided to add more restriction such as:.

- High Reliable
- Temperature
- Tolerance within 20%
- Through hole package
- Life Cycle of at least 2000 hours

After entering this information into DigiKey, we were able to select eight different capacitors that meet all the specifications three of them are rated for 250V which can be used on the secondary side of the DC to DC converter the other 5 are rated for 63V and can be used on the primary side. Shown below is Table 8. with the parameters and prices for each:

Manufacturer Part Number	B43888 F2107M 000	SK101M 250ST	ECA-2EHG101	ESK107 M063A H1EA	MAL2120 18101E3	B41691 A8107Q 7	SK101M 063ST	ECA-1JM101
Manufacturer	EPCOS (TDK)	Cornell Dubilier Electronics (CDE)	Panasonic Electronic Components	KEMET	Vishay BC Components	EPCOS (TDK)	Cornell Dubilier Electronics (CDE)	Panasonic Electronic Components
Description	CAP ALUM 100UF 20% 250V RADIAL	CAP ALUM 100UF 20% 250V RADIAL	CAP ALUM 100UF 20% 250V RADIAL	CAP ALUM 100UF 20% 63V RADIAL	CAP ALUM 100UF 20% 63V AXIAL	CAP ALUM 100UF 63V AXIAL	CAP ALUM 100UF 20% 63V RADIAL	CAP ALUM 100UF 20% 63V RADIAL
Quantity Available	1,621 - Immediate	2,382 - Immediate	1,334 - Immediate	2,100 - Immediate	680 - Immediate	50 - Immediate	728 - Immediate	15,964 - Immediate
Unit Price	$3.20	$3.74	$1.49	$0.11	$3.78	$3.38	$2.53	$0.36
Minimum Quantity	1	1	1	700	1	1	1	1
Series	B43888	SK	NHG	ESK	120 ATC	B41691	SK	M
Part Status	Active	Active	Active	Active	Active	Active	Active	Active
Capacitance	100µF	100µF	100µF	100µF	100µF	100µF	100µF	100µF
Tolerance	±20%	±20%	±20%	±20%	±20%	-10%, +30%	±20%	±20%
Voltage - Rated	250V	250V	250V	63V	63V	63V	63V	63V
ESR (Equivalent Series Resistance)	3.3 Ohm @ 120Hz	1.99 Ohm	-	-	297 mOhm	550 mOhm @ 100Hz	1.19 Ohm	-
Lifetime @ Temp.	-	2000 Hrs @ 85°C	2000 Hrs @ 105°C	2000 Hrs @ 85°C	8000 Hrs @ 125°C	2000 Hrs @ 150°C	2000 Hrs @ 85°C	2000 Hrs @ 85°C
Operating Temperature	-	-25°C ~ 85°C	-25°C ~ 105°C	-40°C ~ 85°C	-40°C ~ 125°C	-55°C ~ 125°C	-40°C ~ 85°C	-40°C ~ 85°C
Polarization	Polar	-	Polar	Polar	-	Polar	-	Polar
Ratings	-	-	-	-	AEC-Q200	-	-	-
Applications	General Purpose	General Purpose	General Purpose	General Purpose	Automotive	Automotive	General Purpose	General Purpose

Table 8. Comparison of Available Capacitors

Manufacturer Part Number	B43888 F2107M 000	SK101M 250ST	ECA-2EHG101	ESK107 M063A H1EA	MAL2120 18101E3	B41691 A8107Q 7	SK101M 063ST	ECA-1JM101
Ripple Current @ Low Frequency	-	-	365mA @ 120Hz	-	-	-	-	270mA @ 120Hz
Ripple Current @ High Frequency	1.18A @ 100kHz	-	547.5mA @ 100kHz	-	1.56A @ 10kHz	2A @ 10kHz	-	459mA @ 10kHz
Impedance	-	-	-	-	249 mOhms	150 mOhms	-	-
Mounting Type	Through Hole	Through Hole	Through Hole	Through Hole	Through Hole	Through Hole	Through Hole	Through Hole

Table 8. Comparison of Available Capacitors

3.5.2 Inductors

Inductors are used to store energy. In our design we are required to use Inductor for the LLC circuit there will be two inductor used Lr = 3.2 uH and Lm = 10 uH and must be able to handle switching frequencies form 80 kHz to 200 kHz and 40 to 60 VDC. We entered the information on mouser.com and had too many components to choses from we then filter the information to only show through hole components to make our design easier as you can see from the Table 9, there is only one manufacturer that makes through hole inductor of value 3.2 uH and is the only choice for Lr. There 5 different inductors for Lm and Lr:

Mfr.'s Part #:	RCH895NP-3R2M	B78108E1103K009	7.44751E+11	HCTI-10-20.0	MA5172-AE	78F100J-RC
Manufacturer:	Sumida	EPCOS / TDK	Wurth Electronics	Bel	Coilcraft	Bourns
Pricing:	$0.67	$0.49	$2.20	$2.37	$7.21	$0.22
Description:	Fixed Inductors 3.2uH 4.5A 15.3mOhms	Fixed Inductors 10uH 2200mA 18MHz HF-Choke Axial 10%	Fixed Inductors WE-FAMI THT 1410 10uH 8.9A 9.5mOhms	Fixed Inductors HIGH CURR TOROIDAL INDUCTOR 10 UH	Fixed Inductors MA5172 Pwr Filter 10kHz 26mOhms	Fixed Inductors 10uH 5%
Datasheet:	Datasheet	Datasheet	Datasheet	Datasheet	Datasheet	Datasheet
Application:	Power	RF	Power	-	Power	RF
Core Material:	Ferrite	Ferrite	Ferrite	-	Powdered Iron	Ferrite
Height:	9.5 mm	-	-	-	12.3 mm	-

Table 9. Comparison of Available Inductors

Mfr.'s Part #:	RCH895NP-3R2M	B78108E1103K009	7.44751E+11	HCTI-10-20.0	MA5172-AE	78F100J-RC
Inductance:	3.2 uH	10 uH	10 uH	10 uH	10 uH	10 uH
Length:	8.3 mm	9.5 mm	11 mm	-	-	7.11 mm
Maximum DC Current:	4.5 A	2.25 A	8.9 A	20 A	6.1 A	370 mA
Maximum DC Resistance:	15.3 mOhms	136 mOhms	9.5 mOhms	5 mOhms	26 Ohms	750 mOhms
Product:	Fixed Inductors	Fixed Inductors	Fixed Inductors	Fixed Inductors	Fixed Inductors	Fixed Inductors
Q Minimum:	-	35	-	-	-	40
Self Resonant Frequency:	-	20 MHz	-	-	25.5 MHz	18 MHz
Series:	RCH-895	B78108E	WE-FAMI	HCTI	MA5172	78F
Shielding:	Unshielded	Unshielded	Shielded	Shielded	Unshielded	Unshielded
Termination Style:	Radial	Axial	Radial	Radial	Radial	Axial
Tolerance:	20%	10%	20%	-	1%	5%
Maximum Operating Temperature:	+ 100 C	+ 125 C	+ 125 C	+ 105 C	+ 125 C	+ 105 C
Minimum Operating Temperature:	- 40 C	- 55 C	- 40 C	- 55 C	- 40 C	- 55 C
Standard Pack Qty:	100	2500	80	-	25	5000
Test Frequency:	7.96 MHz	1 MHz	100 kHz	-	10 kHz	7.9 MHz
Type:	-	-	-	Toroidal Inductors	Power Filter Inductor	-
Stock:	499 Can Ship Immediately,	4,569 Can Ship Immediately,	450 Can Ship Immediately,	149 Can Ship Immediately,	1,270 Can Ship Immediately,	12,058 Can Ship Immediately,

Table 9. Comparison of Available Inductors

3.6 Active Components

In this section we discuss the active components we will be including in our assignment.

3.6.1 Power Mosfets

A power mosfet is essentially a mosfet that is rated for high power applications. A mosfet is a semiconductor that can conduct electricity when the gate is biased appropriately. Being a semiconductor gives them many form of applications, but for this design, their main purpose is to be used as switches. For this design, we will need power mosfets that can handle large amounts of power and have the ability to switch at high frequencies. We will look at three different companies that design power mosfets and from them we will determine which will meet our design criteria for the DC/DC converter stage and the DC/AC inverter stage.

3.6.1.1 Texas Instruments

There are many manufacturers that manufacture power mosfets and Texas Instruments is one of them. The design will consists of a solar panel and battery and their corresponding voltages may go up to Number V. Texas Instruments has mosfets that are rated to support up to that voltage and can also handle large current draw. Now looking into the components themselves, the resistance between the drain and source needs to be as low as possible to make the module power efficient. CSD18531Q5A is the most cost effective out of the three choices shown below in Table 10; however, the drain to source resistance is 5.8 mOhms when the gate is biased to 4.5 V. The one with the lowest resistance is the most expensive out of the three choices listed below, but for a dollar more, the efficiency of the module can be increased without paying a large sum of cash.

Manufacturer's Part Number	CSD18536KTT	CSD18531Q5A	CSD18532KCS
VDS (V)	60	60	60
Configuration	Single	Single	Single
Rds(on) Max at VGS=4.5V (mOhms)	2.2	5.8	5.3
Rds(on) Max at VGS=10V (mOhms)	1.6	4.6	4.2
IDM, Max Pulsed Drain Current (Max) (A)	400	300	400
QG Typ (nC)	108	36	44
QGD Typ (nC)	14	5.9	6.9
Package (mm)	D2PAK	SON5x6	TO-220
Approx. Price (US$)	1.84 | 1ku	0.58 | 1ku	0.81 | 1ku
VGS (V)	20	20	20
VGSTH Typ (V)	1.8	1.8	1.8
ID, Silicon limited at Tc=25degC (A)	349	134	169
ID, package limited (A)	200	100	100
Logic Level	Yes	Yes	Yes

Table 10. Power Mosfets from Texas Instruments

3.6.1.2 Infineon

Another brand that is worth considering is Infineon. They also have components that have desired parameters for the module. Looking at Table 11, the maximum drain currents listed are much higher compared to the mosfets listed for Texas Instruments. This means that these will be rated for higher power which is a great thing since the solar panel and battery together will ideally be outputting around 300 W of power. Despite these good attributes, the pricing is a lot higher compared to Texas Instruments. The IRL60SL216 is the most expensive out of the three but the bonus attributes compared to the other two can be neglected as the current going through the drain will never reach 298 A. The IRL80B216 may be a good candidate for the module as the drain to source resistance is low and the maximum current supported is well within the operating range of the module.

Manufacturer's Part #	IRLS3036	IRL60B216	IRL60SL216
Budgetary Price $/1k	3.64	3.77	6.30
I_D max	190.0 A	215.0 A	298.0 A
I_D (@ TC=100°C) max	190.0 A	305.0 A	210.0 A
I_D (@ TC=25°C) max	270.0 A	215.0 A	210.0 A
Moisture Sensitivity Level	1	N/A	N/A
Mounting	SMD	THT	THT
P_{tot} max	380.0 W	375.0 W	375.0 W
Package	D2PAK (TO-263)	TO-220	I2PAK (TO-262)
Polarity	N	N	N
Q_G	91.0 nC	172.0 nC	170.0 nC
Q_{gd}	51.0 nC	80.0 nC	80.0 nC
R_{DS} (on) max	2.4 mΩ	1.9 mΩ	2.2 mΩ
R_{DS} (on) (@10V) max	2.4 mΩ	2.2 mΩ	1.95 mΩ
R_{DS} (on) (@4.5V) max	2.8 mΩ	1.9 mΩ	N/A
R_{thJC} max	0.4 K/W	0.4 K/W	0.4 K/W 175.0 K/W
Tj max	175.0 °C	175.0 °C	
V_{DS} max	60.0 V	60.0 V	60.0 V
V_{GS} max	16.0 V	20.0 V	20.0 V

Table 11. Power Mosfets from Infineon

3.6.1.3 Microchip

Aside from the two other brands listed before, Microchip was recommended to us by the sponsor's lab assistants for the microcontrollers they have. Since they manufacture power electronic components, they also has power mosfets available to use. Microchip did not have many mosfets to choose from but the three listed in Table 12. depict price changes from the lowest to the highest. MCP87130 has the best price out of all three except that the drain to source resistance is really high and will decrease the efficiency of the module to be designed. The MCP87030 drain to source resistance is much better compared to the MCP87130 and it only costs $0.35 more. Despite these benefits, for $0.40 more, the MCP87018 would be preferred since the goal is to optimize efficiency while minimizing cost.

Manufacturer's Part #	MCP87130	MCP87018	MCP87030
5K Pricing	$0.28	$1.03	$0.63
Vds (V)	25	25	25
Configuration	Single	Single	Single
Polarity	N	N	N
Rds(on) @ 4.5V (mΩ, Max)	16.5	2.2	4
Rds(on) @ 10V (mΩ, Max)	13.5	1.9	3.5
Qg @ 4.5V (nC, Max)	8	37	22
Id (A, Max @ 25C,Tcase)	54	100	100
Vgs(th) (V, Min)	1.1	1	1
Package Size	3.3x3.3mm, 5x6mm	N/A	5x6mm

Table 12. Power Mosfets from Microchip

3.8 Load Management

Solar power is an intermittent form of power generation. In order to ensure consistent power to customers and the grid, load management needs to be studied and taken into consideration. In the following section we discuss different categories of load management and shifting.

3.8.1 Load Management

Load management generally falls into one of three categories peak shaving, load shifting, and valley filling [22] as shown in Figure 6. Two techniques that we will focus on are load shifting and peak shaving, which are techniques used to minimize electrical power consumption during a specific time when power demand drastically increases. By using a secondary power source such as an on-site-generator or and solar energy, you can efficiently deliver power on demand, and reduce wear on the main power supply. Since photovoltaic panels are increasing in popularity and efficiency, it is advisable to develop a system where load shifting and peak shaving are implemented in a quick deployable photovoltaic panel along with a storage system when direct current from photovoltaic is not feasible. To store the energy that the system generates, deploying a battery solution is the best idea. To understand how we should do this we must first understand the load shifting and peak shaving techniques, along with the advantages and disadvantages of common battery technologies.

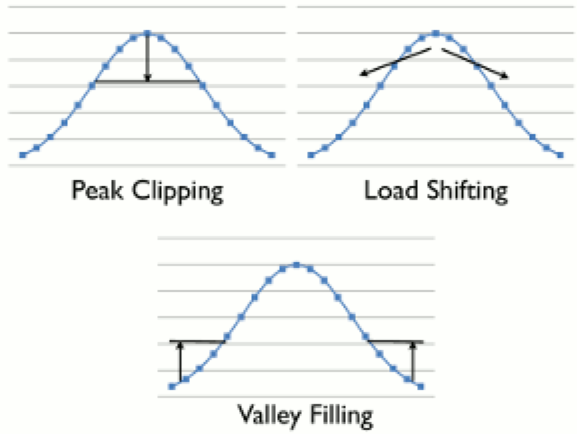


Figure 4. Load Management Types

3.8.2 Load Shifting

Load shifting is the process of shifting high wattage loads to different time slots throughout the day, or even over the period of an hour. Electricity generation in itself is a dynamic process, utilizing many different types of electrical generation technologies, such as coal, solar, wind, nuclear. With these different processes, different factors have to be taken into consideration such as fuel source abundance. With load shifting, entities generating electricity can increase savings and reduce cost by switching to certain electrical generation sources when the cost of generation is lowest. Figure 7. shows a visual aid on load shifting, and the breakdown of multiple power sources.

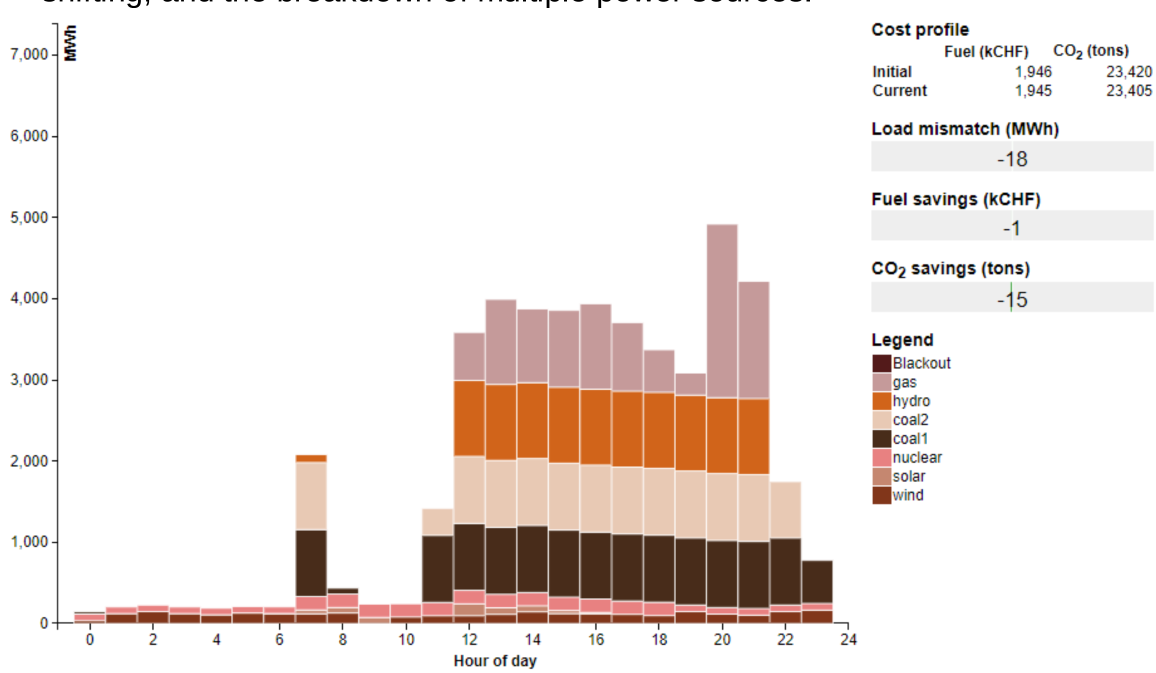


Figure 5. Load Shifting Diagram

3.8.3 Peak Shaving

Peak shaving also known as peak clipping, shares the same main objective as load shifting, which is to reduce cost and promote savings by reducing the amount of power needed by power utility entities. Unlike Load shaving, where the focus of the technique is implemented by power utility entities, peak shaving is a technique usually implemented by the consumer. Instead of shifting the load onto different power sources controlled by power utility entities, the consumer; usually large facilities and factories that maintain a close relationship with the entity that supplies their power, will turn off nonessential systems, and use local onsite generation to supplement all or part of their power demands. Doing this reduces the burden on the power utility entity, which would have the effect of lowering cost during peak hours. There has been case studies, such as Baldor's Westville Oklahoma motor plant showing savings of over $100,000 annually from peak shaving. The facility only had to add three 140kW peak shaving generators and the appropriate paralleling switchgear and monitoring equipment [23].

3.9 Pulse Width Modulation

"Pulse-width modulation (PWM) is the basis for control in power electronics. The theoretically zero rise and fall time of an ideal PWM waveform represents a preferred way of driving modern semiconductor power devices. With the exception of some resonant converters, the vast majority of power electronic circuits are controlled by PWM signals of various forms. The rapid rising and falling edges ensure that the semiconductor power devices are turned on or turned off as fast as practically possible to minimize the switching transition time and the associated switching losses. Although other considerations, such as parasitic ringing and electromagnetic interference (EMI) emission, may impose an upper limit on the turn-on and turn-off speed in practical situations, the resulting finite rise and fall time can be ignored in the analysis of PWM signals and processes in most cases" [24] .

1. Sawtooth Carrier:

The pulse initially starts rising and then abruptly goes back to its initial value periodically. When it drops to the initial value, at this moment in time the signal is modulated when the reference signal varies in amplitude. Another name for this method is called constant-frequency trailing-edge modulation [24].

2. Inverted Sawtooth Carrier:

The pulse starts at its minimum value initially and then increases with a positive slope to its maximum value and then abruptly drops to its initial value periodically. At this moment in time the signal is modulated as the reference signal varies in amplitude. This method is also known as constant-frequency leading-edge modulation [24].

3. Triangle Carrier:
For the triangle carrier, the left side increases with a slope and the right side decreases with a negative slope creating a symmetric triangle pulse. The pulse is centered within a cycle of the carrier when the reference signal is constant. Another name for this method is called constant-frequency double-edge modulation [24].

3.10 Phase Lock Loop

A phase lock loop (PLL) is essentially a control system that synchronizes the phase of the output with the phase of the input. Some applications for this controller is used in frequency modulation or demodulation, frequency synthesis, motor speed controls, and many more [x]. Shown in Figure 9. is a basic block diagram showing the closed-loop control system for the PLL. The main elements that contribute to the control is the phase detector, low pass filter, and a voltage controlled oscillator.

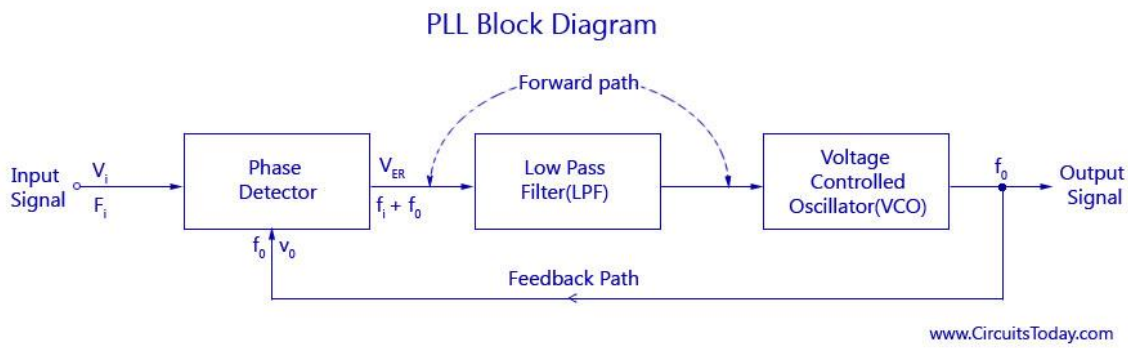


Figure 6. Phase Lock Loop Block Diagram
Pending Permission From: CircuitsToday

For the purpose of the project, this will be required in the inverter stage of the module. When the module is providing power to the grid, the output has to be a 120 VAC 60 Hz sine wave otherwise this may lead to grid instability. The phase detector will compare the input frequency and the output frequency to then generate a DC voltage that is proportional to the phase difference between the two frequencies [x]. The stage that comes after the phase detector is the low pass filter stage and its purpose is to get rid of the high frequency components and noise in the output of the phase detector. After this stage, the voltage coming from the phase detector is used to control the frequency coming out of the voltage controlled oscillator. This then gets fed back to the phase detector until the phase difference is zero. Without implementing PLL, the phases will be shifted thus decreasing the power factor as shown in Figure 10.

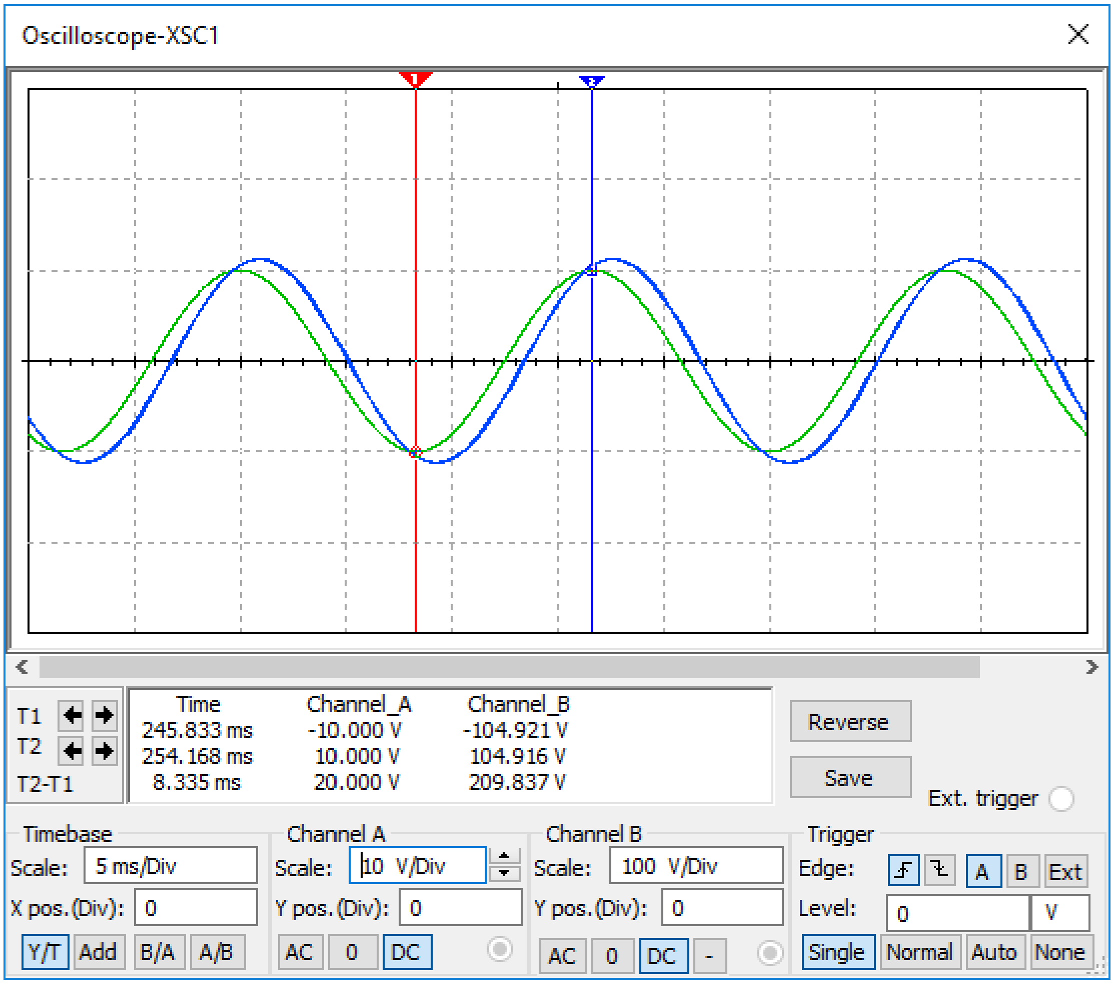


Figure 7. Out of Phase Inverter

3.11 MPPT Algorithms

MPPT algorithm is an algorithm used in PV inverters. It is used to keep the system supplying peak power for a wide range of power inputs from the solar cell as shown in Figure 11. It helps keep the system powering the load even given different inputs from the irradiance collected by the solar cell. MPPT stands for maximum power point tracking. The picture below gives an idea of the effects of these algorithms adjusting the voltage to bring the system to a higher power output [25].

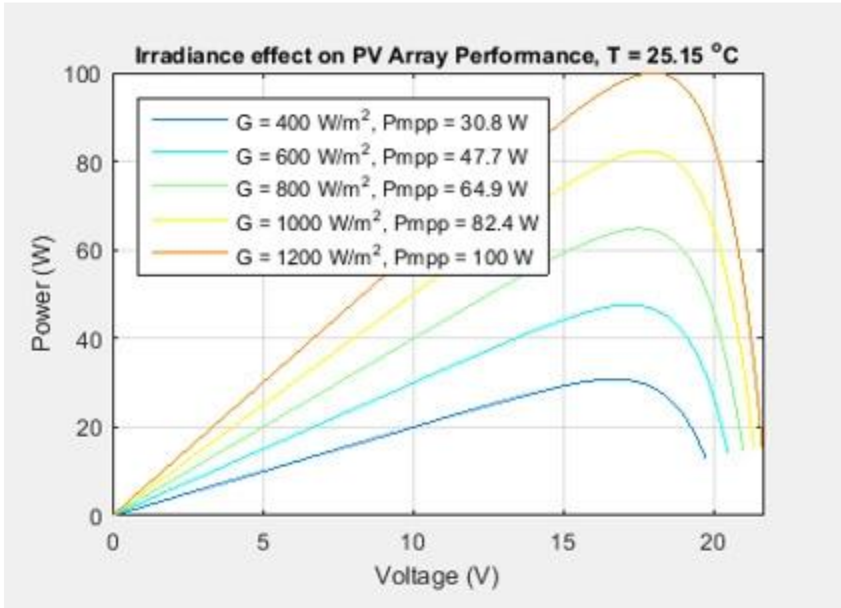


Figure 8. Voltage vs. Power for PV Panel

3.11.1 Perturb and Observe

There are different types of MPPT algorithms, and perturb and observe is one of these types. The overall concept of a perturb and observe algorithm is a set of steps whereby the software detects the voltage and current and either increases, decreases, or keeps the voltage constant in order to meet the designated requirements. It is a cycle that's used to keep the system at the desired setting and is one of the more basic approaches. All 3 of the types described here are similar to this in that they observe the system and make a modification, and the process is repeated to cause the system to be closer and closer to maximum power output [25].

3.11.2 Incremental Conductance

This is the second of 3 popular types of MPPT algorithms and is different from perturb and observe in that it uses incremental and instantaneous conductance as a measure to determine whether to raise or lower the voltage, which results in a constant voltage at the peak power [25].

3.11.3 Fractional Open Circuit Voltage

This type of MPPT algorithm uses the open circuit voltage as a means of measurement, since the maximum power output occurs at a constant fraction of the open circuit voltage, given by:

$$V_{Open\ Circuit} = \frac{1}{k_1} V_{MPPT} \qquad [26]$$

K_1 depends on the solar cell type, fill factor, and the climate, but is usually between 0.71 and 0.78. This type of MPPT is one of the most efficient types, and will be used for our project for that reason [26].

3.11 Power Management System

We will have to create an algorithm to control and manage the power output and program it into the microcontroller. This will control the 4 switches that are required to determine the following two possibilities:

- Battery charging and supplying power to the grid from the solar panels
- Both Battery and Solar panel supplying power to the grid

3.12 Microcontrollers

The microcontroller being research will have to be able to have multiple pulse width modulated outputs to control the duty cycle for the MOSFETs in the dc to dc converter and the inverter also be able to process reference signals and measurement to control the output of the device we will go over microcontroller from the manufacturers below that can meet these specifications.

3.12.1 MicroChip Technology

Microchip technology is one of the world leaders in microcontrollers, they have an assortment of different microcontroller and microprocessors to choose from. In addition to all the choices they also have variety of programing software and application notes to assist in the design process.

3.12.1.1 PIC 16 MCU

The PIC16 MCU is a high performing reduced instruction Set computer (RISC) CPU. It is able to operate on low power and has four Programmable Switch Mode Controller (PSMC) modules additionally it has fourteen 12-bit analog to digital converters(ADC) and four digital to analog converters(DAC) which one of them is 8-bit and the other three are 5-bit. This MCU is available in multiple packages that will be able to meet our design [47]. According to digikey the price per unit is 1 for $2.38, 10 for $2.18 each, and 100 for $1.97 each [48].

3.12.1.2 dsPIC DSC

The dsPIC is a new type of processor form microchip technology that combines a PIC processor and digital signal processor (DSP) into one integrated circuit called Digital Signal Controller (DSC) and are specifically designed for real time controller. Within the dsPIC family there are two controllers that are specialized for power conversion the first is dsPIC30 which has 6-8 PWM control and 6-12 ADC and prices range from $4.78 to $11.56. The second is the dsPIC33 which has 8 PWM controllers and 1 to 2 ADC and prices range from $5.84 to $12.43 [49].

3.12.1.3 Overview

Shown in Table 13, is the comparison between the microchip technology MCUs discussed in the previous section. From this table and the previous information we have decided that the dsPIC33 is best option available from microchip technology. Because of the features and price point.

Device Name	dsPIC30F4011	dsPIC33EP32MC202	PIC16F18323
Status	In Production	In Production	In Production
5K Pricing	$4.02	$1.37	$0.57
Family	16-bit DSC	16-bit DSC	Enhanced Mid-Range
MaxSpeed (MHz)	120	70	32
CPU Speed (MIPS/DMIPS)	30	70	8
Operation Voltage Max (V)	5.5	3.6	5.5
Temp Range Max	125	125	125
Pin Count	40	28	14
Program Memory Size (KB)	48	32	3.5
SRAM (Bytes)	2048	4096	256
Direct Memory Access Channels	0	4	0
Max ADC Resolution (Bits)	10	12	10
Max ADC Sampling Rate (ksps)	1000	1100	100
DAC outputs	0	0	1
Max DAC Resolution (Bits)	0	4	5
Number of Comparators	0	3	2
Comparator max speed (ns)	0	19	220
Number of Op Amps	0	2	0
Max 16 Bit Digital Timers	5	5	1

Table 13. Comparison of Microchip Technology Processors

Device Name	dsPIC30F4011	dsPIC33EP32MC202	PIC16F18323
Max 32 Bit Digital Timers	2	2	0
Number of PWM Time Bases	2	2	1
PWM Resolution (time ns)	33	7	0
Single output CCP (SCCP)	0	0	0
Multiple output CCP (MCCP)	0	0	0
Motor Control PWM Channels	6	6	8
Quadrature Encoder Interface (QEI)	1	1	0
Standalone PWM	0	0	2
Output Compare Channels	4	4	2

Table 13. Comparison of Microchip Technology Processors

3.12.2 Texas Instruments

Texas Instruments is a major manufacturer of microcontroller, they have an assortment of different microcontroller and microprocessor to choose from. In addition to all the choices they also have variety of development kit, programing software and application notes to asset in the design process.

3.12.2.1 C2000 Delfino MCU

The C2000 Delfino is a 32-bit digital signal controller (DSC) it supports low power mode it also has 18 PWM outputs and 6 high resolution PWM outputs (HRPWM) this microcontroller can support software libraries for digital power which would allow us to use example codes to program it. The price range is from $20.70 to $31.06 a piece [50].

3.12.2.2 C2000 Piccolo MCU

The C2000 Piccolo is a 32-bit CPU with an internal temperature sensor. This MCU also has 8 Enhanced PWM and 4 HRPWM outputs. Depending on the packaging that is picked it can have 7 - 13 ADC and 1 - 2 DAC. The price range is from $3.91 to $9.19 a piece [51].

3.12.2.3 C2000 Concerto MCU

The C2000 Concerto is dual subsystem MCU that contains independent communication and real-time control subsystems. The communication subsystem consist of an ARM Cortex M-3 processor and the real time control subsystem consist of 32-bit customized C28X CPU which has 9 (ePWM) Modules, 20 ADC and 6 DAC. The price range is from $16.83 to $30.13 [52]. This MCU is would be good for future proofing the power module we are creating as we can use the independent real-time control subsystem to program and build the module then later, use the communication subsystem to create a more complex network of integrated power models that can communicate with each other.

3.12.2.4 Overview

Shown in Table 14. is the comparison between the Texas Instrument MCUs discussed in the previous section. From this table and the previous information we have decided that the C2000 Piccolo is best option available from TI. Because the price point of the other two MCU are too high to justify for this design.

	TMS320F28333	F28M35H22C	TMS320F280260
Approx. Price (US$)	9.53 | 1ku	14.75 | 1ku	2.20 | 1ku
SubFamily	Delfino Premium Performance MCUs	Concerto Control MCUs	Piccolo Entry Performance MCUs
Total Processing (MIPS)	100	250	50
Frequency (MHz)	100	150	50
Frequency (MHz)	100	100	50
FPU	Yes	Yes	No
Flash (KB)	512	512	16
ADC Resolution	12-bit	12-bit	12-bit
ADC (Ch)	16	20	6
ADC (Ch)	16	20	8
RAM (KB)	68	136	6
Sigma-Delta Filter	0	0	0
PWM (Ch)	12	24	6
High Resolution PWM(Ch)	6	16	0
UART (SCI)	3	6	1
I2C	1	3	1
SPI	1	5	1
CAN (#)	2	2	0
DMA (Ch)	6	1 6-Ch DMA, 1 32-ch DMA	0
QEP	2	3	0
USB	0	1	0
Operating Temperature Range (C)	-40 to 85	-40 to 105	-40 to 105
Operating Temperature Range (C)	-40 to 85	-40 to 125	-40 to 105

Table 14. Texas Instruments Microcontroller Comparison

3.13 PCB Design

PCB's or printed circuit boards are "used to mechanically support and electrical connect electronic components using conductive pathways, tracks or signal traces etched from copper sheets laminated onto a non-conductive substrate" [52]. "The circuits are produced by a slight layer of conducting material deposited on the outside of an insulating board called as the substrate. Separate components are located on the surface of the substrate and soldered to the connect circuits.

The construction of the PCB can be done in three ways, namely single sided, double sided and multi layered. The components on a PCB are connected electrically to the circuits by two different methods such as hole technology and surface mount. In hole technology, every component consists of thin leads, which are pressed through tiny holes in the substrate & soldered to connection boards in the circuits on the reverse side. In surface mount technology, J-shaped or L-shaped terminals on every component get in touch with the PCB directly. A solder paste includes a glue, solder and flux are applied at the contact point to grip the components in position until the solder is liquefied" [53].

"PCBs have copper tracks to connect the holes where the various components are located. They are specially designed for each and every circuit and build construction very easy. Though, making the PCB necessitates special tools. The different types of printed circuit boards mainly include the following" [53].

- Single Sided PCBs
- Double Sided PCBs
- Multilayer PCBs
- Rigid PCBs
- Flex PCBs
- Rigid-Flex PCBs
- Aluminum-Backed PCBs

3.13.1 Single Sided PCBs

"This single sided printed circuit board includes just one layer of base material or substrate. One end of the substrate is coated with a thin layer of metal, usually copper because it is a good electrical conductor. Generally, a protecting solder mask be seated on the peak of the copper layer, and a last silkscreen coat may be applied to the top to mark elements of the board. This PCB consists of various circuits and electronic components on the only single side. This kind of module works most excellent for easy electronics, and beginners often design and build this type of board first. These boards tend to cost less to mass-produce than other types of boards. But although this low cost, they're used rarely because of their intrinsic design limitations." [53].

3.13.2 Double Sided PCBs

Double sided PCBs, are similar to single sided PCBs except both sides of the board have metal conductive layers that elements can attach to [53]. Using two different techniques, through-hole and surface mount technology, we are able to attach the different types of electrical components:

- Through-hole technology- “engages feeding small wires, called leeds, through the holes and soldering every end to the suitable component”

- Surface mount technology- “does not utilize wires. In its place, many little leads get soldered straight onto the board”[53]

“Surface mount technology permits many circuit to be complete in a lesser space on a board, meaning the board can execute more functions, typically at a lesser weight and at faster speeds than through-hole boards let” [53].

3.13.3 Multilayer PCBs

Adding to the complexity of PCB design, multilayer PCBs are exactly what their name suggests, multiple layers of PCBs. “With the accessibility of over many layers in multilayer printed circuit board configurations, multilayer PCBs let designers to make very thick and highly compound designs. The extra layers used in this design are power planes, which both provide the supply to the circuit with power and also decrease the levels of electromagnetic interference which are emitted by designs. Lower EMI levels are attained by placing signal levels in the middle of power planes” [53].

3.13.4 Rigid PCBs

“Rigid printed circuit boards use a solid, rigid substrate material like fiberglass that remains the board from twisting” [53]. “Rigid PCBs makeup perhaps the largest number of PCBs manufactured. These PCBs are used anywhere that there is a need for the PCB itself to be set up in one shape and remain that way for the remainder of the device’s lifespan. Rigid PCBs can be anything from a simple single-layer PCB all the way up to an eight or ten-layer multi-layer PCB. All Rigid PCBs have single-layer, double-layer or multilayer constructions, so they all share the same applications” [54].

3.13.5 Flexible PCBs

“.. Flexible PCBs are made of materials that can flex and move, such as plastic” Similar to rigid PCBs, “flexible PCBs come in single, double or multilayer formats. As they need to be printed on a flexible material, they tend to cost more for fabrication” [54]. Due to the flexibility of the material it can “lead to cost and weight saving since a single flexible PCB can be used to cover areas that might take multiple rigid PCBs.

Flexible PCBs can also be used in areas that might be subject to environmental hazards. To do so, they are simply build using materials that might be waterproof, shockproof, corrosion-resistant or resistant to high-temperature oils” [54].

3.13.6 Flexible-Rigid PCB

“Flex-rigid PCBs combine the best of both worlds when it comes to the two most important overarching types of PCB boards. Flex-rigid boards consist of multiple layers of flexible PCBs attached to several rigid PCB layers.

Flex-rigid PCBs have many advantages over just using rigid or flexible PCBs for certain applications. For one, rigid-flex boards have a lower parts count than traditional rigid or flexible boards because the wiring options for both can be combined into a single board. The combination of rigid and flexible boards into a single rigid-flex board also allows for a more streamlined design, reducing the overall board size and package weight” [54].

3.13.7 Aluminum-Backed PCBs

“Aluminum-backed PCBs are designed in much the same way as their copper-backed counterparts. However, instead of the usual fiberglass used in most PCB board types, aluminum-backed PCBs make use of aluminum or copper substrate board. The aluminum backing is lined with thermally insulating material that is designed to have a low thermal resistance, meaning less heat is transferred from the insulating material to the backing. Once the insulation is applied, a circuit layer of copper, ranging in thickness from one ounce to ten, is applied” [54].

Aluminum-backed PCBs advantages:

- Low cost
- Environmentally friendly
- Heat Dissipation
- Material durability

3.13.8 PCB Manufacturers

In the following section our group will discuss the amount for PCB layers that our group feels adequate for our design. We thoroughly researched multiple different manufacturers and sorted the information in the tables below.

Due to time and financial constraints, we had to take into consideration both single and double layer boards and shown in Table 15. and Table 16. Design parameters from our sponsor were recently given to us and more research will need to be conducted. In the following table, it shows different manufacturers of single layer PCBs, their cost and the amount of days it would take to receive the boards.

Manufacturer	Type of PCB	Cost ($)	Total Days
PCBWay	Single	102.24	8
EasyEDA	Single	57.90	9
ALLPCB	Single	77.09	5
Elecrow	Single	77.96	10
PCBWay	Single	103.31	8
U&I(quickturnpcb)	Single	125.60	8
Eurocircuits	Single	126.87	9
Smart Prototyping	Single	130.30	9
Bay Area Circuits	Single	151.62	10
ShenZhen2U	Single	166.13	10
Bittele (7pcb)	Single	198.73	5
PCB Zone	Single	200.16	8
Aisler	Single	272.32	9
Accutrace PCB4U	Single	289.55	8
ExpressPCB	Single	326.13	4
Advanced Circuits	Single	374.24	8
OSH Park	Single	820.00	6

Table 15. Pros vs. Cons of 1-Layer PCB’s Brands

Manufacturer	Type of PCB	Cost ($)	Total Days
PCBWay	2 Layer	122.47	8
EasyEDA	2 Layer	57.90	9
ALLPCB	2 Layer	96.10	5
Elecrow	2 Layer	77.96	10
PCBWay	2 Layer	123.54	8
U&I(quickturnpcb)	2 Layer	125.60	8
Eurocircuits	2 Layer	126.87	9
Smart Prototyping	2 Layer	130.30	9
Bay Area Circuits	2 Layer	151.62	10
ShenZhen2U	2 Layer	178.04	10
Bittele (7pcb)	2 Layer	198.73	5
PCB Zone	2 Layer	200.16	8
Aisler	2 Layer	272.32	9
Accutrace PCB4U	2 Layer	289.55	8
ExpressPCB	2 Layer	326.13	4
Advanced Circuits	2 Layer	374.24	8
OSH Park	2 Layer	820.00	6

Table 16. Pros vs. Cons of 2-Layer PCB's Brands

As shown in Table 15. and Table 16, the price difference between single and 2 layer PCB boards is minimal. If needed, we would easily be able to afford either type of board. The prices vary from $57.90 to $820 dollars. Depending on time constraints, we can receive our PCB board in as little as 5 days, which is something we may have to take into consideration. In Section 5.0 we further discuss the manufacturer we decided to purchase our PCB from.

3.14 Mechanical Design and Research

In order the figure out the best structure for solar panel system, the main type of current racking system was being compared. The four main type of racking systems for residential home are the standard rail shown in Figure 12, rail-less shown in Figure 13, and shared rail shown in Figure 14.

Figure 9. Rail System [43]

Figure 10. Rail-less System [44]

Rail racking system requires lower learning curve to install. Since it is easier to install, the cost of installation is low for most of the pitched roof have the range of 8 to 44 degrees. Only rails with 45 degrees or greater required better train professionals. However, although rack-less systems don't use rails. That's a time savings, but if the number of attachments is higher, if the parts costs are higher, or the require adjustments, the overall costs can be higher.

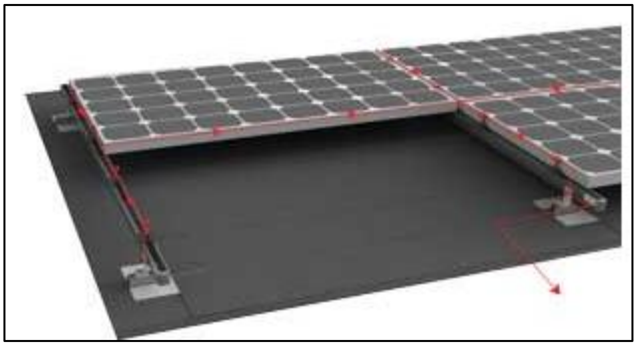


Figure 11. Share Rail System [44]

Share rail solution use rail to hold the modules in place, but reduce components elsewhere, such as mid and end clamps. Shared rail systems cover the entire side of the module, and the module frame becomes “bonded” to the rails and reduces the strain on the module. Because the rails are shared, a two-up installation would require only three rails as compared to four for a standard mid and end clamp system. This provides its own unique nimbleness for either landscape or portrait installations on all roof types. Shared rail also requires fewer roof penetrations, lessening the potential of a “floating” penetration. Shared rail is great when modules are in landscape and the rail must be run E-W and cannot clamp to the short sides of the module, or when the rail has to be run N-S and the module must be in portrait. Less than ideal shared rail applications would be those with sagging trusses, uneven shingles, uneven roof framing or any other situation that would cause difficulty creating perfectly level rows of rail.

Rails provide the suppliers the opportunity to cut manufacturing and shipping costs, and the installers are limiting time on the roof with fewer components to handle and install it is easier to handle any increments of PV modules, which also opens more possibilities such as any pitched roof top with asphalt roofing, roofs with less space or roofs with lots of obstacles. Rail-less mounting can be much quicker but require steeper learning curve. Rail-less is also good for mounting in landscape, but less ideal for portrait orientation.

	Pros	Cons
Rail-Mounting System	More secure	Addition weight
	Works with high winds	Penetration required
	Easy installation	Rigid arrangement
Shared-Rail System	Faster installation	Weighs more than rail less
	Can be installed vertically or horizontally	Shipping cost
	Compatible with tile and composite roofs	Inflexible installation
	Fewer components	More penetration
Rail-less System	Flexibility installation	Less weight distribution
	Lower cost	Deeper penetration
	Fewer components	Harder installation

Table 17. Racking System Comparison

3.14.1 Material Selection

Before selecting the material for racking system many material are compared. The most common type of material used in racking system is the aluminum, stainless steel. Other choice is wood made, plastic made and iron made. Currently, aluminum is the number one choice. It is low weight. Hence, decreasing weight pressure on the roof, pole or tracking system. The other benefit is corrosion resistive, strong and compatible to the solar module frames. Another choice is the stainless steel. Stainless steel racks are very strong and resistant against environmental impacts such as hail, snow and rain. It can last for ages but they are very expensive. Wood made mounting racks are other less used option. It is very cheap and easy to work but are weak in consistence and unreliable in wet environments. Plastic made mounting racks are also cheap but not optimal choice in terms of statics and lifetime. They are easily burn or beak if pressure on the solar panel is too high. The last option is the iron made mounting racks which are also easy to work with and slightly more expensive than wooden racks. However, this system has very bad corrosion resistant and not recommendable in wet environments.

Chrome Stainless Steel		
Property	Value	Units
Elastic Modulus	29007547	psi
Poisson's Ratio	0.28	N/A
Shear Modulus	11167906	psi
Mass Density	0.281793	lb/in^3
Tensile Strength	59989.49	psi
Yield Strength	24995.66	psi
Thermal Conductivity	0.000241	Btu/(lb*sec*F)
Specific Heat	0.109869	Btu/(lb*F)

Table 18. Chrome Stainless Steel Characteristics

Aluminum Alloy 1060		
Property	Value	Unit
Elastic Modulus	10007603.9	psi
Poisson's Ratio	0.33	N/A
Shear Modulus	3916018.92	psi
Mass Density	0.0975437	lb/in^3
Tensile Strength	9998.263	psi
Yield Strength	3999.2996	psi
Thermal Expansion Coefficient	$1.33*10^{-5}$	/°F
Thermal Conductivity	0.00267495	Btu/(in*sec*F)
Specific Heat	0.214961	Btu/(lb*F)

Table 19. Aluminum Alloy 1060 Characteristics

4.0 Design Constraints and Standards

In order to design a safe and functioning project, specific design constraints and standards need to be adhered to. In this section we discuss various constraints and standards we are following in order to complete our senior design project.

4.1 Design Constraints

As in every engineering design, there are multiple limitations that must be examined, which will be referred to as constraints in this section. They will include financial, technological, legal, and deadline-based constraints that must be discussed and handled appropriately.

Currently we are in the process of researching all the standards for solar panels and the electrical grid connections in addition to speaking to our advisors to obtain more information about the project and specific expectations.

4.1.1 Economic and Time Constraints

In the beginning of this semester, both the mechanical and electrical team were informed that we would be receiving financial help with this project. After preparing an estimated cost for the materials we planned out, we found out that we would not be receiving financial help and we would need to finance the project on our own.

To ensure all financial obligations are met, we sat down together and spilt up the cost of material between group members. This has caused financial strain on the group, since we were not fully prepared to pay hundreds of dollars for a senior design project.

In addition, the mechanical team graduates in fall 2018 and the electrical team graduates in summer 2018. We have various time constraints that we need to adhere to. In August of 2018 the electrical team will present and turn in all electrical components of the Smart PV system. We will be unable to attain the full and completed product due to the different times of graduation. In the fall of 2018 a completed Smart PV system will be presented by the mechanical team.

The mechanical team will meet up with the electrical team over their summer break to discuss the progress and different issues that arise within the project.

4.2 Standards and Other Safety Concerns

In this section, various electrical and software standards are examined and discussed to determine the level of various industry standards and applications of our product. Safety concerns will be discussed to ensure the safety of our team members moving forward into the design, implementation, and testing phases. Design and manufacturing constraints will be discussed to ensure that our design is robust.

4.2.1 Soldering Standards

Our group will be using some of the standards discussed on the online resource called “Circuit Technology Center”, which provides detailed instructions and diagrams for proper soldering procedures. After some careful research and discussion with other groups currently enrolled in senior design who are working on their printed circuit board designs, we have decided that our components will be soldered using the gull wing package. This is the most common type of soldering procedure seen on various designs in both industry and in previous senior design showcase projects at the University of Central Florida.

Along with this information, our group has also looked for specific procedures to follow that would allow our project to be as robust as possible, to ensure a valid demo. According to the aforementioned resource, there are several practices that are considered taboo, and should be strictly avoided when soldering electrical components for a design such as ours. For one, solder should always be left to cool down and should not be dried using techniques such as pressurized air. This causes the solder to cool much too quickly and could lead to several problems such as fragile solder joints or terrible connections on the component pins outs. One of the most important aspects of soldering is proper connections being made -- ensuring that the component is properly placed on the printed circuit board and will not become dislodged should the board be moved or placed in an environment where it could be moved. There should be no motion between the components and they should all be affixed to their proper locations. As many sources show, flux should be used to help affix the individual components onto the board. Especially with components such as chips, this allows the group member who is soldering to not have to worry about the chip moving into an improper position during the entire soldering process.

Another important step in ensuring that the printed circuit board has been properly soldered is performing a visual inspection of individual components and then the board overall. This would ensure that the quality of connections made through the solder is high and meets the requirements set by our sponsor. Further, it will also ensure that all components are properly placed in their respective areas. Overall, no complex methods of inspection will be incorporated as the overall design does not warrant it. Multimeter probes should be probed on the pinouts of the device to ensure that all connections are valid through the solder. However, for the sake of our group’s future careers, we will research other methods of printed circuit board inspection since we will likely work on much more complex systems in the future. Therefore, it is important that we stress researching all options available to us in order to adequately prepare.

4.2.2 RoHS compliance

Due to our design potentially being sold as a commercial product, it is important for our group to consider standards and restrictions such as RoHS compliance. This stands for Restriction of Hazardous Substances Directive, which restricts the use of certain hazardous substances used in electrical equipment. Typically, this is a restriction on lead in most electronic applications; however, there are various other chemicals that are documented under this restriction. For the purpose of this design, our group will potentially adhere to this standard as the product could be shipped outside of the United States and therefore must be RoHS compliant.

Our group's main concern with this restriction is Lead (Pb), which is commonly found in a lot of solder material. According to the RoHS compliance, the concentration of lead must be less than 1000 parts per million. Through our research, we have determined that a common and acceptable replacement for lead solder is tin solder. Some drawbacks to using tin solder include fewer acceptable joints and general availability.

4.3 ABET Criteria

In order to receive ABET accreditation, students need to meet the following criteria [50]:

"The program must have documented student outcomes that prepare graduates to attain the program educational objectives. Student outcomes are outcomes (a) through (k) plus any additional outcomes that may be articulated by the program.

a) an ability to apply knowledge of mathematics, science, and engineering

b) an ability to design and conduct experiments, as well as to analyze and interpret data

c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability

d) an ability to function on multidisciplinary teams 2018-2019 Criteria for Accrediting Engineering Programs 5

e) an ability to identify, formulate, and solve engineering problems

f) an understanding of professional and ethical responsibility

g) an ability to communicate effectively

h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context

i) the recognition of the need for, and an ability to engage in life-long learning

j) the knowledge of contemporary issues

k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice."

5.0 Design Process

In this section we discuss the design process that was required to piece our project together and finalize the design.

5.1 Battery

These are a required component for iPV++ since solar panels are unable to deliver steady power if interrupted by weather, residue, shadows, and other disturbances that affect photon farming. The reason lithium-ion batteries are preferred for this application is that they are rechargeable, have a high energy density, and can last several charging cycles. The composition of a lithium-ion battery consists of a cathode and anode, an electrolyte, the separator, and the lithium ions.

When the battery is charging, electrons go from cathode to anode through the load and the lithium ions do the same but through the separator. When the battery is discharging the reverse happens.

There are many types of lithium based batteries, and they all have their advantages and disadvantages. Lithium-ion polymer and lithium-ion are the two main types of lithium battery technologies; however, due to the unsafe nature of lithium-ion polymer batteries, we will be focusing on lithium-ion batteries. For this project, the sponsor has specified that a battery with lithium-ion cobalt based chemistry may be used. Being one of the most common lithium-ion batteries, these are typically used in mobile phones, tablets, laptops, and cameras. These types of batteries have a specific energy of 150-200 Wh/kg, a thermal runaway of 150 °C, and can ideally charge through 500-1,000 cycles.

For the design of the battery, load shifting and peak shaving analysis will be performed to determine the dimensions and capacity of the battery. With the completion of the analysis, this information will be sent to AllCell who will be manufacturing the battery for this project.

5.1.1 Battery Update

Due to time constraints we were unable to obtain a battery. Instead of this, we were able to use a DC voltage source and connect it directly to the DC/DC converter to essentially produce a similar output that we would see with a battery.

5.2 Boost Converter

The boost converter is a circuit designed to step up the voltage when then input is a low voltage source. The primary component used in boosting the voltage at the output is the inductor. When the switch is closed, the voltage source charges the inductor as the switch acts like a short to ground. When the switch is opened, the energy stored in the inductor creates a high voltage spike in series with the voltage source thus charging the battery [11]. Figure 15. shows the DC/DC converter; however, depending on the configuration of the switches, the DC/DC converter can also act as a boost converter. In this scenario, S1 is always on and S2 is always off. The switches S3 and S4 are inversely activated meaning if one is on the other is off. When the switches oscillate between states, this switch mode configuration charges the battery.

5.3 DC/DC Converter

For the purposes of this project, we will be looking at a special variant of the boost converter proposed by the sponsor known as a dual-input LLC resonant converter. There are many stages in the conversion process of the DC power where the first stage consists of a switch network. Shown in Figure 15. is the diagram of the proposed converter where the switches are represented by mosfets.

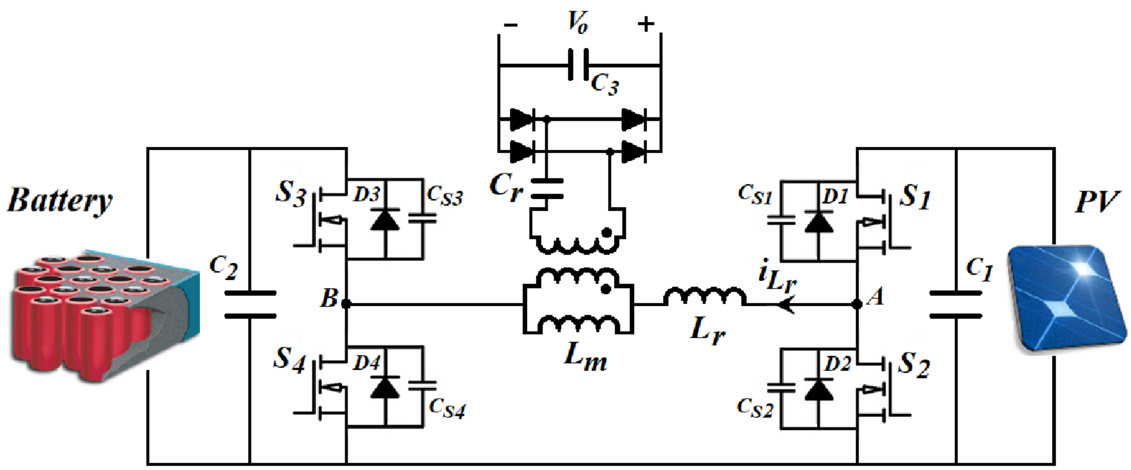


Figure 12. Proposed Dual-Input LLC Resonant Converter

The MOSFET is a transistor that can act as a switch when the gate and source are biased to their threshold voltage thus shorting the path between the drain and source. When switches S_1 and S_4 are shorted and the others are acting as open, the solar panel is generating current in one direction. When switches S_2 and S_3 are shorted and the others are opened, the batteries are generating current in the opposite direction. When this process is repeated, the inputs are acting as an AC signal with the frequency dependent on the switching frequency. This is one of the modes of operation in the converter but it has a specific purpose.

Going into the discussion of the modes of operation, the first mode is configured for both charging the battery and delivering power to the load. Referring to Fig. 4, the configuration for this mode has the switches S1 shorted, S2 opened, and S3 and S4 alternating. What allows this mode to charge the battery is the inductor Lr because the topology of the current configuration mimics that of a boost converter. In this topology when S4 is shorted and S3 is opened, energy is being stored in the inductor Lr. When the switches S4 is opened and S3 is shorted, the energy stored in the inductor combines with the energy coming from the solar panel to boost the voltage to charge the battery. Since this is happening continuously, the current is alternating thus also providing power to the opposite side of the transformer to deliver to the load.

The other feature that this mode will offer is control of how much power is being used to charge the battery and deliver to the load. A simulation was done on LTspice to show the behavior of this feature. Ideally the output voltage of the converter should be consistently around 400 V no matter what load is placed. By changing the switching frequency of the power mosfets, the voltage across the load can stay localized around its nominal value. As shown in Figure 16, the frequency is not a linear relationship with respect to power. Despite this complication, this will be controlled by a microcontroller by using voltage sensing at the output to control the switching frequency to provide 400 V at the output.

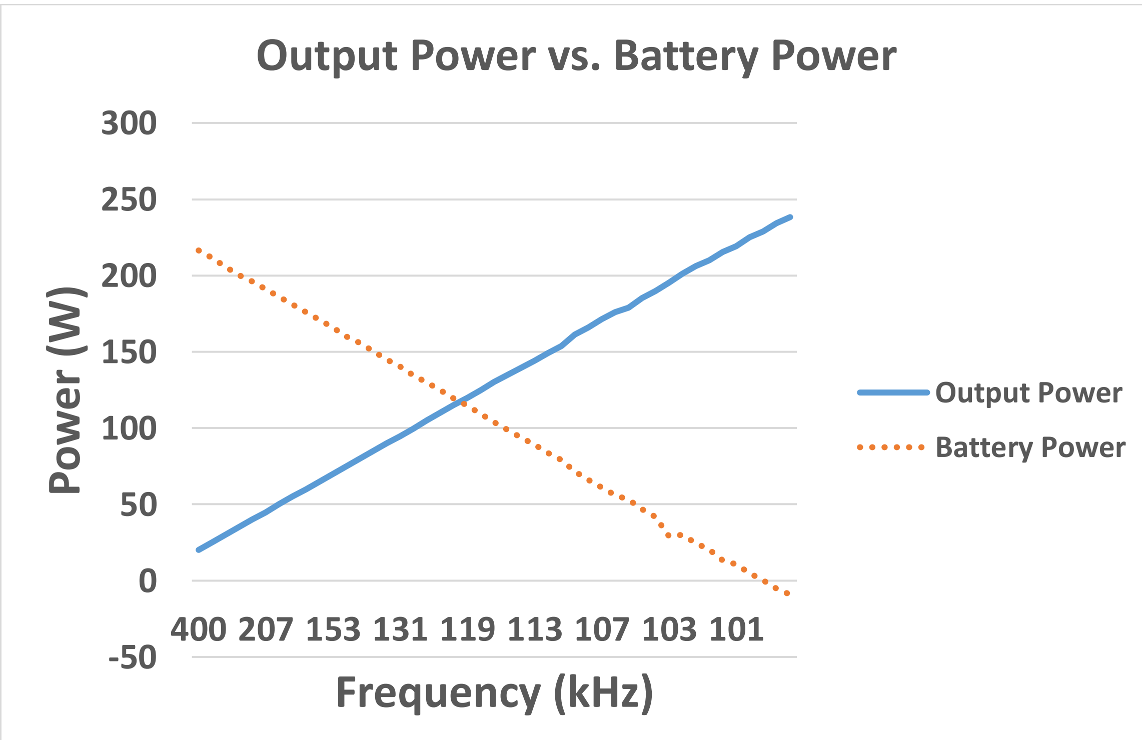


Figure 13. Frequency Manipulation

The other mode of operation is strictly to provide power to the load. As explained before, when switches S1 and S4 are shorted and the other two are opened, the solar panel is generating current in one direction. When switches S2 and S3 are shorted and the other two are opened, the batteries are generating current in the opposite direction. This allows all power from the solar panel and battery to go directly to the load.

Besides being able to supply more power to the load, this mode has a feature that allows how much power is being outputted by either source with phase shift control. Before going into further explanation, S2 is always the inverse of S1 and S4 is always the inverse of S3. When applying a phase shift of one degree, depending on the orientation, there will be a moment in time where S1 and S3 are both on or S2 and S4 are both on. By adding positive phase shift, the solar panel will output less power and the battery will output more power. When the phase shift is negative, the opposite effect occurs. Figure 17 shows the power distribution with respect to phase shift. Comparing the axes, the relationship between phase shift and power is linear which will allow programming the microcontroller to be much easier as opposed to the frequency control.

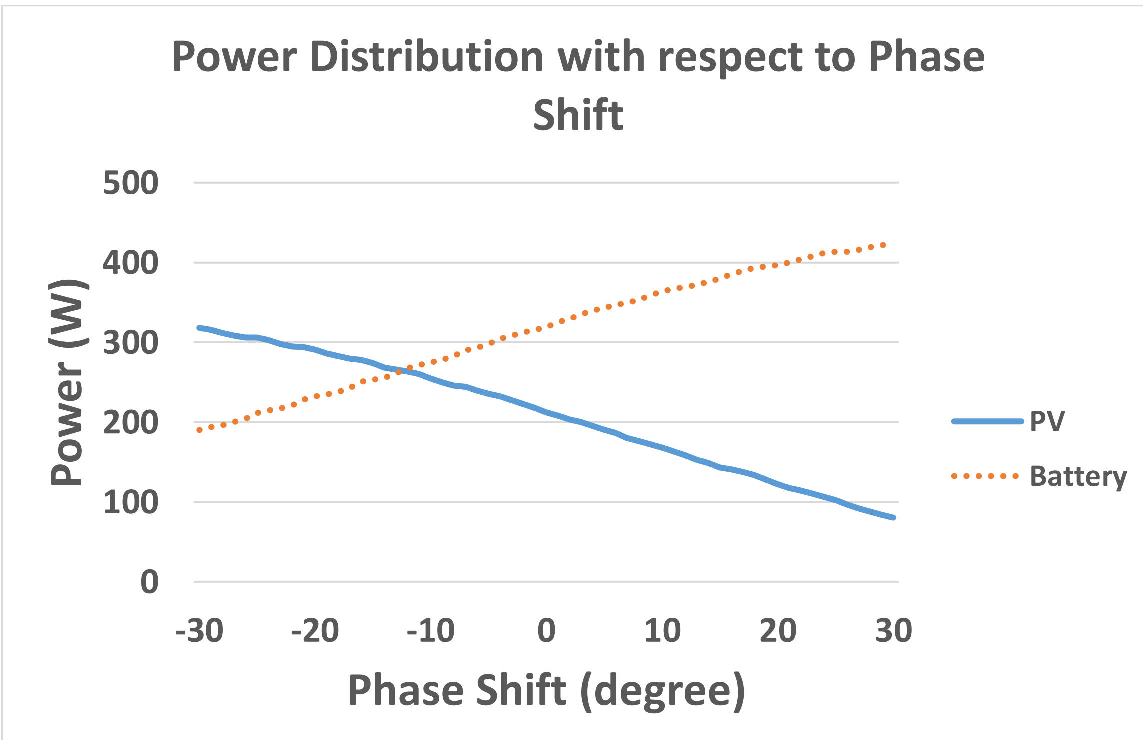


Figure 14. Phase Manipulation

5.4 DC/AC Inverters

According to our sponsor, our group is given free reign over which inverter topology is chosen for our design, one of the most important considerations in the final design implementation and overall operation is the ability to reach high efficiency with power output for multiple desired power configurations.

5.4.1 Off Grid Inverter System

Off grid inverters are used to provide power to a house, building or Recreational vehicles that do not have any access or choose not to be connected to the utility grid. The basic operation of an off grid inverter is to take energy that was stored in batteries by a renewable power source or a fossil fuel generator and invert it to an 120 VAC or 240 VAC 60Hz sine wave that will be able to power basic household appliance as shown in Figure 18. According energyinformative.org off- grid inverter systems are less likely to be used because “To ensure access to electricity at all times, off-grid solar systems require battery storage and a backup generator (if you live off-the-grid). On top of this, a battery bank typically needs to be replaced after 10 years. Batteries are complicated, expensive and decrease overall system efficiency.” [12]. Another reason that off grid are less likely to be use is that states can have laws against being off the grid like the state of Florida.

The advantages of off grid inverter system are being energy self-sufficient and disconnected from the grid when utility power failures occur and if you live in a rural area that's far from the grid“ Off-grid solar systems can be cheaper than extending power lines in certain remote areas. Consider off-grid if you’re more than 100 yards from the grid. The costs of overhead transmission lines range from $174,000 per mile (for rural construction) to $11,000,000 per mile (for urban construction)” [12].

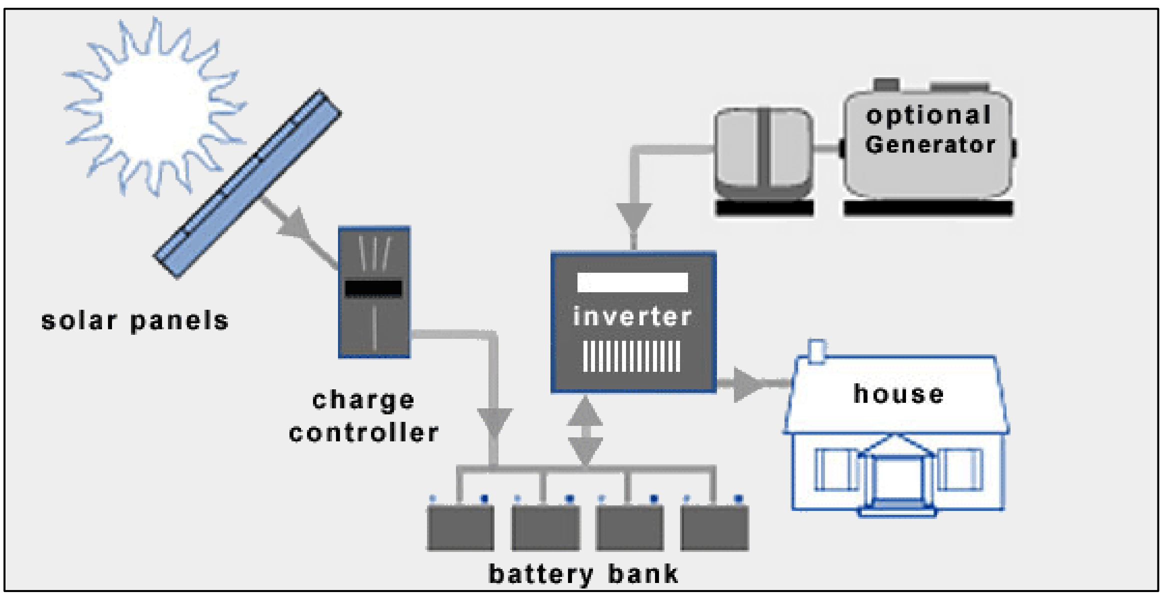


Figure 15. Off Grid Inverter System
Pending Permission From: Energy Informative

5.4.2 Grid Tied Inverter System

Grid tied inverter are bidirectional meaning this type of inverter can be used to provide and take power from the utility grid as shown in Figure 19. Making the system more complicated because you need to have a feedback loop when you are providing power to the utility grid. To “synchronize the phase and frequency of the current to fit the utility grid (nominally 60Hz). The output voltage is also adjusted slightly higher than the grid voltage in order for excess electricity to flow outwards to the grid.” [12]. This type of inverter system also uses regular electricity in your house at night or time of low sunlight to power your house most utility companies will discount the electricity you put in the power grid from your electricity bill.

Advantages of grid tied inverters systems they are usually cheaper since you need to buy less components there is no need to buy a battery bank to charge and replace every ten years.

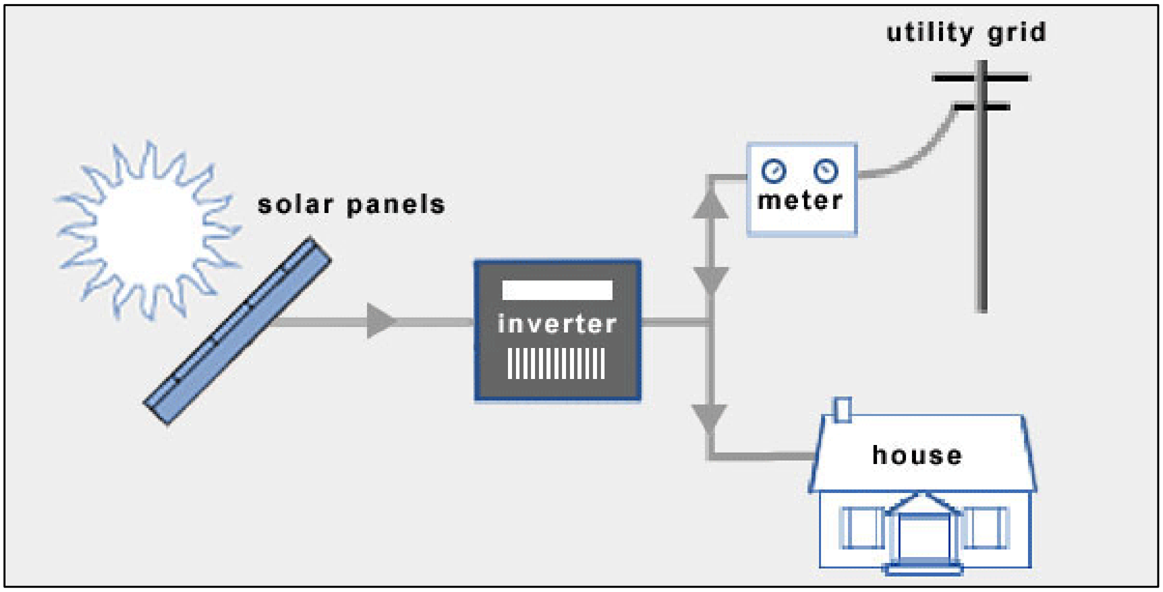


Figure 16. Grid Tied Inverter System
Pending Permission From: Energy Informative

5.4.3 Hybrid Inverter System

A hybrid inverter system is a grid tied inverter that also has a battery bank as shown in Figure 20. In this type of system you can store the power you generate in batteries as in an off grid system and only use the power from the grid when you don't produce enough energy to be self-sustaining. Our project will focus on creating an integrated hybrid micro inverter system that can fit under a solar panel.

Advantages of hybrid inverters system is that you have the option to operate in any mode and will not be left without power if the utility grid goes down and have sufficient charge in your battery bank or vice versa.

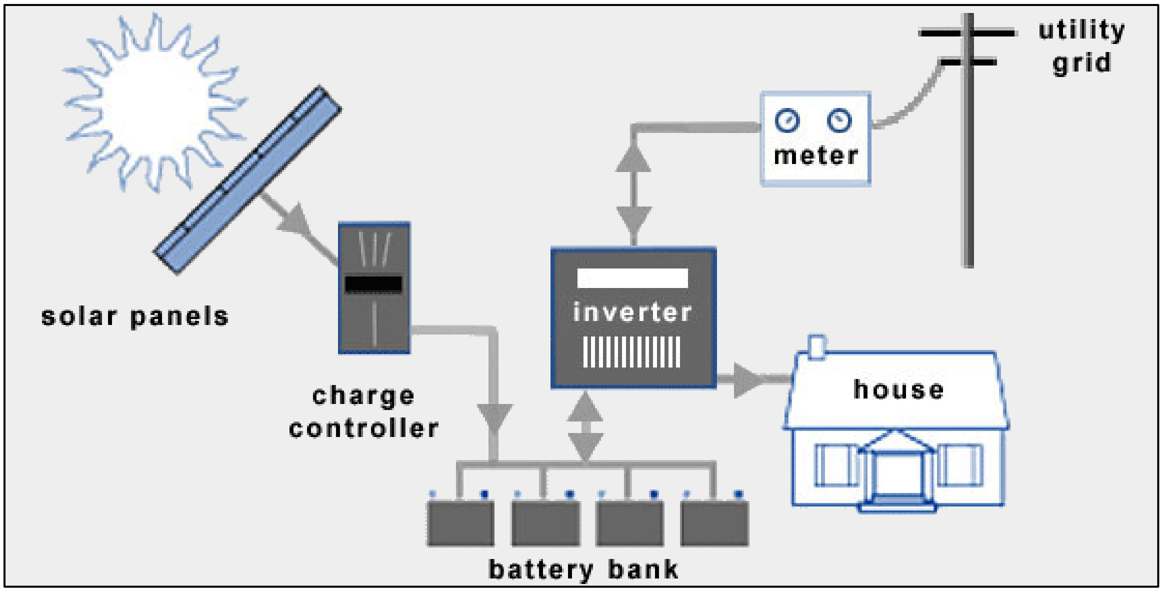


Figure 17. Grid Inverter System with Battery Bank
Pending Permission From: Energy Informative

5.4.4 Pure Sine Wave Inverter

Similar to the square wave inverter, the pure sine wave inverter outputs a sine wave when the input is a DC source. The project requires the inverter to output a 120 V_{RMS} sine wave at 60 Hz. A basic sine wave inverter has a similar topology to the square wave inverter except that it has a low-pass filter at the output. Another difference about this type of inverter is that the switching frequency is dependent on pulse width modulation. This controls how long the switches stay on and what controls this is the reference signal.

For the purpose of this project, the inverter will need to be bi-directional, meaning it can deliver power to the grid and receive power from the grid to charge the battery. This will all be programmed in the microcontroller to determine when to switch the operating modes. Figure 21. shows the output of a pure sine wave inverter compared to the pulses controlling the power MOSFETs.

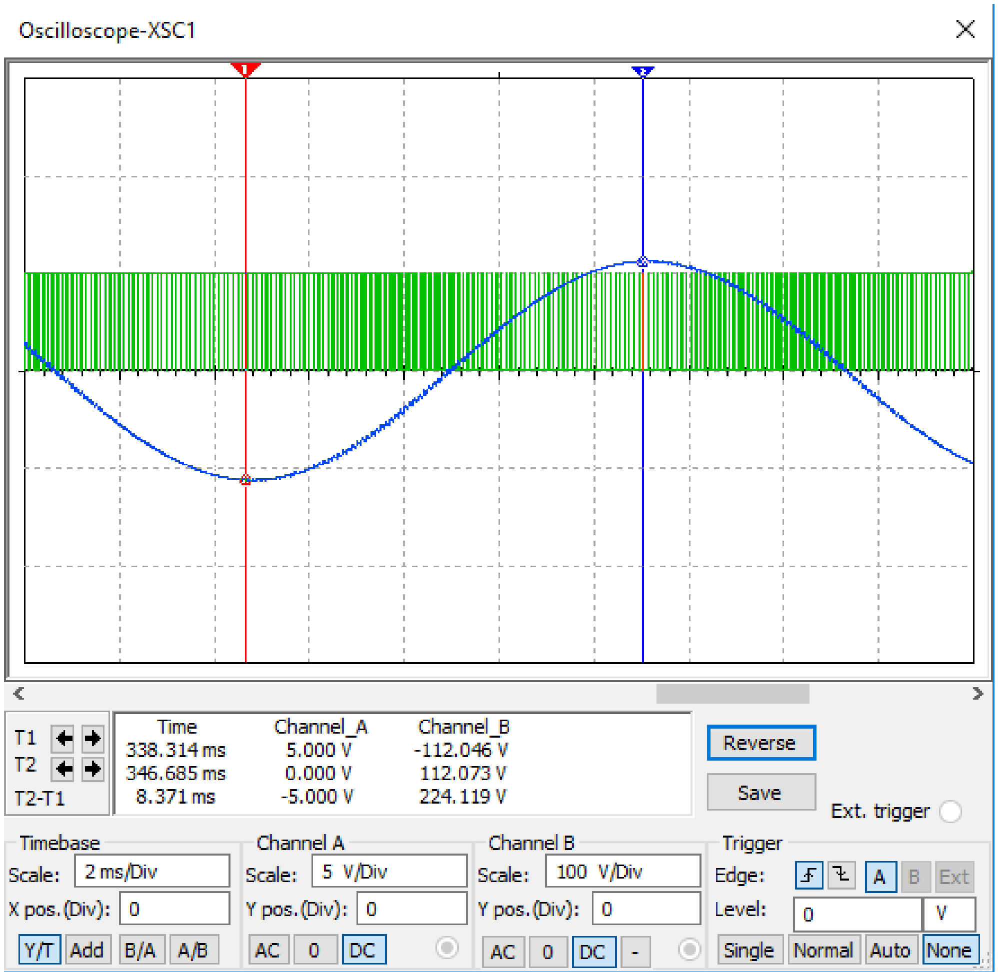


Figure 18. Output of Pure Sine Wave Inverter

5.5 Bi-directional Microinverter

For this project, design specifications require the battery to be charged by the grid which means that the inverter has to be bi-directional. A bi-directional inverter essentially allows the flow of power to travel both ways. The first configuration is to provide power to the grid making the inverter an output. The second configuration is to charge the battery when the grid demand is low thus making the inverter an input.

The reason a bi-directional microinverter is being designed is because in systems were solar panels all share one inverter, when one solar panel fails or is not delivering maximum power, the inverter may fail or not output the optimum power. Shown in Figure 22. is a diagram of a grid tied microinverter.

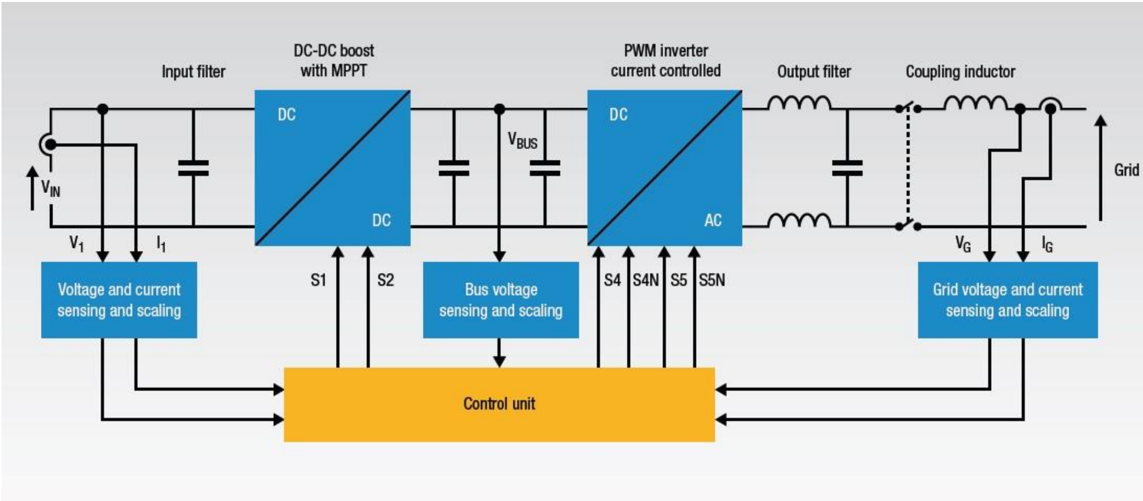


Figure 19. Microinverter Block Diagram
Pending Permission From: STMicroelectronics

In Figure 22, there is one control unit and what that means for our project is that both the first and second stage of power flow will be related to one controller. The microinverter diagram shown is only goes in one direction; however, modifications will be made to allocate power to both the grid and battery.

5.5.1 Bi-directional Microinverter Update

Due to time constraints and several obstacles, the design has been modified to be a standalone uni-directional inverter. This simplified the design to allow a sine wave to be generated through another method. In order to output a sinusoidal wave, it was decided to use sinusoidal pulse width modulation (SPWM). SPWM works by using a reference sinusoidal waveform and comparing it to a triangular waveform to modulate the width of the pulse width signal. The width of the pulse width signal is changed in accordance to the amplitude of the sine wave.

Shown in Figure 23. are three signals that represent the SPWM. SPWM can be implemented through an analog circuit; however, it can also be implemented digitally. The microcontroller for the inverter stage will output the PWM signal to the power mosfets to generate a waveform similar to the square pulses in Figure 23.

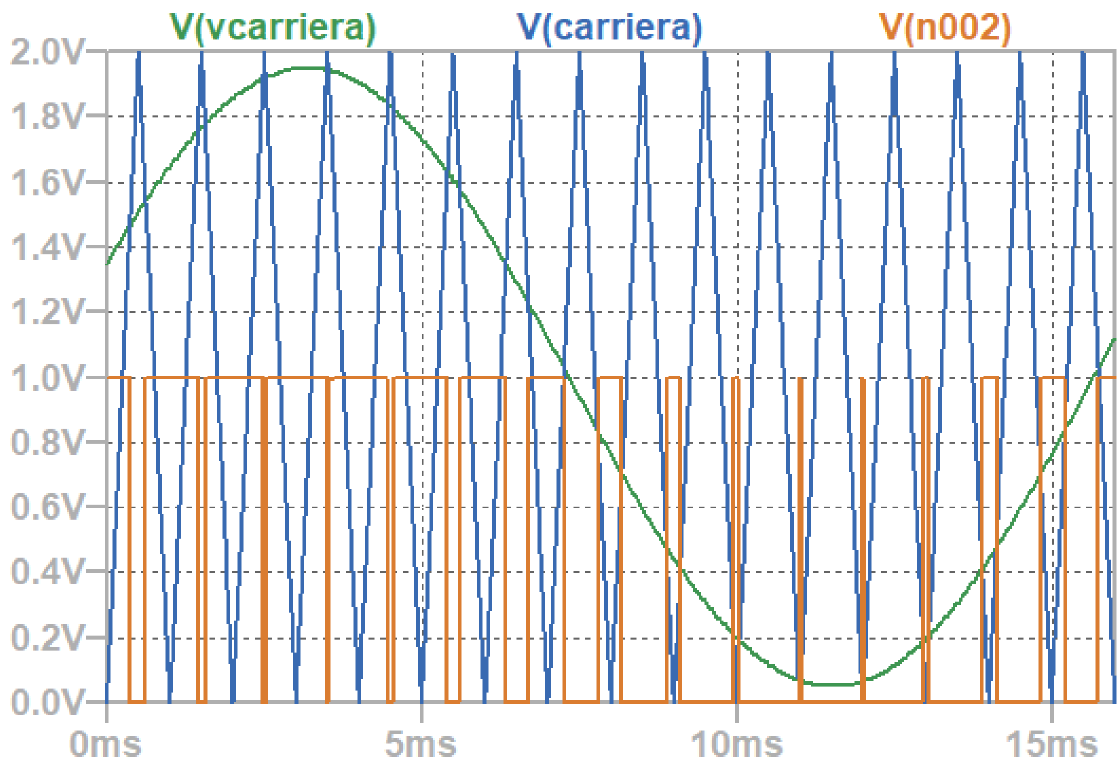


Figure 20. SPWM Signal

5.5.2 LC Filter

To ensure a smooth signal from the output of the inverter, an LC filter was added to the inverter. The reason a filter is needed is to filter out the harmonics of the pulsed square waves. A sine wave usually has a large harmonic in the frequency domain corresponding to its operating frequency. The values of the components were calculated using the following equations:

$$f = \sqrt{f_s \times f_r} \tag{1}$$

$$L = \frac{1}{4C(\pi f)^2} \tag{2}$$

(1) uses the switching frequency fs and the reference sine wave frequency (f_r = 60 Hz) to give the variable *f* that is used in (2) to calculate the values for the LC filter. When the switching frequency increases, the value selected for inductor will also decrease making component selection much more feasible. Using these equations, a spreadsheet was created that varies the switching frequency at a given capacitance to find an inductor value as shown in Figure 24. The values that were chosen for the capacitor was 6 uF and the inductor had a value of 470 uH. These values were configured for a switching frequency around 150 kHz. Shown below in Figure 25. is a plot of the filtered sine wave and the SPWM signal.

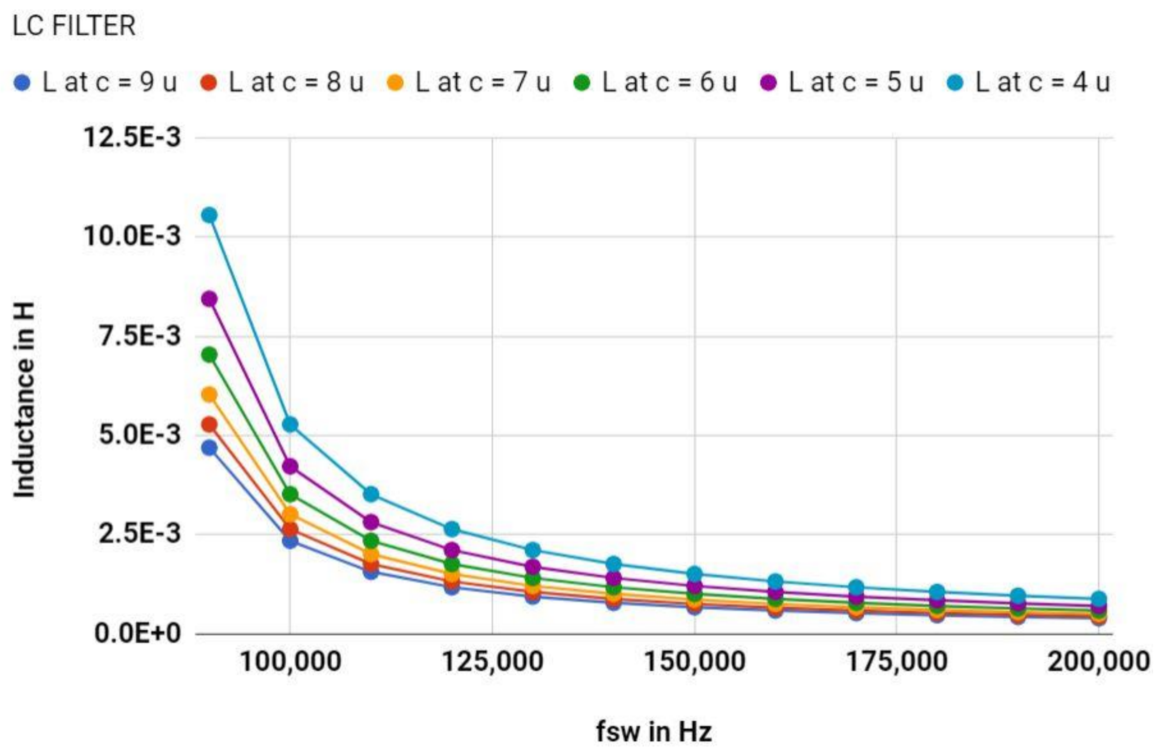


Figure 21. Inductance Value vs. Switching Frequencies

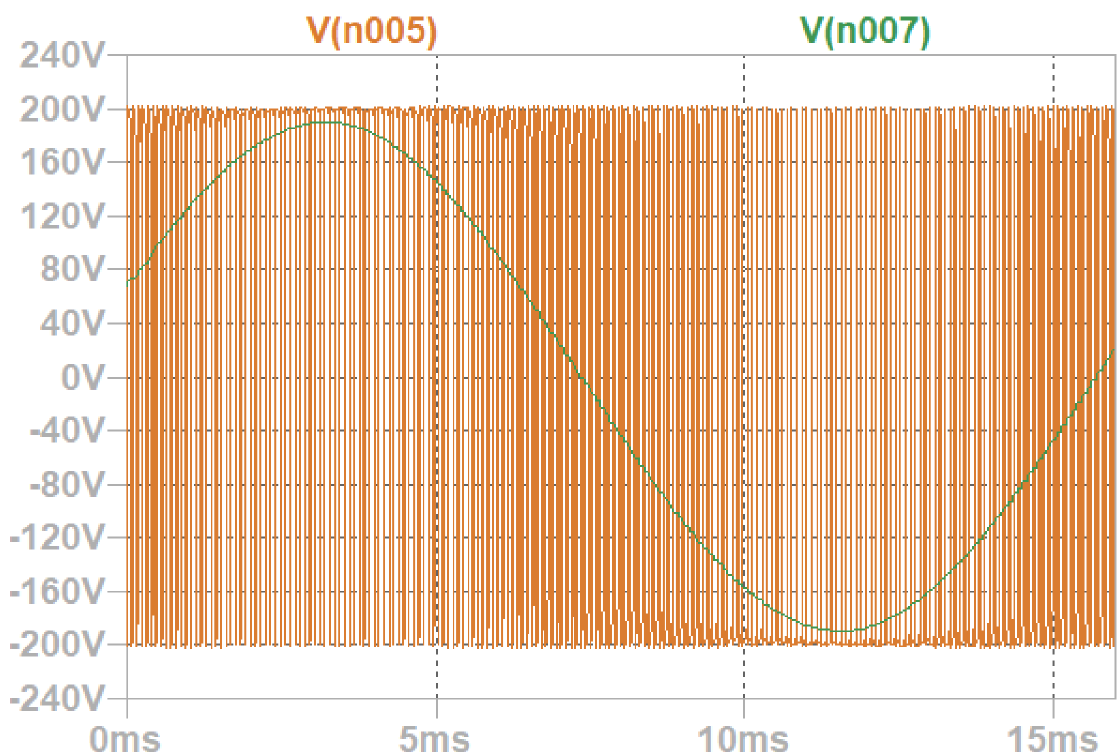


Figure 22. Inverter Output

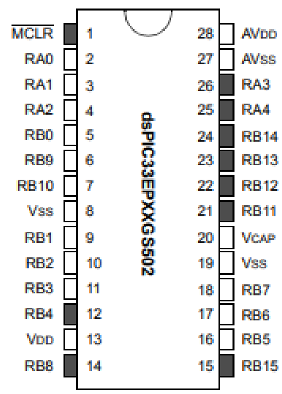
5.6 Microcontroller

After careful consideration and looking at of all the available microcontrollers, it was decided the best fit for this project would be the dsPIC33EPXXGS502 as shown in Figure 26. not only because of the price but also because of all of the features and benefits it has such as [56]:

- 16 - bit processor
- Available in multiple layouts (footprints)
- 6 – 8 PWM output to control the Power MOSFET on the DC to DC converter and the inverter
- Available in a high-temperature option that can operate in 125 C or 150 C to aid in reliability

Pin Diagrams

28-Pin SOIC

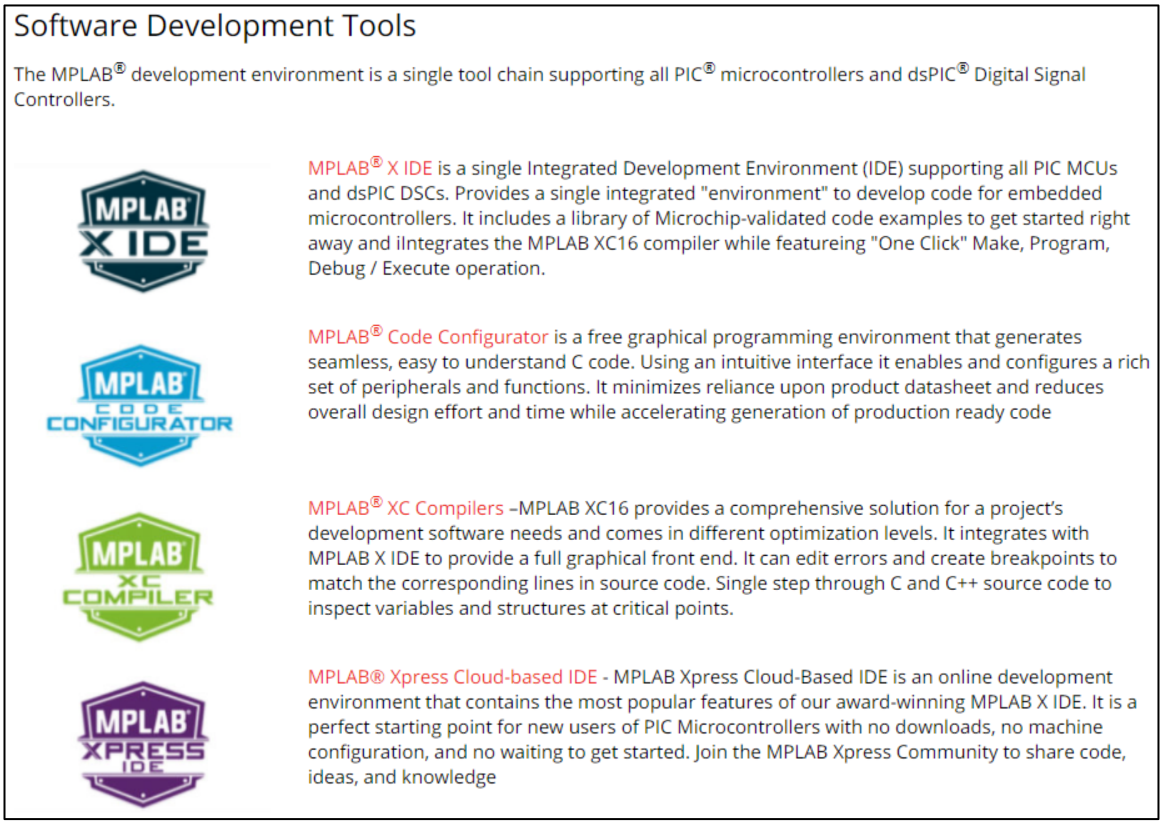


Pin	Pin Function	Pin	Pin Function
1	MCLR	15	PGEC3/SCL2/**RP47**/RB15
2	AN0/PGA1P1/CMP1A/RA0	16	TDO/AN19/PGA2N2/**RP37**/RB5
3	AN1/PGA1P2/PGA2P1/CMP1B/RA1	17	PGED1/TDI/AN20/SCL1/**RP38**/RB6
4	AN2/PGA1P3/PGA2P2/CMP1C/CMP2A/RA2	18	PGEC1/AN21/SDA1/**RP39**/RB7
5	AN3/PGA2P3/CMP1D/CMP2B/**RP32**/RB0	19	Vss
6	AN4/CMP2C/CMP3A/ISRC4/**RP41**/RB9	20	VCAP
7	AN5/CMP2D/CMP3B/ISRC3/**RP42**/RB10	21	TMS/PWM3H/**RP43**/RB11
8	Vss	22	TCK/PWM3L/**RP44**/RB12
9	OSC1/CLKI/AN6/CMP3C/CMP4A/ISRC2/**RP33**/RB1	23	PWM2H/**RP45**/RB13
10	OSC2/CLKO/AN7/PGA1N2/CMP3D/CMP4B/**RP34**/RB2	24	PWM2L/**RP46**/RB14
11	PGED2/AN18/DACOUT1/INT0/**RP35**/RB3	25	PWM1H/RA4
12	PGEC2/ADTRG31/EXTREF1/RP36/RB4	26	PWM1L/RA3
13	VDD	27	AVss
14	PGED3/SDA2/FLT31/RP40/RB8	28	AVDD

Legend: **Shaded pins** are up to 5 VDC tolerant.
RPn represents remappable peripheral functions. See Table 10-1 and Table 10-2 for the complete list of remappable sources.

Figure 23. Pin Diagram of dsPIC33EPXXGS502
Pending Permission From: MicroChip Technology [G]

Another reason we chose this microcontroller is because of all of the option that is available for programming as shown in Figure 27. This is important to us as electrical engineering students as we have only basic programming skills gained from our education. The ability to use MPLAB Code Configurator to build code graphically, the available example codes provided by microchip technology, and application notes on DC to DC converter and inverters will help us in creating the programming codes needed for this project. In addition there are multiple development boards as shown in Figure 28. available to assist us in the design process.



Software Development Tools

The MPLAB® development environment is a single tool chain supporting all PIC® microcontrollers and dsPIC® Digital Signal Controllers.

MPLAB® X IDE is a single Integrated Development Environment (IDE) supporting all PIC MCUs and dsPIC DSCs. Provides a single integrated "environment" to develop code for embedded microcontrollers. It includes a library of Microchip-validated code examples to get started right away and iIntegrates the MPLAB XC16 compiler while featureing "One Click" Make, Program, Debug / Execute operation.

MPLAB® Code Configurator is a free graphical programming environment that generates seamless, easy to understand C code. Using an intuitive interface it enables and configures a rich set of peripherals and functions. It minimizes reliance upon product datasheet and reduces overall design effort and time while accelerating generation of production ready code

MPLAB® XC Compilers –MPLAB XC16 provides a comprehensive solution for a project's development software needs and comes in different optimization levels. It integrates with MPLAB X IDE to provide a full graphical front end. It can edit errors and create breakpoints to match the corresponding lines in source code. Single step through C and C++ source code to inspect variables and structures at critical points.

MPLAB® Xpress Cloud-based IDE - MPLAB Xpress Cloud-Based IDE is an online development environment that contains the most popular features of our award-winning MPLAB X IDE. It is a perfect starting point for new users of PIC Microcontrollers with no downloads, no machine configuration, and no waiting to get started. Join the MPLAB Xpress Community to share code, ideas, and knowledge

Figure 24. Software Development Tools from MicroChip
Pending Permission From: Microchip Technology [G]

dsPICDEM™ MCLV-2 Development Board (Low Voltage) - provides a cost-effective method of evaluating and developing sensored or sensorless Brushless DC (BLDC) and permanent magnet synchronous motor control applications. The board supports Microchip's 100-pin Plug-In-Modules with dsPIC33E or dsPIC33F Digital Signal Controllers

MPLAB Starter Kit for Digital Power - uses the dsPIC33EP64GS502 DSC to implement a buck converter and a boost converter. It is a digitally controlled power supply board that consists of one independent DC/DC synchronous Buck converter and one independent DC/DC Boost converter

Explorer 16/32 Development Kit - is a flexible, convenient and ready to start development, demonstration and testing platform for 16-bit PIC24 MCUs, dsPIC® DSCs and 32-bit PIC32 MCUs from Microchip Technology

Figure 25. Types of Development Boards from MicroChip
Pending Permission From: Microchip Technology [G]

5.6.1 Microcontroller Update

After unsuccessfully programing the dsPIC33, we decided to use a microcontroller that had more open source code. We were able to find multiple codes that were able to output SPWM signals. We took these codes and the data sheet for the ATmega2560 and manipulated it to suit our needs. As shown in Figure 29. and Figure 30, we achieved a 60 Hz sine wave.

Figure 26. SPWM Output from ATmega2560

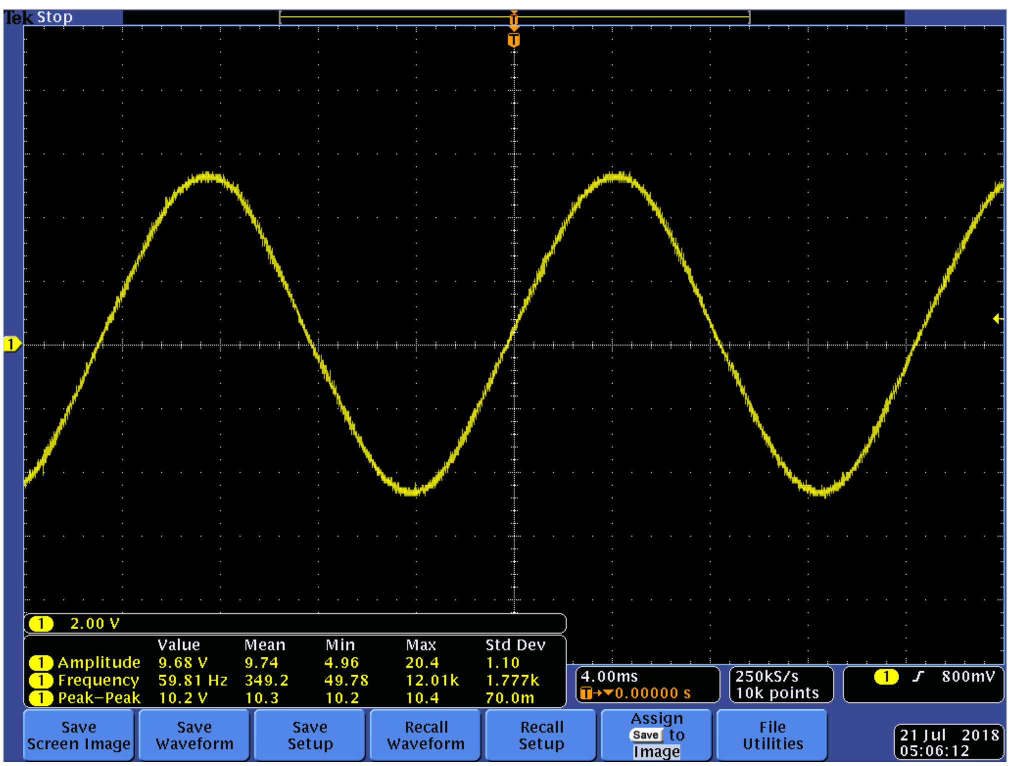


Figure 27. Filtered Output from Inverter Stage

5.7 MPPT Algorithm

The MPPT Algorithm will be designed during the summer of 2018. We need to have all electrical components together in order to begin testing and designing this algorithm.

5.7.1 MPPT Algorithm Update

Due to multiple obstacles, this task was unable to be implemented.

5.8 PCB Board

Through research on multiple sites we were able to put together various PCB manufacturers and ultimately decide where we will purchase our board from. Taking financial and time constraints into consideration, we have decided to go with EasyEDA.

We understand that we will be faced with the possibilities of various issues and may need to reorder the PCB multiple times. Using this manufacturer we will be able to obtain both quick shipment in addition to a purchase that will not hurt us financially.

We plan on finalizing and ordering the PCB in the beginning of summer 2018. This will allow us ample amount of time to change our design and troubleshoot if needed. We plan on using a 2 layer PCB to maximize the amount of space for the design.

5.8.1 PCB Board Update

Instead of ordering the PCB's from EasyEDA, we ordered them from PCBWay since our sponsor recommended them. Many factors are considered in the pricing of PCB's but for our design, we had two PCB's. The first corresponded to the converter stage being 12x12 cm. and the other was the inverter stage being 10x10 cm. Our sponsor already had the converter stage PCB and thus the only thing that needed to be ordered was the PCB for the inverter stage. PCBWay charges $5.00 for ten 10x10 cm. PCB's with a shipping fee of $23.00. This was actually much lower than we expected and that is another reason why PCBWay was chosen.

5.8.2 PCB Design

For the design of the PCB, EAGLE was the primary software used for building the schematic and footprint layout. The process of designing the PCB was very lengthy and time consuming due to everyone's lack of proficiency in this software and knowledge of PCB design. Despite this, over time we became proficient in using EAGLE and were able to successfully design a PCB for the inverter stage.

The initial step in this stage of the design was to find a reference inverter design that our sponsor recommended and to reverse engineer it to meet the project's design specifications. Originally the inverter was three-phase and grid tied;

however, it has been modified to be single-phase and not grid tied. Once the schematic has been modified to meet the design specifications for the project, we had to select parts for the design. Digikey was the vendor that we chose for parts selection as they had a multitude of components to select from and some parts had CAD models to them which could be imported to eagle for the footprint design.

Once the parts have been selected, the schematic and board needed to be made. One of the issues faced was the fact that the default EAGLE library did not have the footprints for many of our components and thus we had to look for options to overcome this issue. Upon looking for footprints for components online, we stumbled upon SamacSys. This was an add-on for EAGLE that had multiple footprints and symbols that could be used for the PCB design and layout. It also had a feature that would allow one to create a custom device on its website; however, EAGLE also had this feature and was used preferred for making custom footprints and symbols.

Once the schematic design was finished, the components had to be oriented manually in the board layout. This stage in the design was very lengthy as we did not know the best configuration for the components. Since we were dealing with circuits that deliver high current and high voltage, we had to isolate low voltage components from high voltage. To handle the large current coming out of the MOSFETS, the copper trace widths were made wider. The traces would technically still not have enough surface area to handle the current; however, since the current is being pulsed at around 150 kHz it was acceptable. Once a layout had been devised, we discovered the concept of a ground plane. This would make routing multiple grounded components much easier and also serve as a natural heat sink for components that dissipate plenty of heat. There were two ground planes, one on the top layer and the other on the bottom layer which were joined by vias. The last thing that was done to the board design was to add isolation to the traces to minimize the chance of short circuits in the manufacturing process.

When the design was finished, we had to export gerber files to send to PCBWay and had to wait for verification. The board layout for the first inverter is shown in Figure 31.

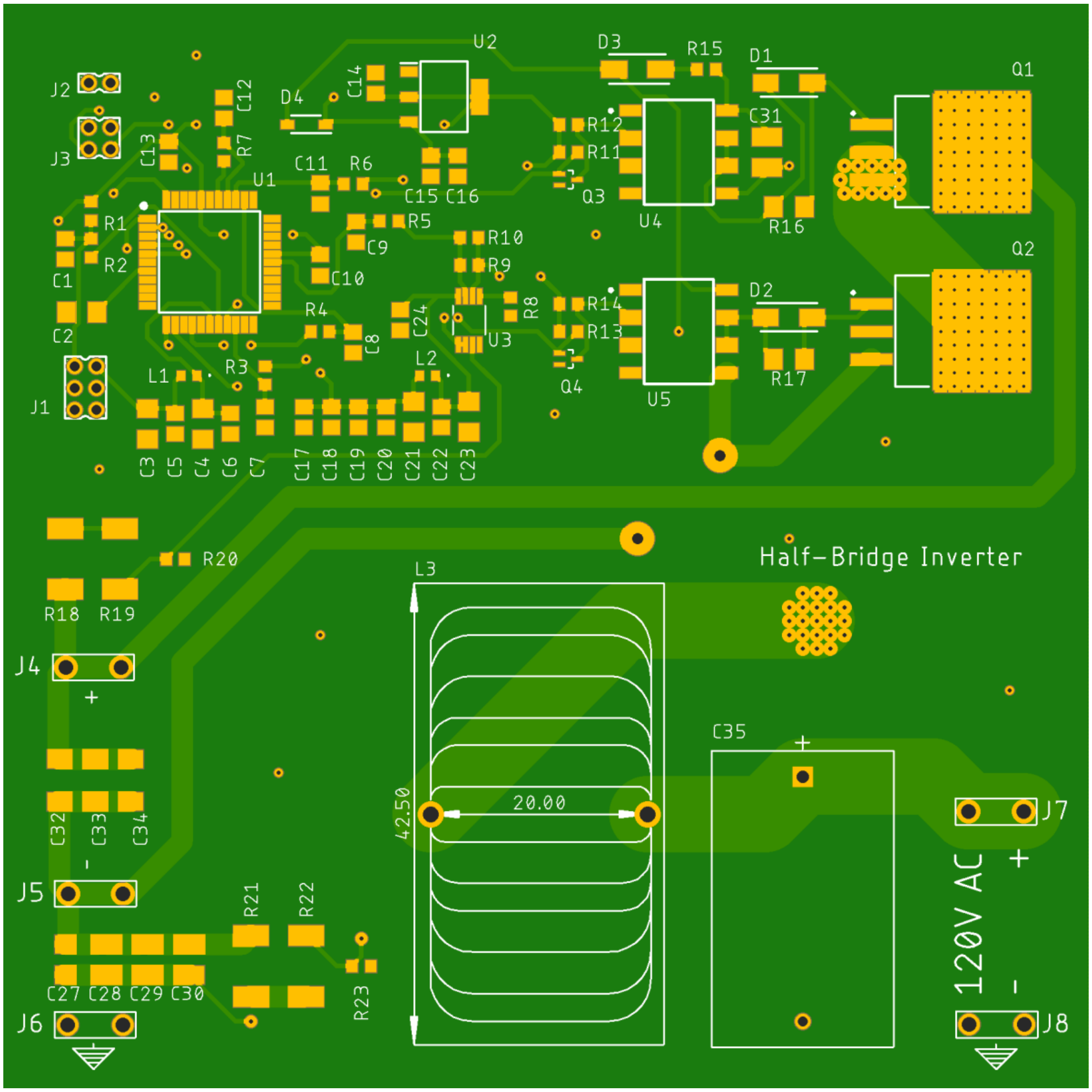


Figure 28. Inverter Board Layout (Revision A)

Once the boards have arrived, we spoke to our sponsor for verification and some design changes had to be made. One of them involved moving the MOSFETS closed to the input headers to minimize power losses which lead to another change which was rearranging components to make space for the filtering stage. Figure 32. shows Revision B of the inverter PCB.

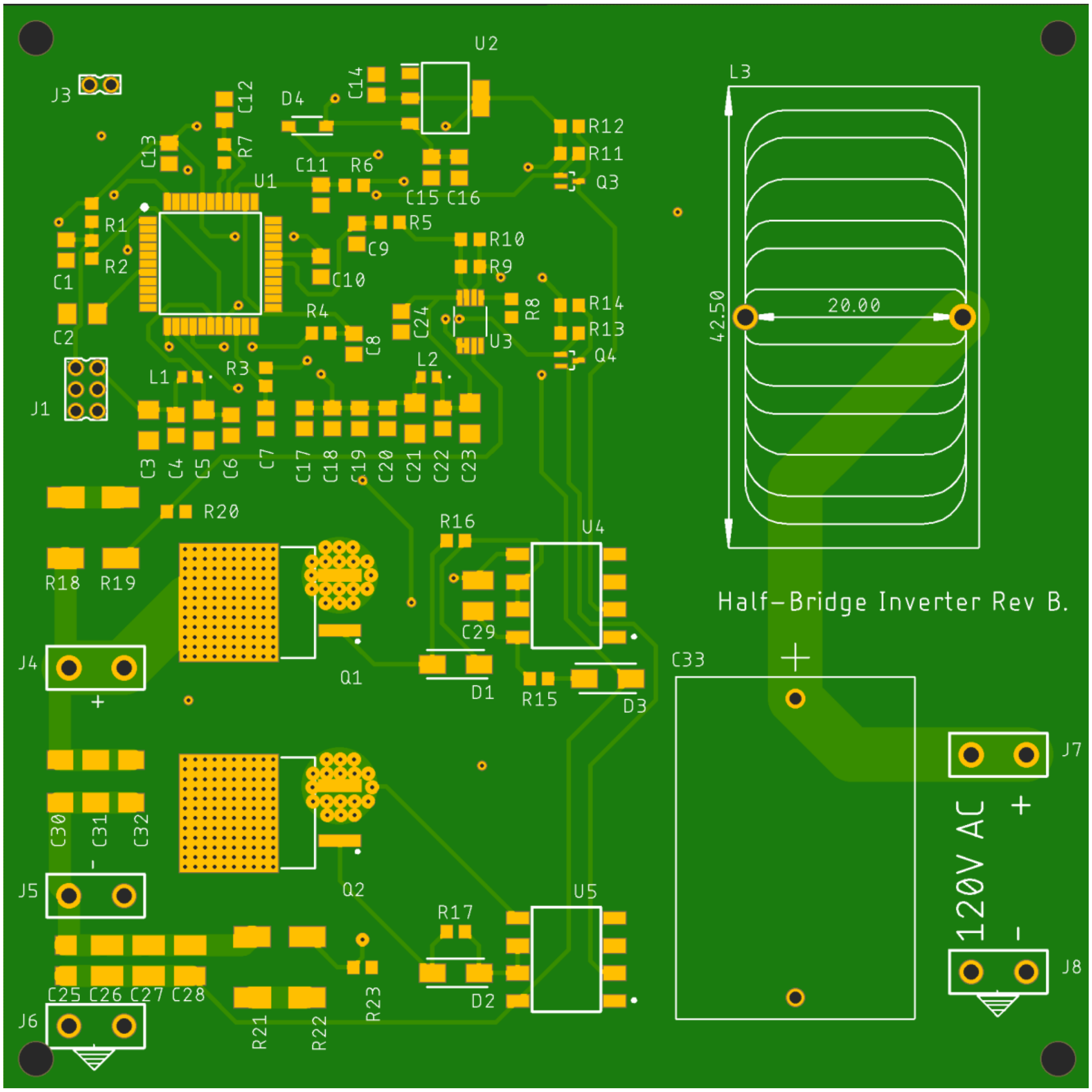


Figure 29. Inverter Board Layout (Revision B)

5.9 Solar Panel

After researching multiple companies, we have decided to purchase our solar panel from CanadianSolar. The solar panel chosen will be a 300 Watt Monocrystalline 60 cell panel. We have chosen this panel due to the fact that it is easily accessible and the cost of the panel is in our price range. The electrical and mechanical technical specifications are shown in Table 20.

Electrical Technical Specifications	
Wattage	300 W
Max Power Voltage	32.5 V
Max Power Current	9.24 A
Open Circuit Voltage	39.24 V
Short Circuit Current	9.83 A
Max System Voltage	DC 1000 V
Operating Temperature	-40 Celsius to 85 Celsius
Power tolerance	0-5 Watts
Module Efficiency	18.33%

Table 20. Electrical Specifications of Chosen Solar Panel

Mechanical Technical Specifications	
Type	Monocrystalline
Dimensions	65” x 39.1” x 1.57”
Weight	40.1 lbs
Frame	Black Anodized aluminum
Connector	Junction Box- IP68, 3 diodes
Cable	4.0 mm^2 (IEC), 12 AWG (UL), 1000 mm (39.4)

Table 21. Mechanical Specifications of Chosen Solar Panel

This panel has a 25 year warranty and comes with the following features [55]:

- 11% more power than conventional modules
- Excellent performance at low irradiance
- High PTC rating of up to 91.90%

- Improved energy production due to low temperature coefficients
- IP68 junction box for long term weather endurance

Below Figure 33. contains information of the voltage and current during certain temperatures.

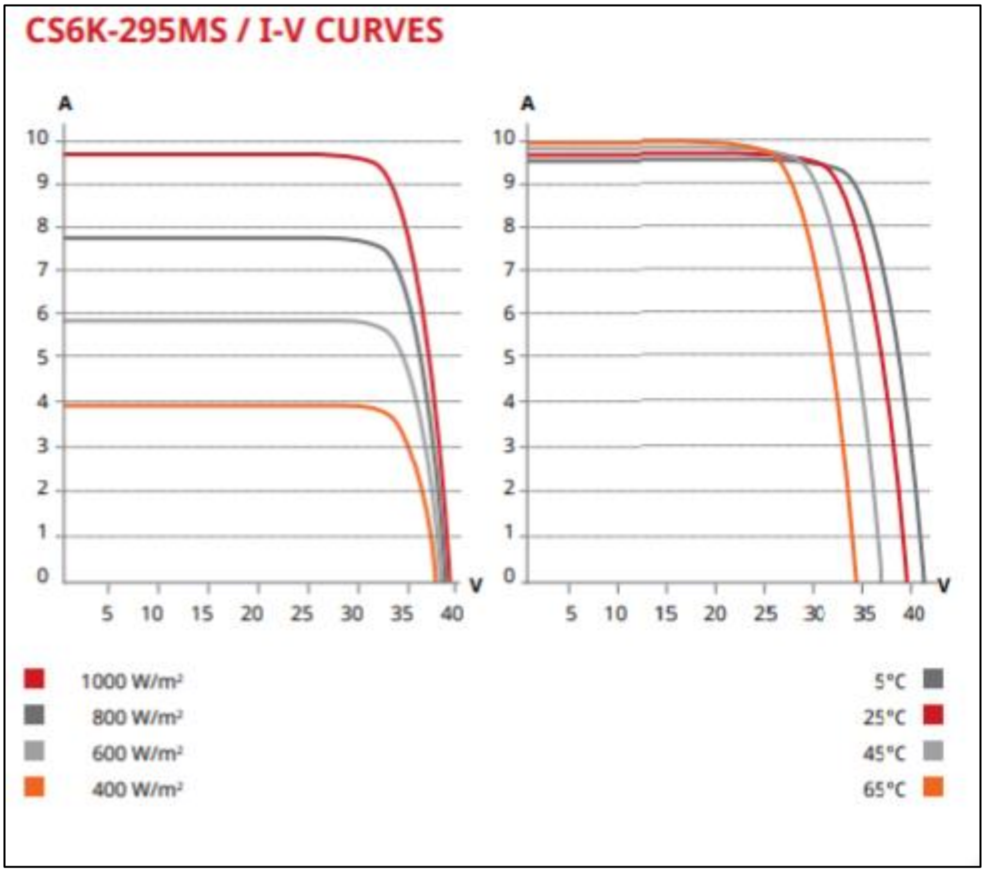


Figure 30. I-V Characteristics of CS6K-295MS
Pending Permission From: CanadianSolar [F]

6.0 Prototype Design

In this section we will discuss the thought process for developing our prototype design, both the mechanical and electrical side of the project.

6.1 Hardware Design

This section includes the design of the hardware for our prototype.

6.1.1 Failure Modes

Shown in Table 22. is a detailed analysis of possible failure modes and assigns each a consequence, likelihood, and detection score. The hazard score is the product of the likelihood and consequence, and it gives a value to each failure mode that can be used to identify the failure modes that are a priority for the product design. The risk priority number is a product of this hazard score and the detection score. It assigns a value based on how likely someone is to be able to detect the failure and take measures to prevent it before it causes major issues or reaches the point of causing the consequence to occur. An example of why the risk priority might be taken into account over the hazard score is for example a screw naturally might come undone under a high vibration cycle, but might not come completely undone right away. If the screw is in a readily available place, the risk involved with operation is much lower than if it were hidden, so detection would play a critical role in design decisions.

For our project, screws aren't undergoing high vibration constantly, but what can become damaged over time are fuses, wires, caulking, and thermal paste/glue. Typical solar panels are not in places that are always accessible so the detection score is going to be higher than if it were accessible. The highest risk priorities for our project are overheating of the battery and circuit board, voltage surge at the transformer, or inverters, and fatigue at the screws, caulking, and glue. These will be a priority when it comes to designing for safety. The controls below will be used to mitigate these risks, however, there are continual requirements that can only be managed through regular maintenance. Given proper maintenance and design modifications, the system as a whole could last upwards of 50 years. An explanation of each score is detailed below the table.

Possible failure modes	Related components	Estimated life cycle (# yrs)	Consequence (1-5)	Likelihood (1-5)	Hazard score	Detection (1-5)	Risk Priority Number	Controls	Est life cycle after controls
Overheat									
	Circuit Board	<1	4	2	8	4	32	Fan	10
	Battery	<1	5	5	25	4	100	Fan	10
	Solar cells	2	4	2	8	1	8	Maint.	infinite
Voltage surge									
	Transformer	2	5	3	15	4	60	Fuse	10
	Inverters	2	4	4	16	3	48	Fuse	10
	Fuse	2	1	3	3	2	6	Maint.	2
Age									
	Circuit board	2	1	1	1	4	4	Maint.	∞
	Fuse	2	1	5	5	4	20	Maint.	∞
	Wires	2	1	1	1	4	4	Maint.	∞
Environmental wear									
	Corrosion	N/A	2	2	4	4	16	Maint.	N/A
	Wind	N/A	5	2	10	1	10	Maint.	N/A
Fatigue									
	Screws	∞	4	2	8	3	24	Maint.	∞
	Nails	∞	4	2	8	3	24	Maint.	∞
	Glue	5	4	2	8	3	24	Maint.	∞
Maintenance cycle	Inspect elec components		How often?	6 months	Cost of repair	<$1000	Time requirement	30 min	
	Glue/Caulk/Solder			6 months		<$10		10 min	

Table 22. Consequence Score of Different Failure Modes

*likelihood based on 1 = once in 40 years, 2 = once in 30 years, 3 = once in 20 years, 4 = once in 10 years, 5 = one time in 1 year
*consequence based on 1 = negligible, 2 = controlled failure, 3 = non-permanent loss of a lot of equipment, 4 = permanent loss of all equipment, 5 = major loss to equipment and home
*Detection based on 1 = able to see it from the ground, 2 = able to see it if you are right next to it, 3 = able to see it if you walk around or move around 4 = able to see it if you remove parts, 5 = need special equipment to see it

6.1.2. Engineering Driven by Customer Needs

Shown in Table 23. is a prioritized list of user wants and needs and related engineering design requirements. The information in the chart is used as a means of taking customer needs, analyzing them, and identifying engineering design constraints and requirements needed to meet the customer needs.

Customer Needs	Importance (1-10)	Engineering Design Requirements	Explanation of Importance
Affordable initial investment	4	Materials need to be affordable	Owners invest in PV systems spend a lot of initial money in the hopes of making a good investment
		Design must not be complex to manufacture	
Requires less time effort than current set up	9	Component locations are accessible	Owner's typically have other obligations and hobbies they'd rather be doing
		Screws and other retainers are minimal	
Requires less knowledge than current set up	9	Intuitive design	Owners are usually knowledgeable, but not technical experts
Requires less money to repair	9	Structure allows replacement of individual parts	Monetary investment benefits decrease with constant maintenance costs
		Electrical grid allows replacement of individual parts	
Provides energy at all times	10	Electrical grid always draws energy from some combination of a stored source or the sun	If they were ok with having no electricity, they wouldn't have got a PV at all

Table 23. Customer Needs and Design Requirements

6.1.3 Competitor Benchmarks

Frames available on today's market for PV systems are just a set of metal fasteners and retainers not sold as a bundle or even as an identifiable piece of a PV structure. As for the electrical grids in use today. They utilize a centralized battery storage system with panels of integrated solar cells. Competitor benchmarks for the electrical grid are offered below, however, for the structure, there are no benchmarks since there are no competitors offering pre built structures**.** Shown in Table 24. is a breakdown of customer needs, and the benchmarks we set for ourselves in our design order to meet those needs.

Customer Need	Competitor Benchmarks (1-10)	Projected Design Benchmarks (1-10)	Explanation
Low initial investment	1	1	PV systems are far more expensive than Oil. Competitor design is similar in initial cost
Low labor hours required for upkeep	1	5	Parts will still need to be replaced, but the ease of doing this is what will be improved
Low maintenance cost	1	5	Replacing individual components is much cheaper than the current method
Low knowledge requirement	1	8	Owners will still need to know the difference between a battery and an inverter, for example, but not how to wire everything together to replace a part.
Attractive	3	3	No change in outward appearance
Provides energy at all times	8	10	Today's systems use back up energy from the outside power grid, our design will only need its own power.

Table 24. Competitor Customer Needs and Design Requirements

6.1.4 Design Aspects Determination and Critical Performance Parameters

Table 25. identifies the critical performance parameters for the proposed system design along with preliminary target values and acceptable ranges for performance. The top row shows the engineering design and below it the subcategories associated with them. The left column shows the customer needs, and the column to the right of it, shows what our targets are for those needs. Each design category is ranked on how well they meet the customer needs based on the values set by the target. If one design meets more of the targets and has a higher quality of doing so, it will have a higher total of points at the end. The design with the highest total value is the design we go with since it meets the most customer needs and has the highest quality of aspects. As you can see, a steel frame with a sliding cartridge meets the customers' needs best compared to aluminum and compared to stationary cartridges. Lithium ion batteries meets the customer needs above lead acid batteries. Attractable design is what put Lithium batteries ahead of lead acid batteries in this case, and throughout our report, it has been a better choice, so we will be utilizing them in our design.

			Engineering Design						
	Design	Target	Aluminum Frame		Steel Frame		Lithium Battery on each panel	Lead acid battery on each panel	Current
	Sub category		Sliding cartridge for each part	Stationary cartridge for each part	Sliding cartridge for each part	Stationary Cartridges	Draws energy from battery as back up	Draws energy from battery as back up	
Customer need	Low initial investment	.04: Less than $100 addtl cost per panel; .01: Less than $1000 per panel	0.025	0.03	0.015	0.02	0.01	0.02	0.04
	Low labor hours required for upkeep	.09: Less than 5 minutes a year; .01 less than 1 hour per year	0.08	0.08	0.09	0.09			0.01
	Low maintenance cost	.09: less than 1% replacement of parts per year; .01 less than 10%	0.06	0.06	0.09	0.09			0.01
	Low knowledge requirement	.09: Plug and play set up; .01 requires a technical manual	0.09	0.08	0.09	0.08			0.01

Table 25. Engineering Design and Customer Needs Design Targets

	Design	Target	Aluminum Frame		Steel Frame		Lithium Battery on each panel	Lead acid battery on each panel	Current
Customer Needs	Withstands winds up to 80 mph and rain	.2 withstands winds up to 80 mph and rain; .01 withstands winds up to 4 mph	0.15	0.15	0.2	0.2	0.2	0.1	0.15
	Attractive	.05: adds to home value; .01 decreases home value	0.02	0.02	0.04	0.04	0.05	0.025	0.02
	Provides energy at all times	.1 provides energy 100% of the time; .01 provides energy 10% of the time, draws the rest from outer grid					0.1	0.1	0.05

* Blank area means no effect

Table 25. Engineering Design and Customer Needs Design Targets

6.2 Heat Transfer Analysis

In this section we discuss various aspects of heat transfer analysis, including but not limited to: Thermal Circuit analysis, the location and speed of the fan, solidworks simulations of heat transfer and structural analysis. This section has been authored by the mechanical engineering team of this project.

6.2.1 Thermal Circuit

Batteries are filled with an electrolyte solution and surrounded by a metal casing often nickel plated steel [39]. The thermal conductivity of nickel is 90 W/mK at 20^{o}C and nickel Wrought is 61-90 W/mK at 1-100^{o}C, so we will use the value 90 W/mK. Stainless steel is 12-45 W/mK at 20^{o}C. Low nickel steel is .445 W/mC at 100^{o}C and .427 W/mC at 200^{o}C [40]. The emissivity of electroplated nickel is .03 at 300K. The convective heat transfer coefficient for air is 0.5-1000 W/m^{2}K for free convection and 10-1000 W/m^{2}K for forced convection. The Boltzmann constant (σ) for radiation is 5.67*10^{-8} W/m^{2}K^4

$h_{elec}(T_0 - T_1)$ $\quad$ $k_{steel}(T_2 - T_1)$ $\quad$ $0.03\sigma(T_3^4 - T_2^4) + h_{air}(T_{inf} - T_2)A_2$

Electrolyte(T_o) $\rightsquigarrow$ Steel Plate(T_1) $\rightsquigarrow$ Nickel Plate(T_2) $\rightsquigarrow$ | $\rightsquigarrow$ Circuit board(T_3)

$h_{air}(T_{inf} - T_2)A_2$

| $\rightsquigarrow \mathrm{Air}(T_{inf}) \uparrow hair(T_{inf2} - T_3)A_3$

The convection coefficient of air (h_{air}) is dependent on air speed. In order to determine it, we need to know two things:

1. Is the air turbulent? Is Re less than 10^5?

   Re = Vx/(15.06*10^{-6} m^2/s); the length of our battery is about x = 10 cm.
   = 6640.1 V; As long as V < 15.06 m/s it is laminar

2. What is the prandtl number?

   Pr = (15.06*10^{-6} m^2/s)/(1.9*10^{-5} m^2/s) = 0.792 > 0.5 so it's high.

   What is the Nusselt Number?

   $Nu_L = 0.664Re_L^{.5}Pr_L^{.343}$ = 193.8 at 15 m/s since it's laminar, if it was turbulent, $Nu_L = 0.037Re_L^{.8}Pr_L^{1/3}$

   h_{AIR} = Nu*k_f/L
   =193.8*.445/.1
   = 862.41 W/m^2K

Assuming battery temperature of 100^{o}C and air 20^{o}C

Since the operating temperature must stay below 100^{o}C, we will use this as a basis for analysis for the battery temperature. The total heat loss to the board from the battery is given by UA(T_{batt}-T_{board}) where U is the thermal resistance between the battery and board.

U =1/resistance = (diffusivity/thickness). In our analysis we will consider a distance of 10 cm, 15, and 20 cm. In our thermal circuit, the battery temperature at the nickel is 100C which gives off radiation and convection energy. The convection energy is carried by the air through thermal diffusivity, resulting in a temperature gradient whereby the point closest to the board heats the board through convection. The energy due to radiation is .03*σ*(T_{nickel}^4-T_{board}^4). The thermal diffusivity of air is 1.9*10^{-5} m^2/s [39]. We will consider the temperature of the board to be at the temperature of the environment initially and determine the temperature at different wind speeds given in the Table 26. The heat transfer due to convection is h_{air}*A_s*(T_s-T_{air1}) from the battery to the air, and h_{air}*A_s*(T_{air2}-T_{board}) from the air to the circuit board. Distance*velocity*T_{air1}/diffusivity =T_{air2}.

Battery Temp	Air Temp	Circuit Board Temp (C)	Total heat loss	Battery Temp	Air Temp	Circuit Board Temp (K)	Battery Temp	Air Temp	Circuit Board Temp (K)	Battery Temp	Air Temp	Circuit Board Temp (K)
60	20	59.0	697.2									
100	20	77.3	1097.5									
Forced convection 10 m/s				Forced convection 20 m/s			Forced Convection 30 m/s			Forced Convection 100 m/s		
50	20	40.92	3675	50	20	40.91	50	20	40.91	50	20	40.89
55	20	42.59	4287.5	55	20	42.59	55	20	42.58	55	20	42.57
60	20	44.01	4900	60	20	44.01	60	20	44.01	60	20	43.99
65	20	45.27	5512.5	65	20	45.27	65	20	45.27	65	20	45.25
70	20	46.42	6125	70	20	46.41	70	20	46.41	70	20	46.40
75	20	47.47	6737.5	75	20	47.47	75	20	47.47	75	20	47.45
80	20	48.46	7350	80	20	48.45	80	20	48.45	80	20	48.43
85	20	49.38	7962.5	85	20	49.38	85	20	49.38	85	20	49.36
90	20	50.27	8575	90	20	50.26	90	20	50.26	90	20	50.24
95	20	51.11	9187.5	95	20	51.11	95	20	51.11	95	20	51.09
100	20	51.92	9800	100	20	51.92	100	20	51.92	100	20	51.90
105	20	52.71	10412.5	105	20	52.71	105	20	52.70	105	20	52.69
110	20	53.47	11025	110	20	53.47	110	20	53.46	110	20	53.45
Cp	1 kj/kg K	10		20		20		30	30		100	100
Re		67567.6		135135.1		135135.1		202702.7	202702.7		675675.7	675675.7
Pr		0.8		0.8		0.8		0.8	0.8		0.8	0.8
Nu		158.4		224.0		224.0		274.4	274.4		501.0	501.0
h		52.8		74.6		74.6		91.4	91.4		166.8	166.8

Table 26. Resulting Circuit Board Temperature by Forced Convection

Table 26. shows the results of theoretical temperatures for the circuit board given a variety of forced convection wind speeds. Assuming that the battery could reach temperatures of up to 100C regularly, the battery has to be far enough away and enough wind has to pass through in order to prevent the circuit board from overheating (60C) [41].

6.2.2 Recommended Wind Speed and Location of Fan

The recommended distance is at least 10 cm away and wind speed is at least 10 m/s if the surrounding air temperature is 20ºC, however, temperatures in summer can easily reach 105ºF. The recommended wind speed is at least 27.62 m/s at those temperatures and a distance of 10 cm. Calculations at 1 cm resulted in temperatures of at least 100ºC rising exponentially. Slower wind speeds could cause the circuit board to overheat if the battery temperatures reach even 80ºC. Further study of the heat transfer will be conducted through simulation.

6.2.3 Assumptions

The assumptions in this analysis include:

1. The battery and circuit board are both 10cm x 10cm x 1 cm.

2. The battery temperature of up to 100C occurs at the nickel air interface.

3. The circuit board can be modeled as a lump body, and their internal temperature gradient isn't important. Checking that the Biot number=h_{air}/k_{board}<.1 will confirm this assumption is true.

4. Temperatures range up to 105ºF.

5. The battery can be placed between 1 and 10 cm from the circuit board.

6. The temperatures of other components such as the transformer, fuse, and inverters won't reach dangerous temperature first. From our research, we believe the battery to be the hottest component, however, we will monitor the temperatures of other components and if it is determined that one of them is a higher risk, we will conduct heat transfer analysis and modify our design accordingly.

6.2.4 SolidWorks Simulation of Heat Transfer

Figure 34. shows a simulation of the heat transfer from the battery to the circuit board. The materials chosen for the analysis were silicon for the board, and nickel for the battery with sizes 10 cm x 10 cm x 1 mm. Under free convection, and radiation, the temperature of the board reached 56ºC. The chosen values of

temperature were 100ºC for the battery, 41ºC for the board initially, and 41 for the atmosphere. The values in the model are lower than that calculated theoretically, which might be due to the convection and conduction coefficients used by the simulator being different, and the difference in ambient temperature. The results from the simulation would imply that at a distance of 10 cm, free convection is enough to keep the board at a safe temperature.

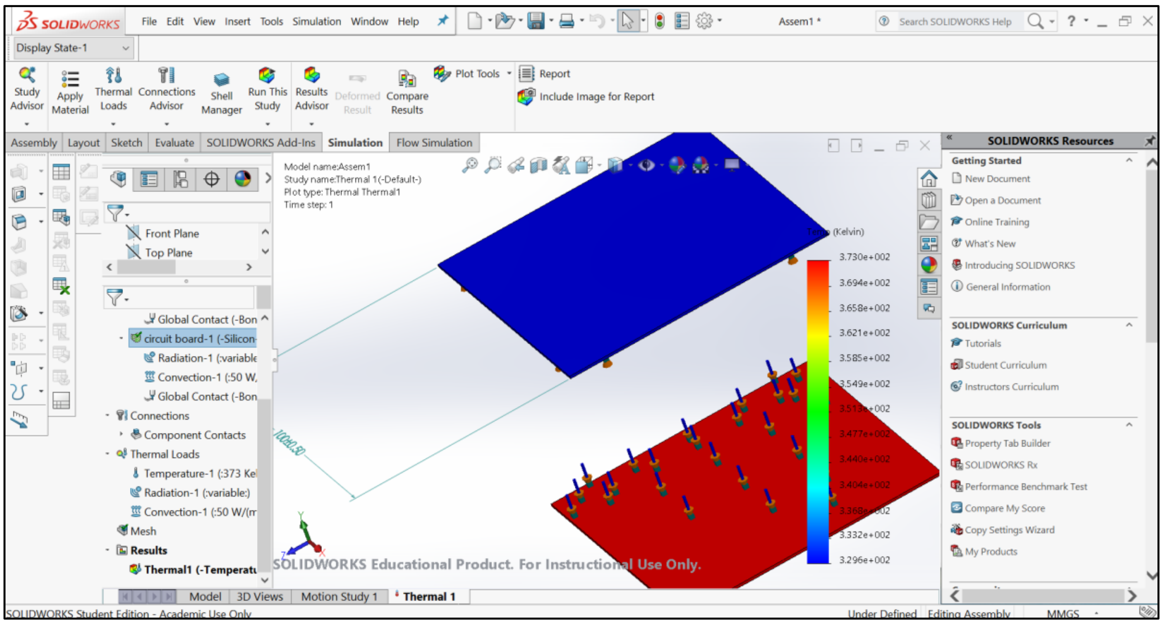


Figure 31. Natural Convection Between Battery and Circuit Board

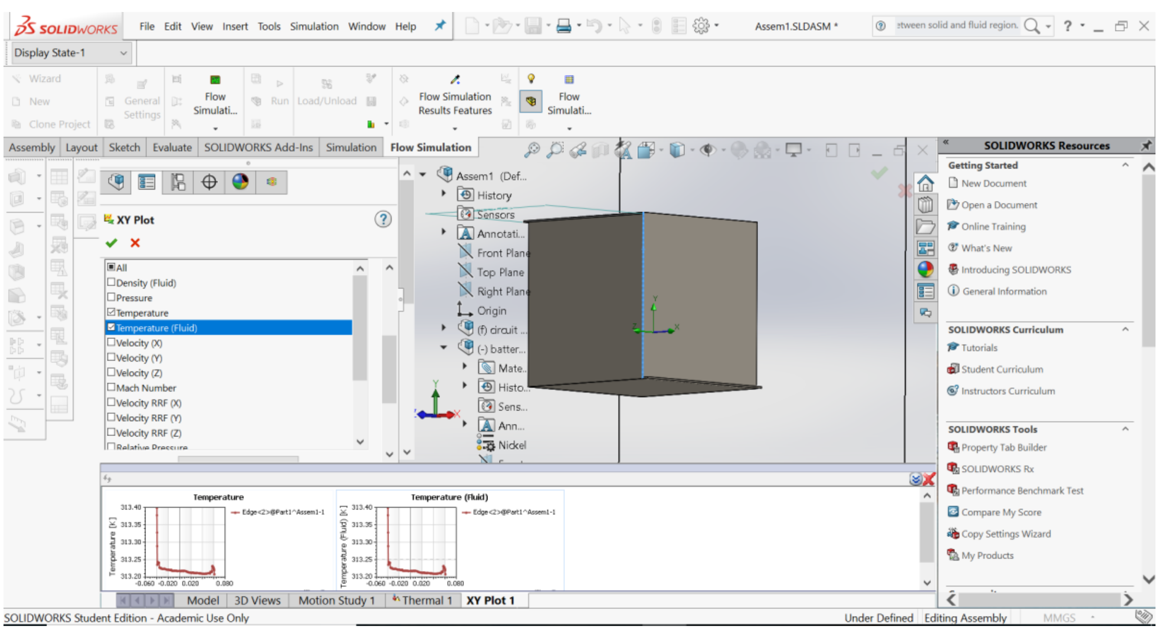


Figure 32. Simulation of Forced Convection

In order to simulate flow, and analyze the heat transfer, the same model was used with a solid nickel extrude around the area where a fan would push air through. Figure 35. shows the model. An airflow of 10 m/s was used and the same temperatures as the first simulation. Figure 36. and Figure 37. show the results of the simulation.

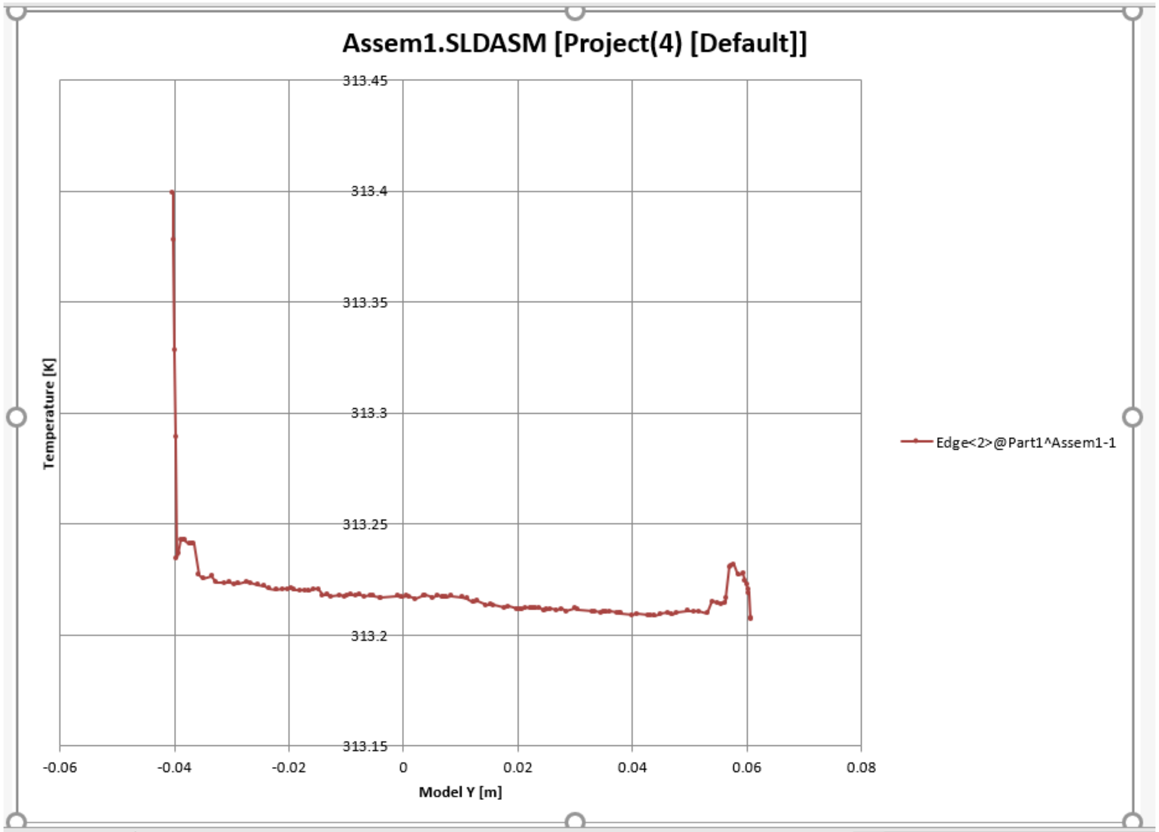


Figure 33. Temperature as a Function of Distance Along Y-axis

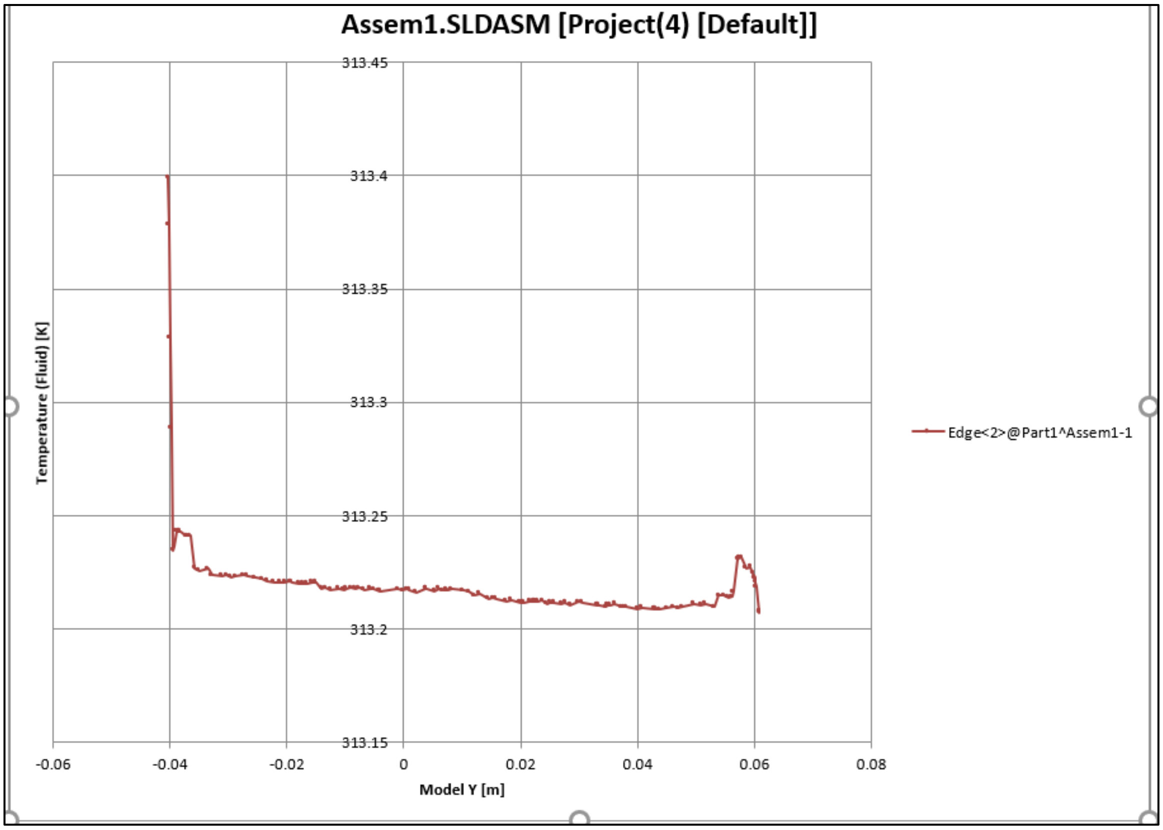


Figure 34. Temperature of the Fluid as a Function of Distance Along Y-axis

Figure 36. and Figure 37. show the temperatures for overall and for fluid temperature respectively. As you can see the temperature at .06 m from the x axis rises to 41.125ºC in both cases, which is well within the safe operating temperature of the board. The x axis for the coordinate system was located at .04 m above the battery. The chart below shows the data associated with the charts above. As you can see, the rise in temperature doesn’t occur quickly as the distance along the y axis increases.

Temperature [K]		Temperature (Fluid) [K]	
Model Y [m]	Edge<2>@Part1^Assem1-1	Model Y [m]	Edge<2>@Part1^Assem1-1
0.06	313.21	0.06	313.21
0.06	313.21	0.06	313.21
0.06	313.22	0.06	313.22
0.06	313.22	0.06	313.22
0.06	313.22	0.06	313.22
0.06	313.22	0.06	313.22
0.06	313.23	0.06	313.23
0.06	313.23	0.06	313.23
0.06	313.23	0.06	313.23
0.06	313.23	0.06	313.23
0.06	313.23	0.06	313.23
0.06	313.22	0.06	313.22
0.06	313.21	0.06	313.21
0.06	313.21	0.06	313.21
0.05	313.21	0.05	313.21
0.05	313.22	0.05	313.22
0.05	313.21	0.05	313.21
0.05	313.21	0.05	313.21

Table 27. Results for Temperature Under Forced Convection

Name	Minimum	Maximum
Density (Fluid) [kg/m^3]	1.08	1.13
Pressure [Pa]	101289.61	101399.53
Temperature [K]	313.17	373.20
Temperature (Fluid) [K]	313.17	373.20
Velocity (X) [m/s]	-4.226	11.348
Velocity (Y) [m/s]	-3.855	3.743
Velocity (Z) [m/s]	-6.823	6.886
Mach Number [ ]	0	0.03
Velocity RRF (X) [m/s]	-4.226	11.348
Velocity RRF (Y) [m/s]	-3.855	3.743
Velocity RRF (Z) [m/s]	-6.823	6.886
Relative Pressure [Pa]	-35.39	74.53
Shear Stress [Pa]	0	6.01
Bottleneck Number [ ]	2.4763516e-017	1.0000000
Heat Transfer Coefficient [W/m^2/K]	0	190.278
ShortCut Number [ ]	6.0962316e-017	1.0000000
Surface Heat Flux [W/m^2]	-27.351	15222.262
Surface Heat Flux (Convective) [W/m^2]	-3585691.443	15222.262

Table 28. Overall Data Associated with the System

6.2.5 Structural Analysis

Structural analysis was done using solidwork. Due to the fact that we have yet to receive solar panels that was supposed to given to us, we used the Renogy 300 Watt Monocrystalline Photovoltaic PV Solar Panel to conduct this study. This model fit the requirement of out project. This model weight 171.2 pounds and have the dimension of 65x39.2x1.6. This study include two simulations and six tests. The two simulations are static and fatigue. Three tests run under static simulation was the stress, displacement and strain tests. The other three test was fun under fatigue study. They are the damage, life and load factor.

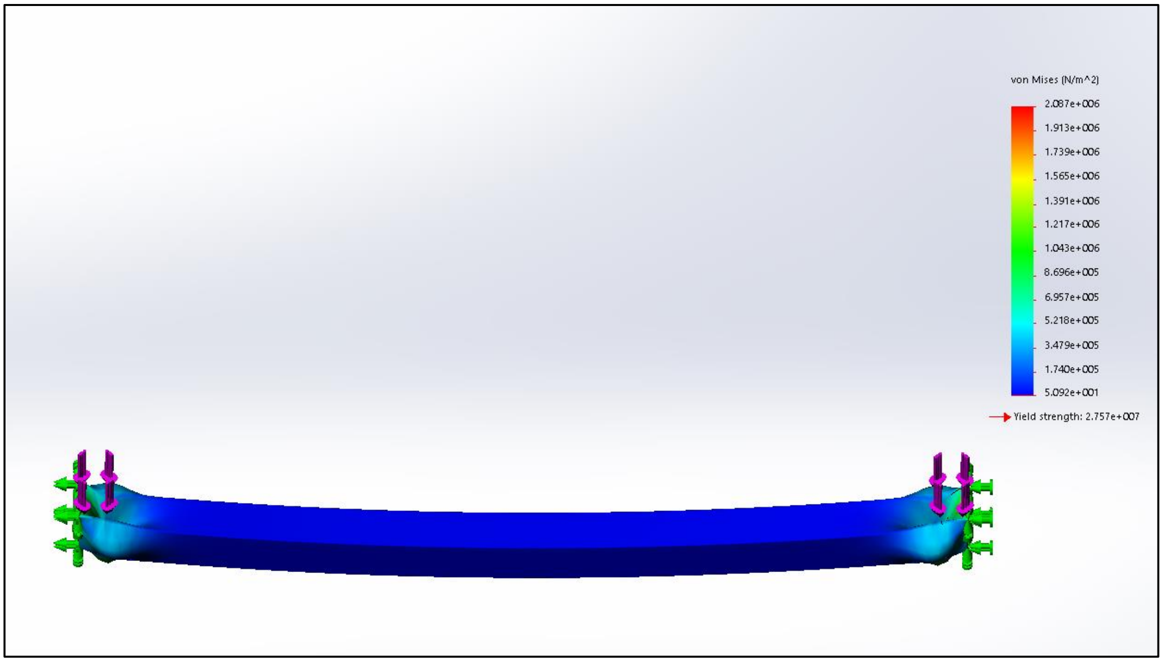


Figure 35. Stress Distribution

In Figure 38, it shows the stress distribution of the racking beam after the weight of 42.8lb in two different spot of the beam. Since the weight of the solar panel is 171.2lb and it will be supported by two beam. Each beam with support half of the load in two different spots. As we can see the stress is center at the two main spots of the beam. The maximum von Mises was measured at $2.087 * 10^6$ (N/m^2).

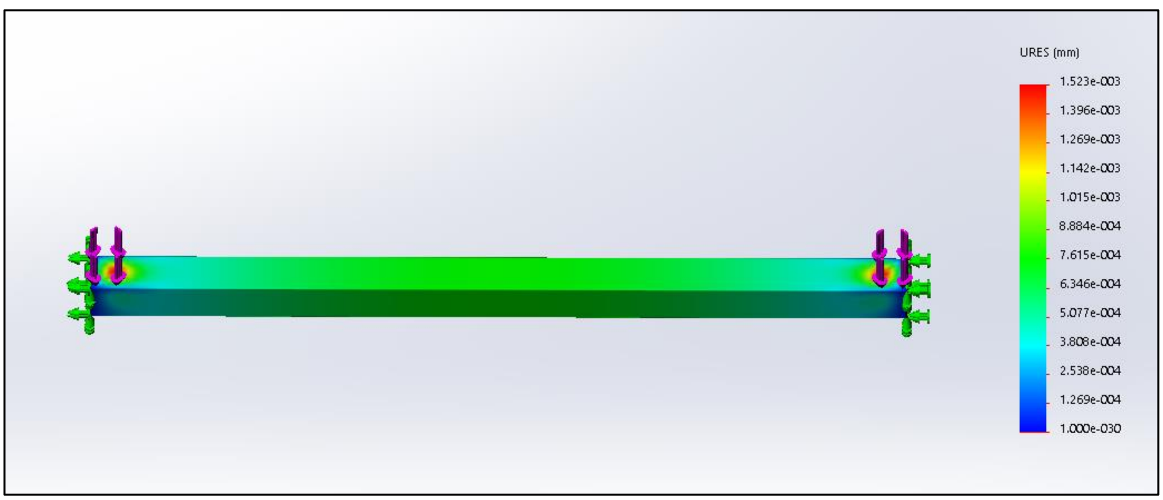


Figure 36. Displacement Distribution

In Figure 39, displacement of the beam is shown. This simulation was done using the deformation scale of 1. The maximum displacement was measured at the spot where force were applied and it has the displacement of 1.523*10^{-3}mm. This displacement is so small that it human eye won't be able to distinct. This displacement won't create any structural damages as it can be confirmed later in the fatigue simulation.

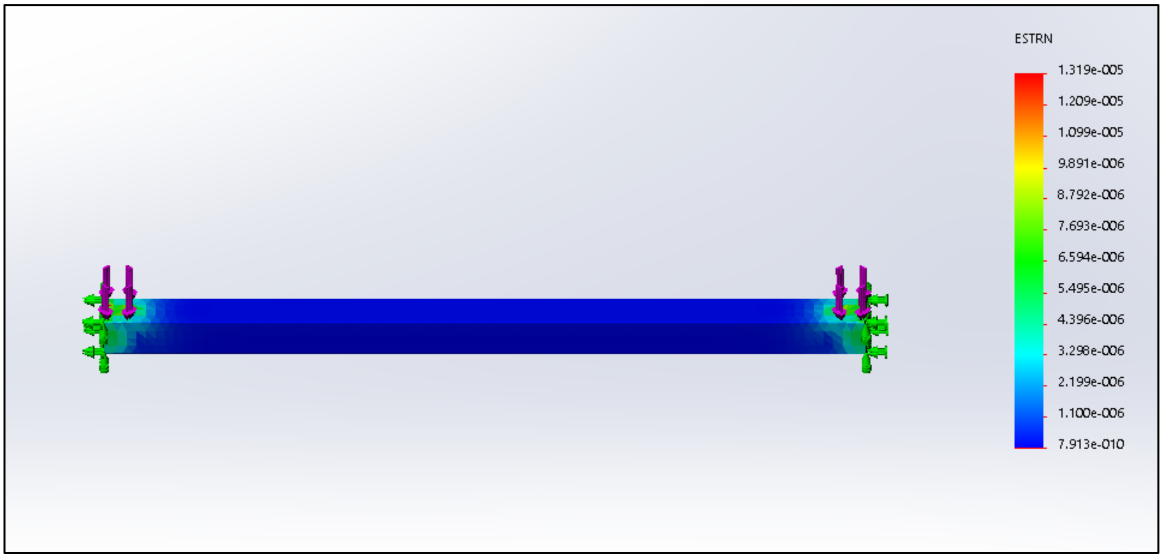


Figure 37. Strain Distribution

In Figure 40, strain was measured after the weight of the solar panel was applied. Solidwork take input data and calculate strain using the formula ESTRN=2 [(ε1+ε2)/3](1/2). The maximum strain located at the spot where the force were applied. It was measured to be 1.319*10-5.

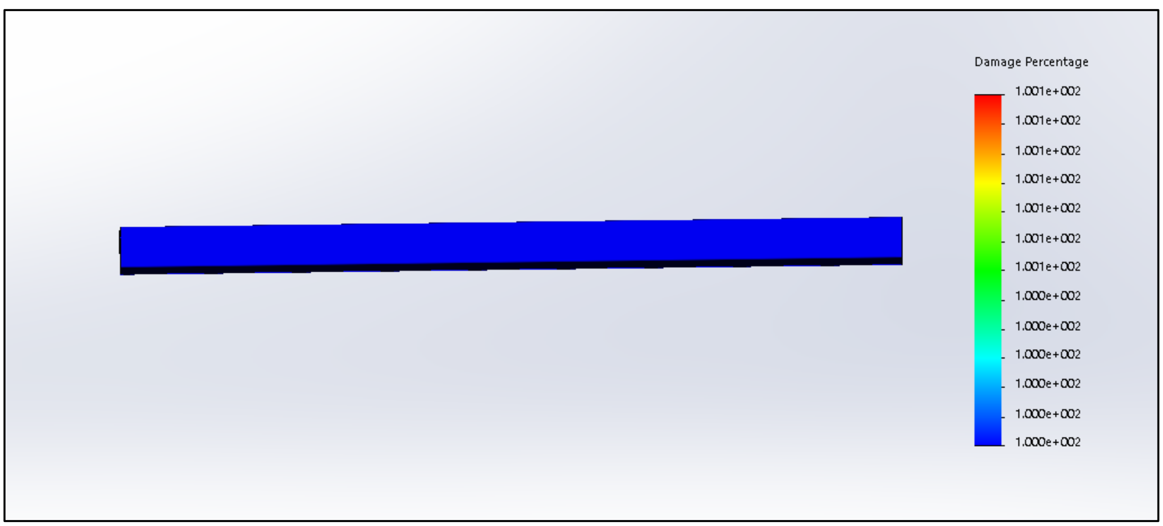


Figure 38. Damage Percentage

The damage percentage test was ran using the same loads as the static simulation. The weight of 42.8 lb was applied to two spot. Afterward, a million cycle was applied to the system.

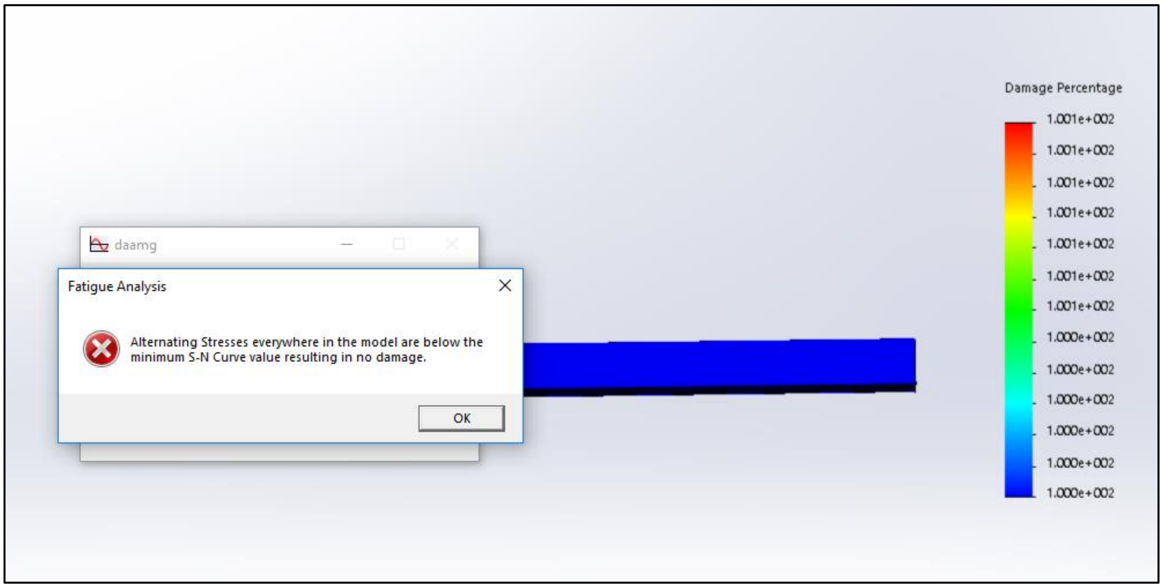


Figure 39. One Million Cycle Stress Test

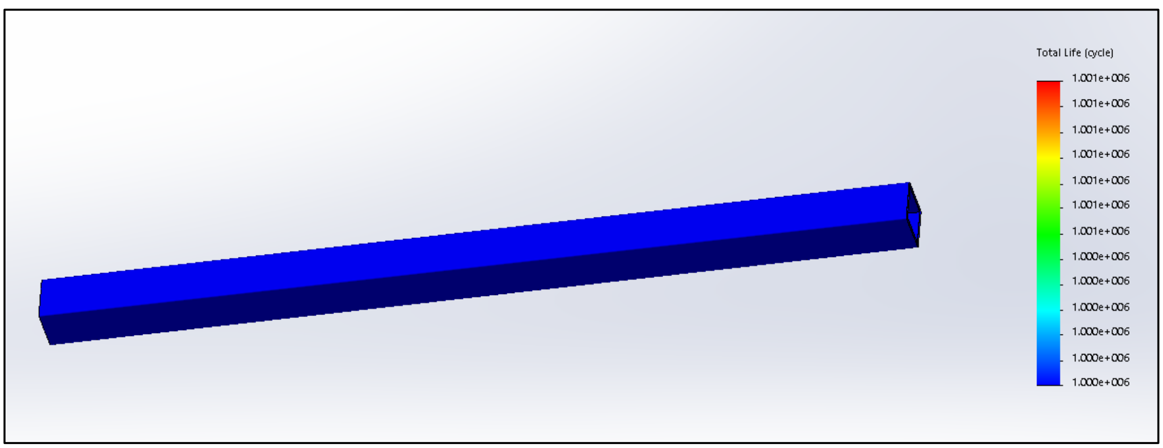


Figure 40. Total Life Cycle of the Beam Locally

Figure 43. shows that the total life cycle of the beam does not change locally. This shows the results convergence with the damage test. As the alternating stresses are below the minimum S-N curve.

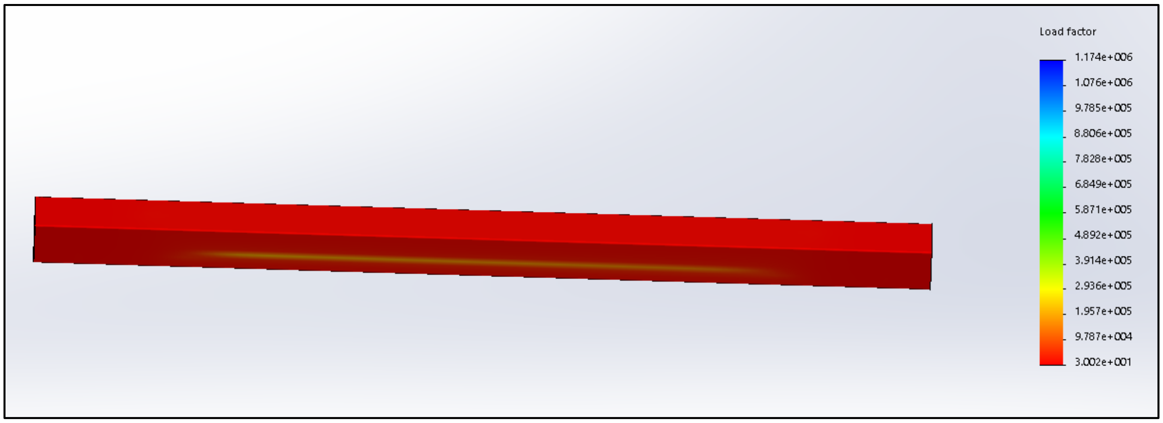


Figure 41. Load Factor

Figure 44. shows the result of load factor. The higher the load factor is safer and more reliable is the system. When the load factors are less than 1 it indicate failure. In this figure, the load factors distributed on the beam are all higher than 1. The plane perpendicular to the plane where force was applied have slightly lower load factor. However, it is still at an accessible rate as the data is still higher than 1.

6.3 Software Design

Due to time constraints, the software design on this project has been postponed until summer 2018. Information for this section will be updated in the near future. Software design for this project will control the switches for the DC to DC converter and the AC to DC inverter. This will allow us to control the output of the power module.

6.3.1 Software Design Update

During our time in Senior Design II we were able to complete the code for the DC/AC inverter and part of the code for the DC/DC converter. The DC/AC inverter code was originally edited from open source code that was found on the internet. We were able to successfully manipulate the code to output the SPWM signal we were trying to obtain.

For the DC/DC converter, we were able to obtain partial code for the maximum power mode from a graduate student that was working directly under our sponsor. We then implemented this onto our DC/DC converter and successfully generated one out of two modes, the maximum power mode.

7.0 Testing and Troubleshooting

In this section we will discuss the various types of ways we will test our design to confirm we have met all design requirements. This includes failure analysis, structural strength testing, heat testing, voltage surges and power production and storage capacity under varying conditions.

7.1 Failure Analysis

Testing our solar panel will involve testing its ability to perform without breaking. Factors that may cause it to break include wind turbulence over the panel, debris damage, voltage surges, and battery charging/discharging and overheating. Below we will describe the methods that will be used to test the products ability to perform under typical conditions.

7.1.1 Structural Strength Testing

We will test our product with winds up to 200 mph to simulate wind gusts that may occur during the worst hurricanes possible, which have achieved speeds of 165 mph [33]. Since the likelihood of these winds is low, we think 200 mph is a sufficient factor of safety. Our campus has wind tunnel testing materials which can be used, however, given the size of our panel, we will most likely only be able to do impact testing, which will still provide sufficient data to determine whether the structure is strong enough to withstand 200 mph winds. Under these conditions, objects such as mailboxes, tree limbs, and rocks may impact the panel, however, the cost of protection against those obstacles would require bullet proof glass and high strength steel that are much too expensive. For this reason, we will not test for those situations.

7.1.2 Heat Testing

As described in section 3, the operating temperature of our battery can reach up to 60ºC. Outside temperatures may also be as hot as 100ºF, however, in testing for heat protection, the lab will likely be at room temperature (70ºF) Given the maximum operating temperature of a typical lithium battery to be below 100ºC before causing permanent damage, our product will be tested to determine if the cooling system can maintain a temperature below 100ºC [34].

7.1.3 Voltage Surges

Voltage surges can be caused by a variety of sources mainly categorized into electrostatic discharge and electrical overstress. Electrostatic discharge occurs in nature and can be seen as common of an occurrence as in thunderstorms. Electrical overstress, is a continuous input of charge, often in the form of a wave. It is more likely to occur due to poor engineering or maintenance than natural causes. Each requires a different level of safety. Components can handle much higher levels of electrical discharge than electrical overstress and for this reason, we will test the components to handle electrical overstress. Components should be able to handle at least an additional .5V. In the case of a higher voltage, the fuse should break and stop the current from reaching the other components. Since a bad ground can cause issues with electrical distress, we will test for a good ground as well [35]. A multimeter will be used to test the resistance of the ground which should give us an idea of how good the ground is. The multimeter will be set to read 100 ohms or less. A reading of less than 25 ohms will show that the ground is good [36]. The multimeter will also be used to test if soldering connections are good.

7.2 Power Production and Storage Capacity Under Varying Conditions

A multimeter will also be used to test the voltage difference across the solar panel. Our solar panel produces 12V, so the reading should give 12V under perfect conditions. Photosynthesis is conducted in nature at wavelengths within 400 to 700. Although it is a common concern that under overcast skies, photovoltaics won't work, according to Bartlett [38], it is accepted that irradiation that can be used for photosynthesis is near (within 3.8%) optimal conditions even under overcast skies [38]. This means, we should be still drawing at least 11.544V even in cloudy conditions. In order to test this, we will place a sheet over the solar panel at a distance of 3 feet so that it casts a shade on the panel, and we will test the voltage that is produced at the panel. The sheet will be brought closer and tested at 2 feet, 1 foot, and directly on top of the panel, and the produced voltage will be measured. The voltage drawn from the battery will also be measured at these conditions, in order to see if the system is producing the required power under all conditions. A simulated load will be used in the form of an attached light bulb (100W). The light bulb will be used to test the panel's ability to supply power for up to 2 days without sunlight.

8.0 Administrative Content

In this section we have included the appendices and works cited for our project.

Appendices

Appendix A – Copyright Permissions

Smart PV System focus is on the energy deliver and management system more so than the actual photovoltaics itself. Because of this patents that were researched focused more on the structure and implementations of these systems. The closest and most relevant patent in the scope of the research is a patent from Young Min KANG and Young Gyu Yu; patent US20150025702A1. All information contained in the report is for educational purposes only. Under title 17 of the United States Code, the authors reserve the right to control the use of this work for a limited time. All works cited are listed below and were not used for any other purpose other than education, and it is our intent that they remain only for educational purposes.

Appendix B – Codes

The Solar ABCs is currently involved with the IEEE Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage (IEEE SCC21). The IEEE SCC21 oversees the development of standards in the areas of fuel cells, PV, dispersed generation, and energy storage and coordinates efforts in these fields among the various IEEE Societies and other affected organizations to ensure that all standards are consistent and properly reflect the views of all applicable disciplines. The IEEE SCC21 systems-level focus is on technology to grid interconnection, integration and impacts, and, Smart Grid interoperability including electric-sourced transportation and energy storage systems.

A list of IEEE standards and common practices along with regulations pertaining to photovoltaic.

- IEEE 1547 - Standard for Interconnecting Distributed Resources with Electric Power Systems

- IEEE 1547.1 - Standard for Conformance Tests Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems

- IEEE 1547.2 - Application Guide for IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems

- IEEE 1547.3 - Guide For Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems

- IEEE 1547.4 - Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems

- IEEE 1547.6 - Recommended Practice For Interconnecting Distributed Resources With Electric Power Systems Distribution Secondary Networks

- IEEE P1547.7 - Draft Guide to Conducting Distribution Impact Studies for Distributed Resource Interconnection

- IEEE P1547.8 - Recommended Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE Standard 1547

- IEEE 937 - IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic Systems

- IEEE 1013 - IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic Systems

- IEEE 1361 - IEEE Guide for Selection, Charging, Test and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic Systems

- IEEE 1526 - Recommended Practice for Testing the Performance of Stand Alone Photovoltaic Systems

- IEEE 1561 - Guide for Optimizing the Performance and Life of Lead-Acid Batteries in Remote Hybrid Power Systems

- IEEE 1562 - Guide for Array and Battery Sizing in Stand-Alone Photovoltaic Systems

- IEEE 1661 - Guide for Test and Evaluation of Lead-Acid Batteries Used in Photovoltaic (PV) Hybrid Power Systems

- IEEE 2030 - Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads

- IEEE P2030.1 - Draft Guide for Electric-Sourced Transportation Infrastructure

- IEEE P2030.2 -Draft Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure

- IEEE P2030.3 - Draft Standard for Test Procedures for Electric Energy Storage Equipment and Systems for Electric Power Systems Applications

Appendix C – Permission to Use Figures

[A] https://circuitglobe.com/difference-between-step-up-and-step-down-transformer.html

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For any queries, message or information, you can contact us by filling this form. We will revert back to you within 7 working days.

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Emmanuel ortiz

YOUR EMAIL (REQUIRED)

Ejortiz2009@gmail.com

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Thanks,
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To whom this may concern,
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Thanks!
Eric

Grid-Tied, Off-Grid and Hybrid Solar Systems - Energy ... ×

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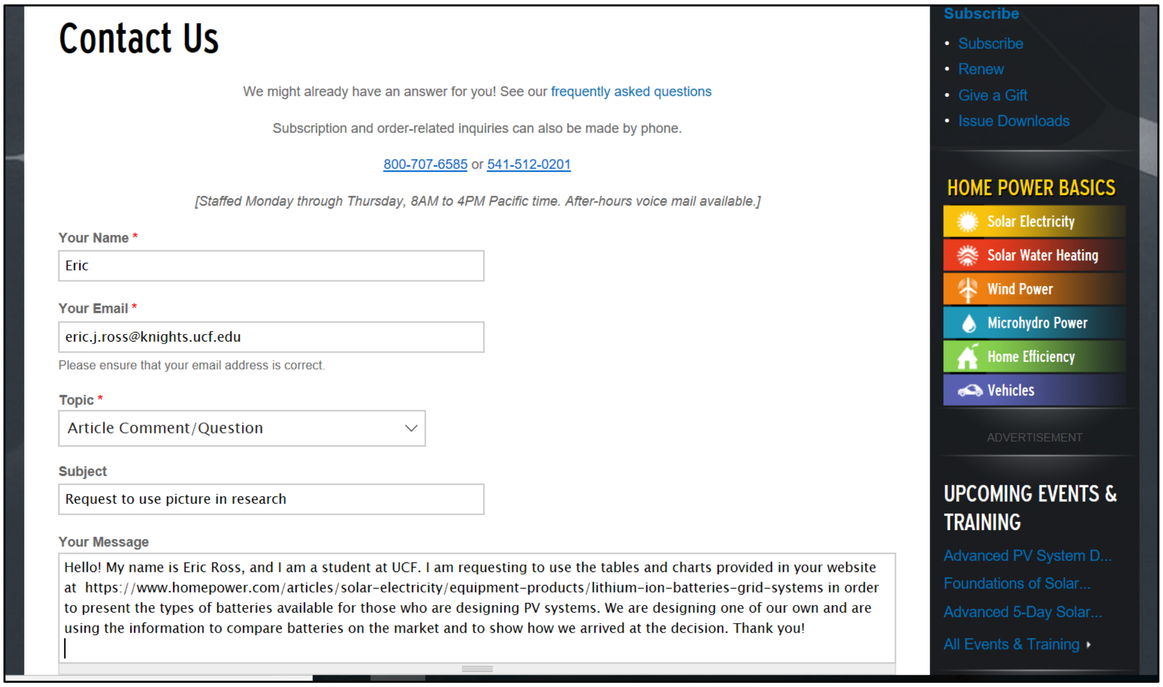
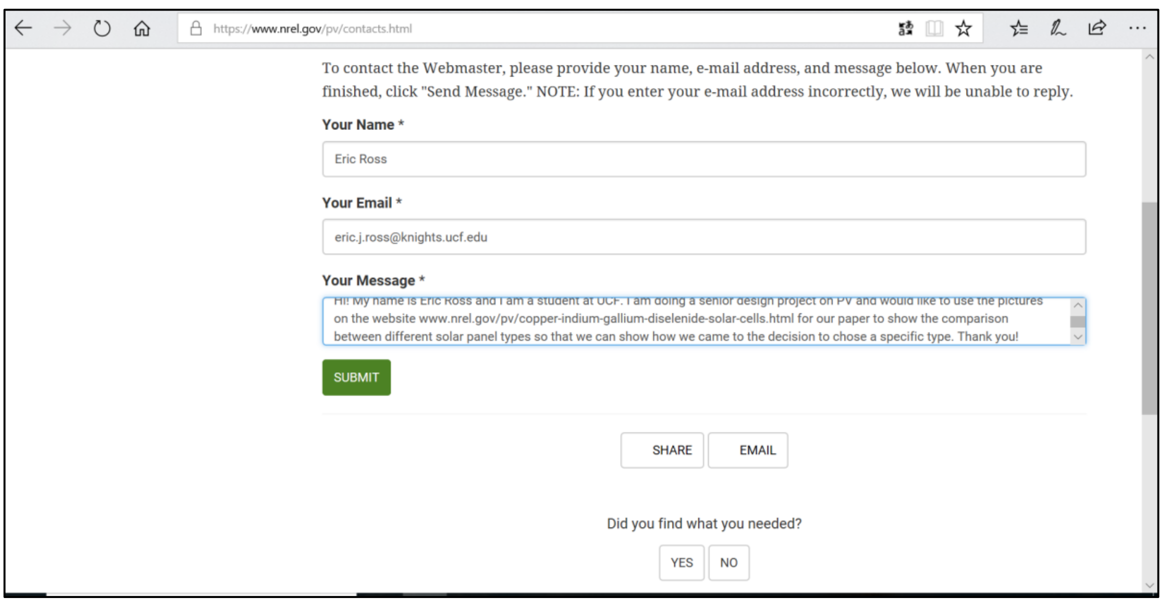


[E] www.nrel.gov/pv/copper-indium-gallium-diselenide-solar-cells.html



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To whom this may concern,

My name is Angelica Becker and I am requesting to use information and pictures from your data sheet on my electrical engineering senior design document.The pdf document is as follows: https://s3.amazonaws.com/ecodirect_docs/CANADIAN/CS6K/Canadian_Solar-Datasheet-SuperPower_CS6K-MS_en.pdf

Please let me know if you have further questions.

Thank you,
Angelica Becker

[G] http://www.microchip.com/design-centers/16-bit

university@microchip.com

Picture Permission

To whom this may concern,

My name is Emmanuel Ortiz, and I am requesting to use information and pictures from your data sheet and website on my electrical engineering senior design document.

Thank You,
Emmanuel Ortiz

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