The DC House Project:
Electrical System Design & Construction

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Abstract

This project entails the design and assembly of the photovoltaic system, switchboard panel enclosure, and battery enclosure for the DC House's main electrical system. The intended purpose of this project is to provide the electrical framework necessary for future students to easily modify and add to this rendition of the DC House. The principle design implements a variety of renewable energy sources, however this senior project only uses solar power in order to maintain a manageable scope. Each of these renewable energy sources are stepped down to a voltage of 24V and input to a Multi Input Single Output DC to DC converter (MISO) located within the switchboard panel enclosure. The MISO then connects to a set of batteries which power the loads of the DC House operating at 48V. The finished assembly of the photovoltaic array and panel enclosure will then be retrofitted to a small house located at the Student Experimental Farm (SEF). After the retrofit, the electrical system will be tested at the source and load sides to ensure that proper system functionality.

1. Introduction

The DC House project is a humanitarian, non-profit project that aims to service the basic electrical energy needs of those living in energy poverty. In many cases, those who live in energy poverty often live in areas with no access to electrical utility districts. Many of these areas are remote, and are thus deemed financially infeasible to construct transmission lines to. The International Energy Agency reports that about 1.3 billion people live without access to electricity, and another 2.6 billion live without clean cooking facilities.

As the name suggests, the DC House is a self-sustained living environment that runs solely on DC Power. Renewable energy sources such as solar panels output DC power instead of AC power. While most commercial buildings in both residential and non-residential environments integrate these renewable energy sources into AC power systems, converting DC to AC power results in an intermediary power loss. This power loss imposes a reduction in overall system efficiency which results in a greater cost for operation. Greater initial costs are also imposed when employing the use of renewable energy sources such as solar panels into AC power systems since purchasing a compatible power inverter is also required for these sources. By utilizing loads that can run on DC power, the power loss due to DC to AC conversion is bypassed and a greater amount of energy is available as a result.

The DC House aims to construct and optimize an effective electrical system that can provide for the basic necessities required to sustain a small living environment. Energy needs are modelled with loads such as a small DC refrigerator, LED lighting, and low-power cooking devices. The ultimate goal of the project is therefore to

eventually prove that DC power can be used as a reasonable means of powering a small living environment, and to demonstrate its ability to produce electricity in a remote environment where power utility grids are inaccessible. This constitutes drafting the final power system, and assembling the electrical system with consideration to the local environment, geography, functionality, practicality, and the possible integration of future student projects to the same site.

2. Background

The DC House project is a recognized Cal Poly project that has been featured in many technological publications, and has fostered partnerships with a multitude of universities, engineering colleges, and company sponsors [1]. Starting in 2010, the project has progressed through 4 principle phases that have contributed to the current electrical system design of the DC House. Each phase is comprised of smaller individual senior projects or masters theses which implement the “Learn by Doing” philosophy that Cal Poly encourages its students to pursue.

2.1 Phase 1

Phase 1 spanned the 2010-2011 academic school year, and involved the initial designs of many of the electrical systems, generators, and the DC-DC converter. A major milestone completed during this phase of the project was the Multi-Input Single-Output DC-DC Converter (MISO) [1], which is directly applicable and essential to the final design of the DC house. This device allows the use of multiple renewable energy sources varying from 12V to 24V to be input into the electrical system, and output on a single busway which can then charge a battery for energy storage. The MISO is an important part of the DC House which forms the backbone of the electrical system design. A block diagram of the electrical system is shown below in Figure 2-1.

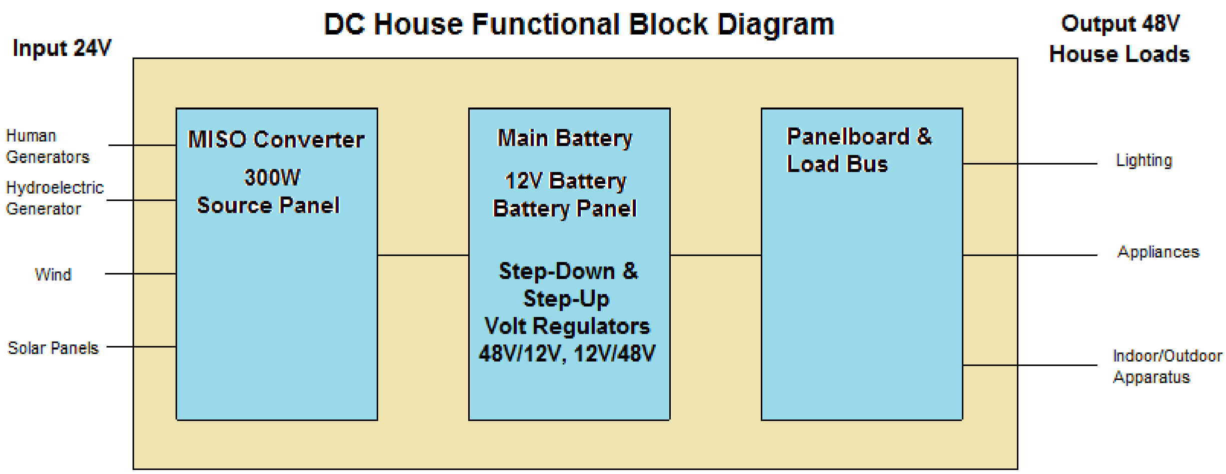

Figure 2-1: DC House Operational Block Diagram

2.2 Phase 2

Phase 2 (2011-2012) completed a temporary DC House model which featured the inclusion of a DC light bulb, another essential component when considering the final design. The DC LED light bulb allowed for highly efficient lighting without an LED driver, allowing for extremely high efficiency lighting (up to 5 times greater than fluorescent bulbs). These bulbs will serve as the primary lighting source in the final construction of the DC House. This phase also improved upon the MISO Converter design made in Phase 1.

2.3 Phase 3

Phase 3 (2012-2013) explored other power generation sources and involved designing the initial human powered generators including a Swing generator and Merry-Go Round

Generator, and improving on the MISO converter design. Additionally, this phase allowed for the introduction of several other improvements to the DC House which merited a multitude of other individual senior projects including the AFCI (Arc Fault Circuit Interrupter), and the portable nano-hydropower generator.

2.4 Phase 4

Phase 4 is the intended final phase of the DC House project with the goal of ultimately demonstrating a fully functional DC House. The final DC House will employ a multitude of energy sources, 2 operational MISO DC-DC converters, an optimized battery management system to power the loads, and a 12.8'x16.75' house with DC receptacles and lighting. The major power generation sources intended for use include a DC wind power generator, solar panel arrays, simulated hydro power and human-powered swing or merry-go-round generators.

2.5 Observations on Renewable Energy

According to the U.S. Energy Information Administration, the United States produced over 4000 billion kilowatt hours of electricity in 2013. 67% of this total was produced from fossil fuels including coal, petroleum, and natural gas. Figure 2-2 shows the heavy reliance Americans place on fossil fuels for their primary energy source.

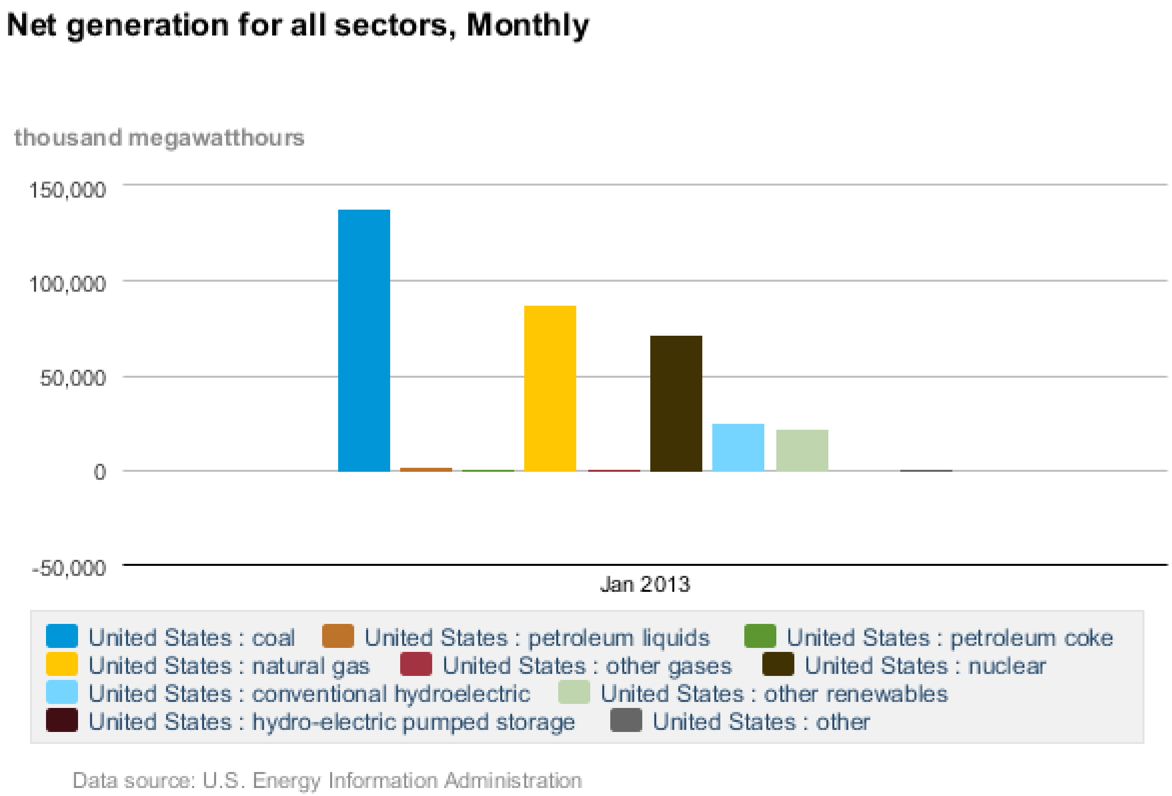

Figure 2-2: EIA Comparison of all energy sources in the U.S. [2]

Renewable energy sources only make up a rough 15% of the total power generation in the United States. While these Renewable energy sources offer a more environmentally friendly alternative to fossil fuels, renewable energy in heavily populated regions have been ousted as an effective power source for a multitude of reasons:

1. Reliability – Renewable energy depends heavily on fluctuating weather patterns to produce energy. As a consequence, if the demand for energy increases greatly, a renewable energy source may not be able to meet that demand if the natural environment does not produce the ideal climate conditions.

2. Large Scale Production – In comparison to fossil fuel and nuclear energy sources, it is very difficult for renewable energy plants to generate enough electricity to meet the high demand of consumers in populated regions.
3. Capital Costs – Renewable Energy plants are extremely expensive, requiring very large up-front investments for the development and construction of the plant. Additionally, in order to compete with the energy production of fossil fuel plants, renewable energy plants require a large landmass to set up wind farms or solar panel fields.

From these points, we can observe that renewable energy sources are therefore more suited for smaller scale energy demands that must interact well with a natural ecosystem, rather than large scale power generation in commercial areas which require continuous up-time.

2.6 Defining a New Market

According to the International Energy Agency, "…over 1.3 billion people are without access to electricity and 2.6 billion people are without clean cooking facilities. More than 95% of these people are either in sub-Saharan African or developing Asia and 84% are in rural areas." [4] Access to electricity has proven crucial to the well-being of the human condition as well as a "country's economic development", yet almost a one-fifth of the world's population is living in energy poverty.

Humanitarian organizations such as the Global Environment Facility (GEF) seek "to assist in the protection of the global environment and to promote environmental

sustainable development" (GEF Website) providing "$13.5 billion in grants and leveraged $65 billion in co-financing for 3,900 projects in more than 165 developing countries." (GEF Website). GEF also possesses many agencies within its infrastructure including the Asian Development Bank, the African Development Bank, and Conservation International (CI), each of which are major advocates for projects dealing in renewable energy sources and the improvement of human condition.

Organizations such as The Climate Investment Fund (CIF) also provide funding for environmentally friendly "green" projects on an international scale. The CIF is comprised of two major trust funds: the Clean Technology Fund (CTF), and the Strategic Climate Fund. Both funds are geared towards up-scaling renewable energy solutions in low-income countries and are heavy advocates for providing energy access to individual households based on sustainable energy technology.

The functionality of the DC House project relates very well to the goals these humanitarian organizations pursue, suggesting that with some refinement and optimization, the DC House could be a potential contender for one of the grant programs funded by such organizations. Additionally, at the domestic level, many companies within California endorse renewable energy including:

- NextEra Energy Resources
- Sacramento Municipal Utility District (SMUD)
- Center for Resource Solutions (CRS)
- EPA Green Power Partnership
- Sterling Planer
- PG&E

- Sunpower
- All Earth Renewables

And on an international scale:

- Iberdrola (Spain)
- Calpine Corp.
- China Yangtze Power
- Siemens
- Suzlon Energy
- First Solar
- LDK Solar
- Bronzeoak Philippines Inc.

While renewable energy is a large market exhibiting a rapid growth and change in energy consumption, the DC House project is fairly unique in its application and method. No other projects employ the same design as the DC House, however, several comparable projects implementing renewable energy with sustainability in mind include:

- Tiny Green Cabins
- The ZEM (Zero Emission) – Renewable Energy House
- SMUD’s tiny house competition

2.7 Strengths, Risks, and the Window of Opportunity

As listed above, many large for-profit companies and government organizations endorse renewable energy. As a small-scale project seeking a humanitarian solution for those in poverty, one key fact that the DC House can leverage is that it is a non-profit project funded solely by donations. Students who work on the DC House project volunteer to pursue the opportunity, seeking to apply their knowledge while also helping those in need rather than simply obtaining a profit. With these motivations in mind, the major obstacle that the DC House project faces is funding. Once this barrier has been overcome, the DC House team will be free refine renewable energy solutions without the issues concerning company investment and corporate hierarchy. Table 1 summarizes the advantages and disadvantages the DC House project possesses in the renewable energy market:

Table 2-1: Advantages and Disadvantages of the DC House

Advantages	Disadvantages
Humanitarian Project with non-profit goals in mind.	Dependent on donations and funding from outside sources.
Free of constraints imposed by deliverable-based corporate structure (not required to order parts from one manufacturer for example).	Not as reliable of an energy source as utility grid power sources.
DC House humanitarian objectives parallel the mission goals of several large humanitarian organizations including the GEF and CIF	Dependent on environmental weather conditions and human power generation.
Uses a multitude of renewable energy resources leaving little to no carbon footprint in the natural environment.	Less cost effective than fossil fuels or nuclear energy when used on a large scale.
More economical in remote locations which are distant from a utility grid.	Large initial cost to construct.

The renewable energy market has grown significantly in the past decade, with the solar energy market growing over 800% from 2000 to 2007 [1]. This growing interest in renewable energy offers a wide window of opportunity for the DC House project. However, as the industry grows rapidly, a greater multitude of renewable energy solutions and greater competition will enter the picture, meaning that it will be much more difficult to enter the market. It would therefore be most beneficial if the DC House project is finished and released sooner rather than later.

3. Requirements and Specifications

3.1 Objective

The primary objective of this project is to construct a basic electrical system that future students on the DC House project can easily modify as phase 4 progresses. This rendition of the DC House will be built at the Student Experimental Farm in order to validate its functionality and utility in life-scale model. Following the final designs proposed earlier in Phase 4, the major components used in the DC House model must be either reselected or transferred over to the larger site of the final DC House. Some major components that will require this transitioning include the MISO DC-DC converters, 12V batteries, a battery enclosure, a solar charge controller, panel enclosure with a back panel mount, feeder boxes, circuit breakers, and indoor appliances. Additionally, any outdoor appliances must also be considered when assembling the final product, adding supplementary DC power sources as needed.

3.2 Limitations

Before the design parameters and materials can be selected, the working limitations of the project must be acknowledged in order to fully ascertain what the product of this initial electrical system can and should be. The primary limitations of this design are as follows:

3.2.1 Power Capability of the MISO

While the MISO DC-DC Converter makes the DC House electrical system a possibility, it is still a work in progress. The end product of the Phase 4 design is intended to implement 2 MISO converters capable of handling up to 600W of input power. However, a MISO capable of handling this input power requirement has not been developed yet and as such a more prototypical version of the device must be used in its place. For the purposes of this project, a 150W rated MISO converter will be used.

3.2.2 Solar Panel Selection

In order to more efficiently use the resources available on hand, Dr. Taufik suggested the use of a set of donated solar panels which are currently unused: the E20/435 Sunpower solar panels. While these solar panels provide a great power generation capacity up to 435W and would normally cost over $1000 apiece, their power generation capability is far too great for a single 150W MISO to handle. Additionally, the solar panel rated output voltage is rated at 72.9V which is also too large for the MISO input which can handle up to 24V. Design considerations must reflect a practical solution to bypass these issues for the initial electrical system.

3.2.3 Non-Permanent Site Selection

The phase 4 DC House site is at the Student Experimental Farm (SEF). The SEF is devoted to care and sustenance of the local land and does not promote the use of permanent installations such as concrete mounts or grounding rods. Additionally, a good portion of the land near the DC House is used on an annual basis for grazing and

feeding farm animals. This necessitates that the design for power generation sources not only to be functional, but also portable so it does not impact the other purposes that the SEF fulfills for other projects in the area.

3.2.4 Lack of Battery Management System

A microcontroller-operated battery management system to track and control the charge on the main system battery is needed to safely power the loads from the MISO. However, this device has yet to be created or even attempted as another senior project. For the purposes of this project, its inclusion will be omitted from the assembly of the initial electrical system.

3.3 Requirements

With the limitations of the project now established, the design requirements can be determined based on the site location and the intended purpose. Listed below are these project requirements, which are further expanded upon and justified in the Design section (Chapter 4).

1. Select a panel enclosure for circuit breakers, power distribution blocks, field terminal blocks, and a mountable back panel plane.
2. Find an appropriate mounting location and construct a portable mount for the E20/435 Sunpower solar panel.
3. Select a charge controller to step down the E20/435 solar panel voltage from 72.9V to 24V.

4. Create an appropriate battery enclosure for the 12 volt batteries and charge controller mount.
5. Produce a maximum of 150W for the testing phase, but design the electrical system to handle up to 600W input power.
6. Provide for the electrical power to the DC House safely using circuit breakers, appropriately sized conductors, and grounding terminals.
7. Use weather-proof equipment to enhance sustainability.
8. Create a cost-effective design below $15,000 in price.

4. Design

In order to achieve the requirements detailed in Chapter 3, the design of the electrical system must consider many factors. This section covers the panel enclosure layout, the solar panel mount design, the solar charge controller selection, and the electrical system connections. Shown below in Figure 4-1 is the ideal design of the DC House.

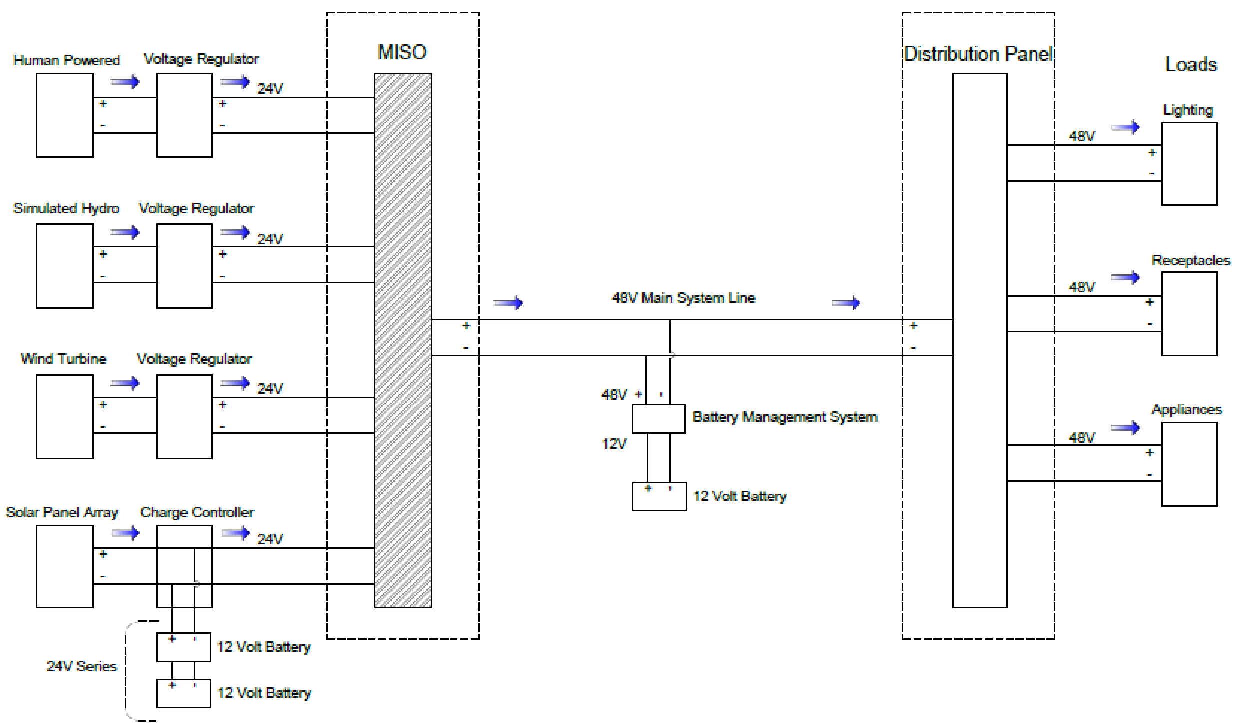

Figure 4-1: DC House Electrical System Design

While the project strives to achieve the ideal electrical system design, the preliminary design must bypass the battery management system and exclude the inclusion of the wind turbine, simulated hydro, and human powered generator sources. The resulting electrical system is shown in Figure 4-2.

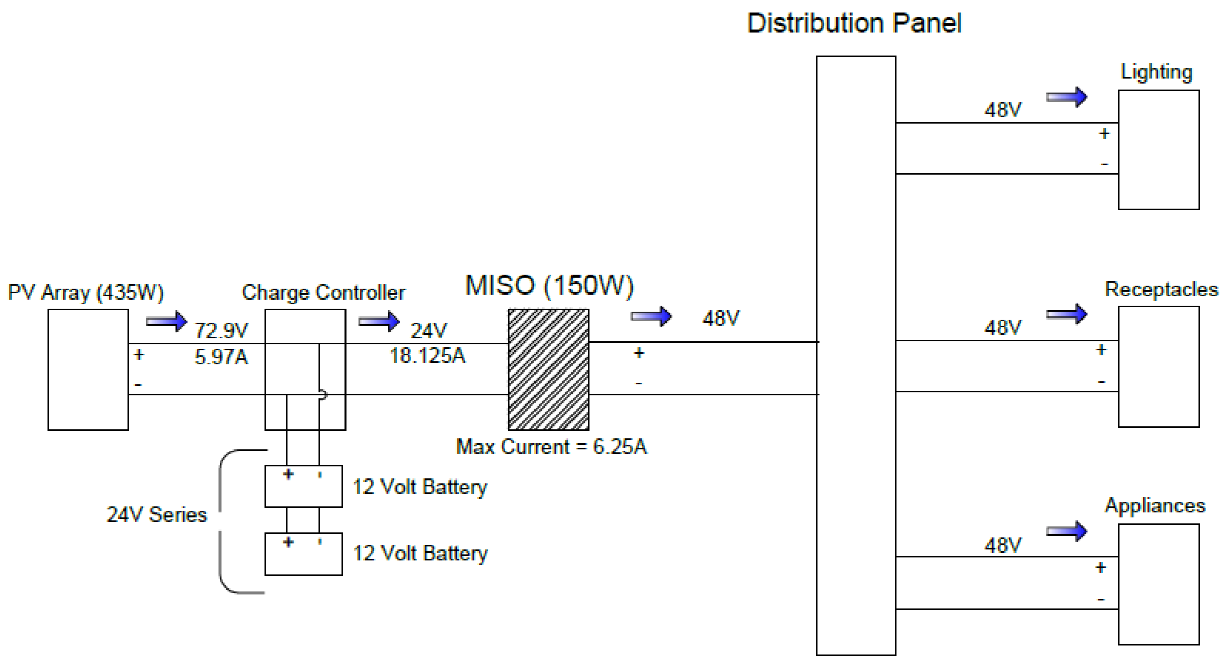

Figure 4-2: Preliminary Electrical System Design

One major design consideration when observing the diagram above can be determined based on the potential output current of the Charge Controller. Assuming the solar panel is capable of producing 435W at a rated voltage of 72.9V, the output current of a charge controller stepping down the voltage to 24V can be determined.

Pin = Pout

Pin = (Vin)*(Iin)

Pout = (Vout)*(Iout)

435W = (72.9V)*(5.97A) = (24V)*(Iout)

Iout = <u>18.125A</u>

The output current of the charge controller can potentially be 18.125A. However, the MISO is only rated for 150W, and could therefore only safely receive 6.25A

maximum at 24V input. To safely test the MISO, the circuit breakers placed prior to the MISO at the output of the battery must be sized less than 6.25A to ensure that the breaker will switch off in the event that the current supplied to the MISO may exceed its rated capacity.

4.1 Panel Enclosure

This section details the panel enclosure selection and layout design. As with most houses that use utility district power, power is distributed from a main point of entry which feeds into a service panel, or panel box. This box contains all the necessary circuit breakers and fuses in order to safely distribute power to the various electrical branches of the house. Similarly, the DC House has input power fed into the MISO from several different sources whose power must be delivered to various electrical load branches which power the appliances and lighting in the house. Some design considerations when selecting a panel enclosure include the appropriate sizing for the inclusion of circuit breakers, field terminal blocks, and power distribution blocks.

The enclosure chosen was the 14 gage steel N412-WC ultimate series from Wiegmann. This enclosure features a viewing window, a locking door, and mounting holes for attaching a steel back panel to. It is designed to protect electrical and electronic equipment within from be harsh or dirty environmental conditions, and thus can be used for indoor or outdoor applications. The product specifications are shown in Table 4-1.

Table 4-1: N412-WC Ultimate Series Specifications

PRODUCT SPECIFICATIONS

Application	Designed To House And Protect Electrical And Electronic Components From Harsh, Dirty Environments. For Use In Installations Where Dirt, Dust, Oil, Water, Or Other Contaminants are Present
Catalog Description	Hubbell Wiegmann N12C ULTIMATE Series Enclosures are designed to house and protect electrical and electronic components from harsh,dirty environments. For use in installations where dirt, dust, oil, water, or other contaminants are present. Streamlined styling, flush latching, and attrative durable finish complement any high tech electronic equipment.
Catalog Number	N412242408WC
Color	ANSI-61 gray smooth
Construction	Continuously Welded Seams
Country of Origin	US
Cubic Capacity	4608 Cubic-Inch
Finish	ANSI 61 Gray Polyester Powder-Coated Inside and Outside
GTIN	00786725859511
In Stock	Yes
Includes	Window
Invoice Description English	N412,SD,WINDOW,24X24X8,CONCEPT
Item	Single Door Enclosure
Material	14 Gauge Steel Body and Door
Mfr/Vendor	Wiegmann
Mounting	Wall
NEMA Rating	NEMA/EEMAC 4, 12, 13

Figure 4-3: N412-WC Ultimate Series Wiegmann Enclosure

This enclosure was appropriate for this application because the house being used does not have the ideal indoor environment with many particles of dirt and dust still present. It also possesses a viewing window which can be used to observe the contents of the enclosure without needing to unlock open the door every time. This allows for easy inspection of the circuit breaker status and the condition of the electronics within. Figure 4-4 shows the general layout of the circuit breakers, power distribution blocks, and field terminal blocks on the 22’x22’ back panel mount.

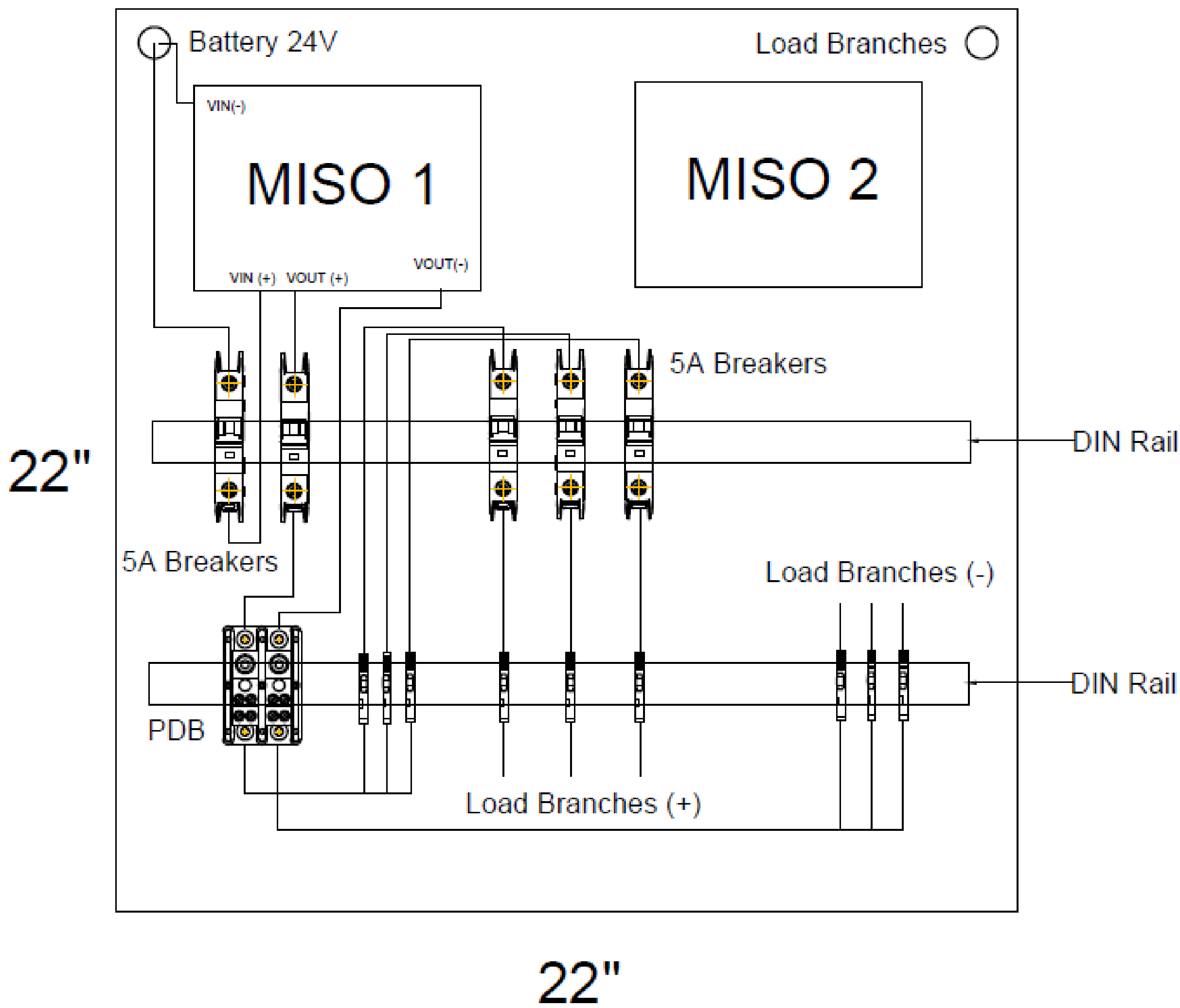

Figure 4-4: Panel Enclosure Component Layout

The enclosure is split into 3 main sections. The topmost section is devoted to the MISO converter mounts. While the design shown in Figure 4-3 shows that there are 2 MISOs, this project will only use one for the testing phase. The second MISO location is marked so that future versions of the device can be mounted on as well, increasing the potential input power that the electrical system can handle. The second section right below the MISOs consists of the circuit breakers which are mounted on din rail. All of

the circuit breakers shown are sized at 5A maximum current to prevent overloading the MISO and the loads. The third section at the bottom of the back panel mount is devoted to wire management including the field terminal blocks which can be color coded to track negative and positive lines, and the power distribution block which splits an input branch into several smaller output branches.

Conductor sizing is also a determining factor in this layout design. In order to easily manage the wiring, stranded core conductors were used. The selection process for the wiring involved sizing the gauge of the wire to match the maximum ampacity of the application it will be used for. For this application, the anticipated maximum input into the enclosure will be no more than 5A for the testing phase. However, future projects on the DC House may use the solar panel for its maximum power generation capacity. As discussed in the beginning of this chapter, the maximum current output of the charge controller and solar batteries can reach up to 18.125A. Using a 15A breaker to limit the input power going to the MISO converters, the wire gage of the power transmission line connecting the solar batteries to the MISO must be rated for 15A under maximum conditions. Table 4-2 shows a listing of the American Wire Gauge (AWG) sizing and their respective ampacities for power transmission.

Table 4-2: AWG sizing and ampacity chart

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission
OOOO	0.46	11.684	0.049	0.16072	380	302
OOO	0.4096	10.40384	0.0618	0.202704	328	239
OO	0.3648	9.26592	0.0779	0.255512	283	190
0	0.3249	8.25246	0.0983	0.322424	245	150
1	0.2893	7.34822	0.1239	0.406392	211	119
2	0.2576	6.54304	0.1563	0.512664	181	94
3	0.2294	5.82676	0.197	0.64616	158	75
4	0.2043	5.18922	0.2485	0.81508	135	60
5	0.1819	4.62026	0.3133	1.027624	118	47
6	0.162	4.1148	0.3951	1.295928	101	37
7	0.1443	3.66522	0.4982	1.634096	89	30
8	0.1285	3.2639	0.6282	2.060496	73	24
9	0.1144	2.90576	0.7921	2.598088	64	19
10	0.1019	2.58826	0.9989	3.276392	55	15
11	0.0907	2.30378	1.26	4.1328	47	12
12	0.0808	2.05232	1.588	5.20864	41	9.3
13	0.072	1.8288	2.003	6.56984	35	7.4
14	0.0641	1.62814	2.525	8.282	32	5.9
15	0.0571	1.45034	3.184	10.44352	28	4.7
16	0.0508	1.29032	4.016	13.17248	22	3.7

Based on this chart, AWG #10 wiring can be used as the input line to the MISO. The current coming out of the MISO at Vout(+) is halved due to the voltage increasing from 24V to 48V. While an AWG #13 has roughly half the current carrying capacity that AWG #10 wire has (7.4A and 15A respectively), which would work for the testing phase of this application, AWG #12 was chosen instead. #12 wiring, which is rated at 9.3A, was selected since the Vout(+) terminal is the only output busway of the MISO. In future projects, this terminal will account for additional sources increasing the output current at

this terminal. As the output of the MISO is distributed across 3 separate load branches which power the lighting, receptacles, and appliances for the DC House, AWG #14 wire is selected to minimize conductor losses due to the greater length of the wiring required to retrofit the DC House site.

4.2 Solar Panel Mount Design

The solar panel used is the Sunpower E20/435 series. Its electrical specifications are shown below in Table 4-3. This solar panel is capable of producing a large 435W of power under ideal conditions.

Table 4-3: Electrical Specifications for the E20/435 Solar Panel

MODEL: SPR-435NE-WHT-D

ELECTRICAL DATA Measured at Standard Test Conditions (STC): irradiance of 1000 W/m², AM 1.5, and cell temperature 25° C		
Peak Power (+/– 5%)	P_{max}	435 W
Cell Efficiency	η	22.5 %
Panel Efficiency	η	20.1 %
Rated Voltage	V_{mpp}	72.9 V
Rated Current	I_{mpp}	5.97 A
Open-Circuit Voltage	V_{oc}	85.6 V
Short-Circuit Current	I_{sc}	6.43 A
Maximum System Voltage	UL	600 V
Temperature Coefficients	Power (P)	– 0.38%/K
	Voltage (V_{oc})	– 235.5 mV/K
	Current (I_{sc})	3.5 mA/K
NOCT		45° C +/– 2° C
Series Fuse Rating		20 A
Grounding	Positive grounding not required	

Figure 4-5: E20/435 Solar Panel

The install site location is a major factor when considering the annual solar access of the solar panel. As stated earlier in Chapter 3, the installation of the solar panel cannot be on permanent fixture such as concrete mounts, and must be movable if other projects on the SEF require the space used. To address this, the donated trailer shown below in Figure 4-6 was used as the mounting base plane for the solar panel frame to be assembled on.

Figure 4-6: Donated Trailer for Solar Panel Frame

This trailer can be pulled by truck and possesses a weatherproof container measured at 28”x17”x17.5” (Length x Width x Depth) in size. This container which is welded to the trailer can double as a battery enclosure and charge controller container, and it appropriate for the outdoor conditions that these electronics and electrical equipment will be placed in.

Now that a solution is in place for moving the solar panel, an appropriate setup location must be determined. The ideal mounting location will provide the greatest amount of solar access throughout the year, a flat and stable ground to mitigate inefficiencies due to any natural slope tilt, reasonable distance from the DC House location, while also minimizing the presence of hard shadows in the surrounding environment. To start, the surrounding area around the DC House was inspected for possible sites that matched this criteria. These sites are referred to as Skyline 1, Skyline 2, Skyline 3, and Skyline 4 in the ensuing discussion.

Skyline 1 is located in the nearby open fire pit courtyard roughly 50ft south-west of the DC House. This site is very flat with very few surrounding trees and buildings which may impose hard shadows throughout the day. However, this site is quite far from the house and is likely to induce a large voltage loss due to the length required for a power transmission cable feeding to the enclosure located in the DC House.

Skyline 2 is located 10ft directly south of the DC House. While the location is very close and would mitigate the voltage drop due to the transmission line length, the presence of trees and vegetation in this location may create more hard shadows which will reduce the power generation capacity of the solar panel.

Skyline 3 is directly southeast of the DC House, about 40ft away. This site is relatively flat, however it is located nearby a tall tree southwest of intended mounting location which may induce large shadows in the evening.

Skyline 4 is located 30ft directly east of the DC House. This location has very few surrounding trees and vegetation, minimizing the amount of hard shadows on the surface of the solar panel throughout the day. The land however is not perfectly flat, and has a slight incline when facing directly south towards the sun.

In order to measure the effectiveness of each of these sites to efficiently produce the power necessary to run the DC House, the solar access throughout the year was measured using a shade measurement tool. The Solmetric Suneye 210 is one such tool, and possesses many features as shown in Figure 4-7.

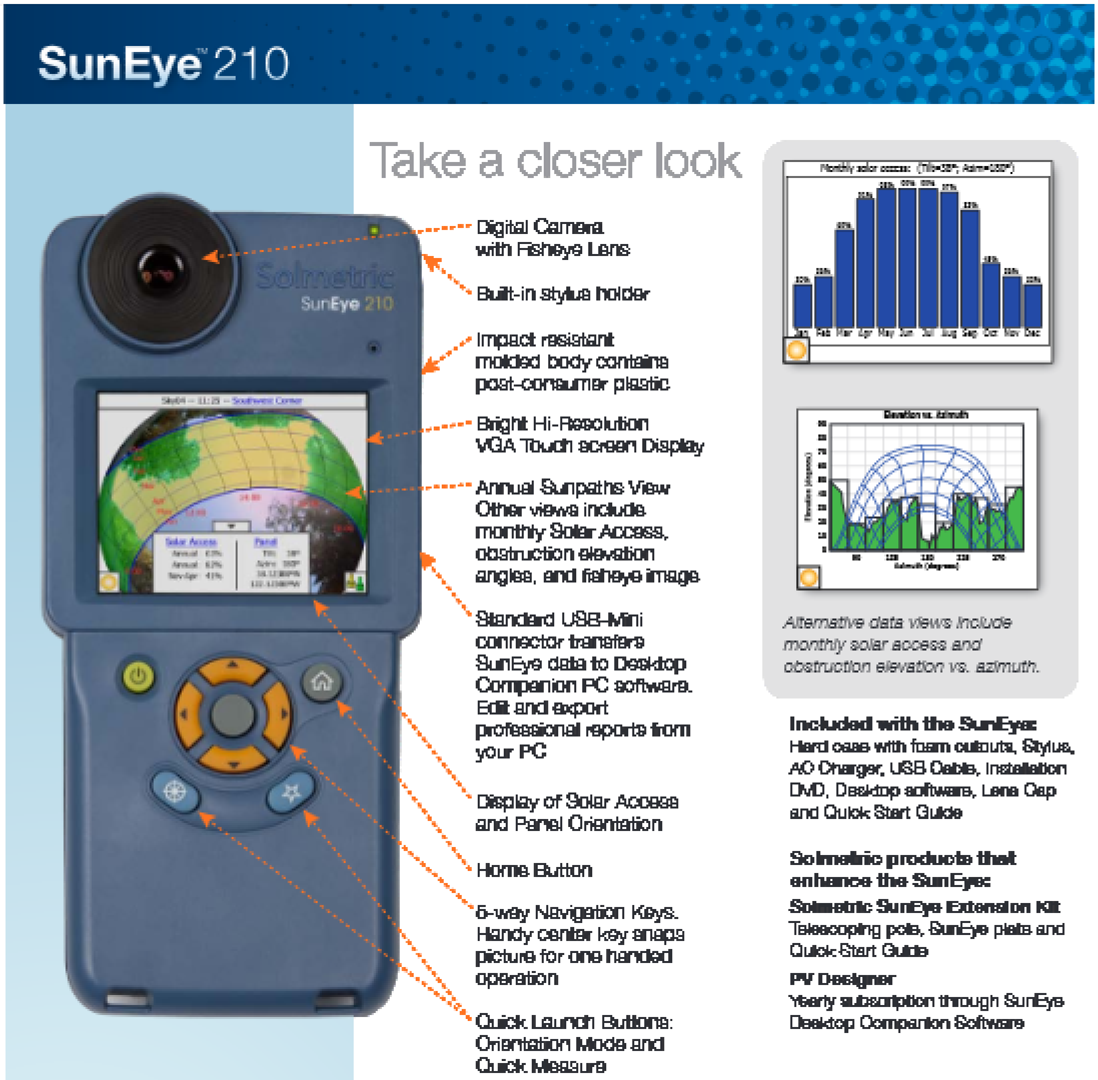

Figure 4-7: Solmetric Suneye 210

The Solmetric Suneye 210 is a professional measurement tool used to estimate the expected solar access throughout the year. To achieve this, the solar azimuth and tilt angle of the solar panel must first be manually calculated and input to the Suneye. After this, the Suneye takes a picture of the skyline to account for hard shadows that may be caused by buildings or trees in the surrounding environment. The solar azimuth angle can be calculated using the equation shown below:

Solar Azimuth Angle:

$$cos(\theta) = \ (\sin(\delta) - \sin(\alpha) * \sin\,(\varphi))\ /\ (\cos\,(\alpha) * \cos\,(\varphi))$$

$\theta = Solar\ Azimuth\ Angle$

$\delta = Solar\ Declination\ Angle$

$\alpha = Solar\ Elevation\ Angle$

$\varphi = Local\ Latitude = 35.274°$

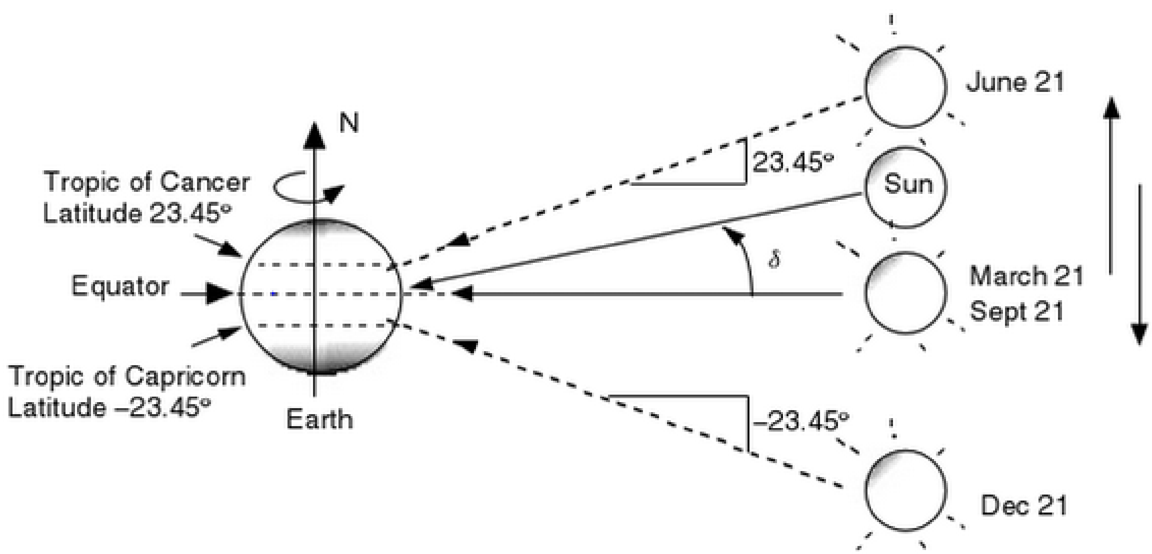

Figure 4-8: Solar Declination Angle

In order to determine an appropriate azimuth angle for our purposes, some assumptions must be made beforehand. Figure 4-8 shows how the solar declination angle can change throughout the year. The solar declination angle can be any range of values between 23.45° to -23.45° due to the tilt of the Earth's axis. This declination angle will increase from -23.45° during the winter solstice to 23.45° on the summer solstice. When plotted, the angle rises and falls in an oscillatory motion similar to a

wave function. The average angle would therefore be 0° throughout the year. The Solar Elevation angle must first be determined prior to calculating the solar azimuth angle. The calculation shown below can be used to determine the solar elevation angle α. The solar declination is assumed to be 0 since the solar panel will be on a fixed mount which cannot track the solar declination throughout the year. The hour angle is also set to 12 noon (h = 15°*12 = 180°) in order to simplify the calculation.

Solar Elevation Angle :

$h = Hour\ Angle\ (15° * hour\ number)$

$\sin(\alpha) = \cos(h) * \cos(\delta) * \cos(\varphi) + \sin(\delta) * \sin(\varphi)$

$\sin(\alpha) = \cos(180°) * \cos(0°) * \cos(35.274°) + \sin(0°) * \sin(35.274°)$

$$\underline{\alpha = -54.726°}$$

Azimuth Angle:

$cos(\theta) = (\sin(\delta) - \sin(\alpha) * \sin(\varphi)) / (\cos(\alpha) * \cos(\varphi))$

$cos(\theta) = (\sin(0°) - \sin(-54.726°) * \sin(35.274°)) / (\cos(-54.726°) * \cos(35.274°))$

$$\underline{\theta = 59.976°}$$

Following this, the next step is the calculation of the ideal tilt angle for the solar panel. This calculation is rather simple in comparison since the solar declination was assumed to be 0. β represents the altitude angle of the sun.

$Tilt = 90° - \beta$

$\beta = 90° - \varphi - \delta$

$\beta = 90° - 35.274° - 0 = 54.276°$

$Tilt = 90° - 54.276° = 35.274°$

With the solar azimuth angle and the tilt angle of the solar panel determined, the possible mounting sites can now be evaluated for their annual solar access. The results of this comparison are shown in Table 4-4.

Table 4-4: Comparison of Skyline solar access

Solar Access	Skyline 1	Skyline 2	Skyline 3	Skyline 4
Annual:	89%	76%	74%	93%
May - Oct	96%	83%	73%	94%
Nov - Apr	80%	67%	75%	92%

From this data, Skyline 4 shows the most favorable solar access throughout the year, with the highest solar access annually. The site for installation will therefore be 30ft east of the DC House. The frame for the solar panel must be assembled on top of the donated trailer with the solar panel facing directly south at a tilt of 35° above the base plane.

4.3 Solar Charge Controller Selection

The solar charge controller is a current/voltage regulator that prevents the connected batteries from overcharging. Two 12V batteries will be connected in series to create a voltage of 24V nominal. However, the voltage output of the E20/435 panels is rated at 72.9V, much higher than the potential of the batteries. This input voltage is also

much too high for the charge controllers used in previous renditions of the DC House. This necessitates the selection of a new solar charge controller which can take high input voltage and output 24V while tracking the charge of the batteries.

The Xantrex C40 charge controller was selected for this application. With multiple voltage output settings (12V, 24V, 48V), this controller does not require another voltage regulator. At the input terminal, the controller can take loads up to 125V, safely above the 85V open circuit ratings of the Sunpower solar panel. Table 4-5 details the electrical specifications of the Xantrex C40.

Table 4-5: Xantrex C40 Charge Controller Specifications

Electrical Specifications	C40
Voltage Configurations	12, 24, and 48 VDC
Maximum PV Open Circuit Array Voltage	125 VDC
Charging / Load Current (@ 25 °C)	40 amps DC
Maximum Peak Current	85 amps
Maximum Voltage Drop Through Controller	0.30 volts
Typical Operating Consumption	15 ma
Typical Idle Consumption	3 ma
Recommended Breaker Size	50 amps
Recommended Wire Size	#8 AWG
Lead Acid Battery Settings	Adjustable
NiCad Battery Settings	Adjustable
Load Control Mode	

4.3.1 Charge Controller Configuration

The Xantrex can operate under 3 different modes: PV charge control mode, diversion load control mode, and dc load control mode. The PV charge control was selected for this design in order to safely operate the solar panels and batteries together. The mode is set simply by adjusting the internal jumper pin within the charge controller to “charge control”.

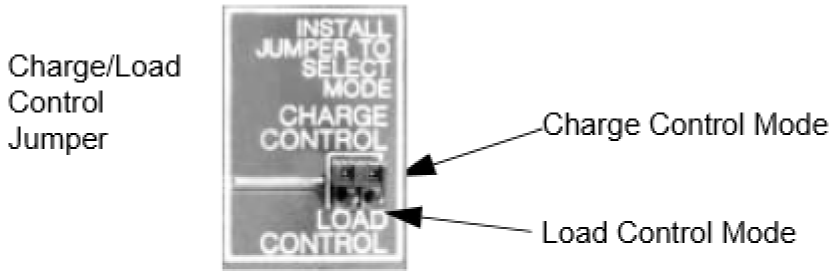

Figure 4-9: Charge Control Mode Jumper

Additional settings that can be altered with the jumper pins include the output voltage setting (24V) and the battery equalization setting.

The next step in controller configuration for the charge control setting requires an explanation of the three-stage battery charging process used by the Xantrex C40. The first of these stages, the Bulk stage, involves charging the batteries by maximizing current input to the batteries. As this occurs, the voltage of the batteries (assuming they were initially discharged) will steadily rise to their maximum voltage. Once the maximum voltage capacity is achieved, the controller switches to the Absorption stage where the current slowly reduces while maintaining the bulk voltage. The float stage is the final stage of this process, where the float voltage is maintained. At this point, the batteries are almost fully charged, and require a lower voltage and current input than the bulk stage in order maintain the battery voltage. In the float stage, the batteries can begin supplying full current to the system loads. Figure 4-10 below shows the general voltage and current behaviors throughout the different charging stages.

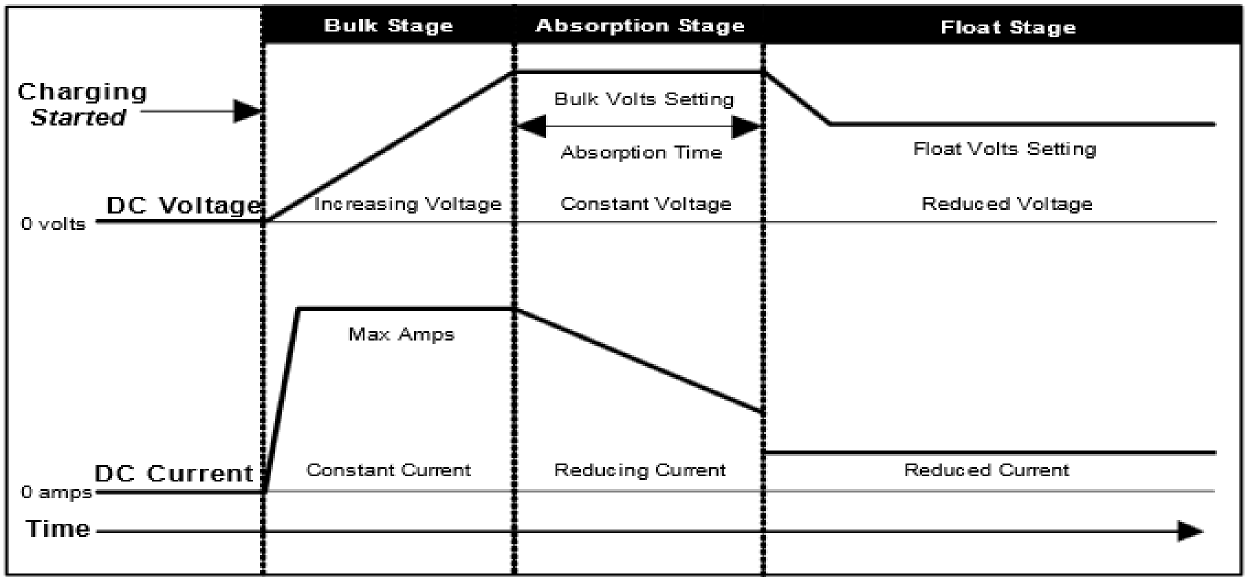

Figure 4-10: Xantrex C40 3-Stage charging process

To ensure safe operation, the bulk voltage and float voltage must be set based on the battery cell voltages. The batteries being charged are two Werker WKA12-100C/FR batteries in series. The specifications for these batteries are shown below in Table 4-6.

Table 4-6: Werker WKA12-100C/FR Battery Specifications

Specifications

All Specifications are Rated at 77°F Unless Otherwise Noted

Nominal Voltage			12V
Ampere Hour Capacity (20hr Rate to 1.75VPC)			100Ah
Dimensions		inches	millimeters
	Length	12.09"	307mm
	Width	6.65"	167mm
	Height	8.31"	211mm
	Height w/Term.	8.46"	215mm
Weight		60.57lbs	
Case Plastic		ABS Resin	
Maximum Charge Current		0.3C or 30.0A	
Recommended Charging	Float Use Voltage		2.28V/Cell
	Float Use Current		<15.0A
	Cycle Use Voltage		2.45V/Cell
	Cycle Use Current		<30.0A
Shelf Life		1 Month	97%
		2 Months	91%
		3 Months	83%
Temperature	Range	32°F to 104°F	
	Charge	5°F to 122°F	
	Discharge	5°F to 104°F	
Capacity Affected by Temperature (20hr rate)		77°F	100%
		32°F	85%
		5°F	64%

These batteries possess 6 cells apiece, each of which operate at 2.28V/Cell during the float stage, and 2.45V/Cell in the charge stage. Based on these specifications, the bulk voltage and float voltage settings on the Xantrex C40 can be determined.

Float Stage Voltage:

$$(2.28V) * (6\ cells) * (2\ batteries) = 27.36V$$

Bulk Stage Voltage:

$$(2.45V) * (6\ cells) * (2\ batteries) = 29.4V$$

4.3.2 Charge Controller Electrical Connections

After determining the necessary configuration settings, the charge controller can then be wired to the batteries and solar panel array. Figure 4-11 shows the recommended wiring scheme from the Xantrex C40 manual.

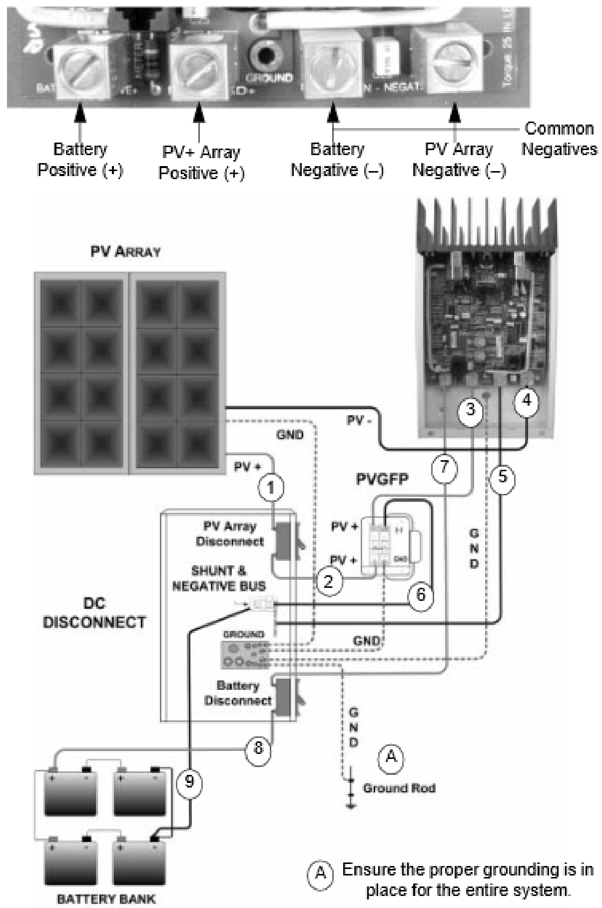

Figure 4-11: PV Charge control mode electrical wiring

5. Construction and Testing

This section documents the resulting electrical system construction based on the designs detailed in Chapter 4. Each of the main system components including the panel enclosure, solar panel mount, and the battery enclosure are assembled separately before connecting all components together to culminate in the final electrical system.

5.1 Panel Enclosure Construction

The panel enclosure was assembled using din rail to mount each of the main system components to. Firstly, the back panel was mounted to the enclosure and secured using a set of provided hex nuts with lock washers. Next, the vertical din rail channels were cut to 22” length using a band saw. The din rail channels were then secured using hex nuts with flat washers to increase surface area exposure. Each of the hex nut-washer connections were made on the mounting screws provided with the enclosure mount. Following this, two more din rail channels were cut to 22”. These two channels were secured horizontally to the vertical channels on each side of the back panel. These horizontal channels were placed at the 6 inch mark above the bottom of the back panel, and the 11 inch mark above the same point. This placement provided enough room for the circuit breakers, power distribution blocks, and field terminal blocks to be placed nearby each other without direct contact. The remaining din rail channels were cut into 11 inch sections which would be used as the mounting grid for the MISO. The mounting holes for these sections were carefully placed to match the 7.5” x 5” area of the MISO circuit board. The resulting enclosure is shown in Figure 5-1.

Figure 5-1: Panel Enclosure Construction

After the initial din rail framework was in place, the MISO was screwed in to the din rail channels using screw in stands to elevate it at least 1.5 inches off of the back panel plane. This was done to prevent accidental metal contact with the back plane when banana leads are connected. After it is securely mounted, the MISO then receives input power from the first circuit breaker directly below it marked “Battery (+)” via an AWG #12 wire with banana lead connection. This first breaker controls the input power from the solar panel batteries. The output of the MISO then feeds into a second circuit breaker via AWG #12 wire. These connections are shown in Figure 5-2.

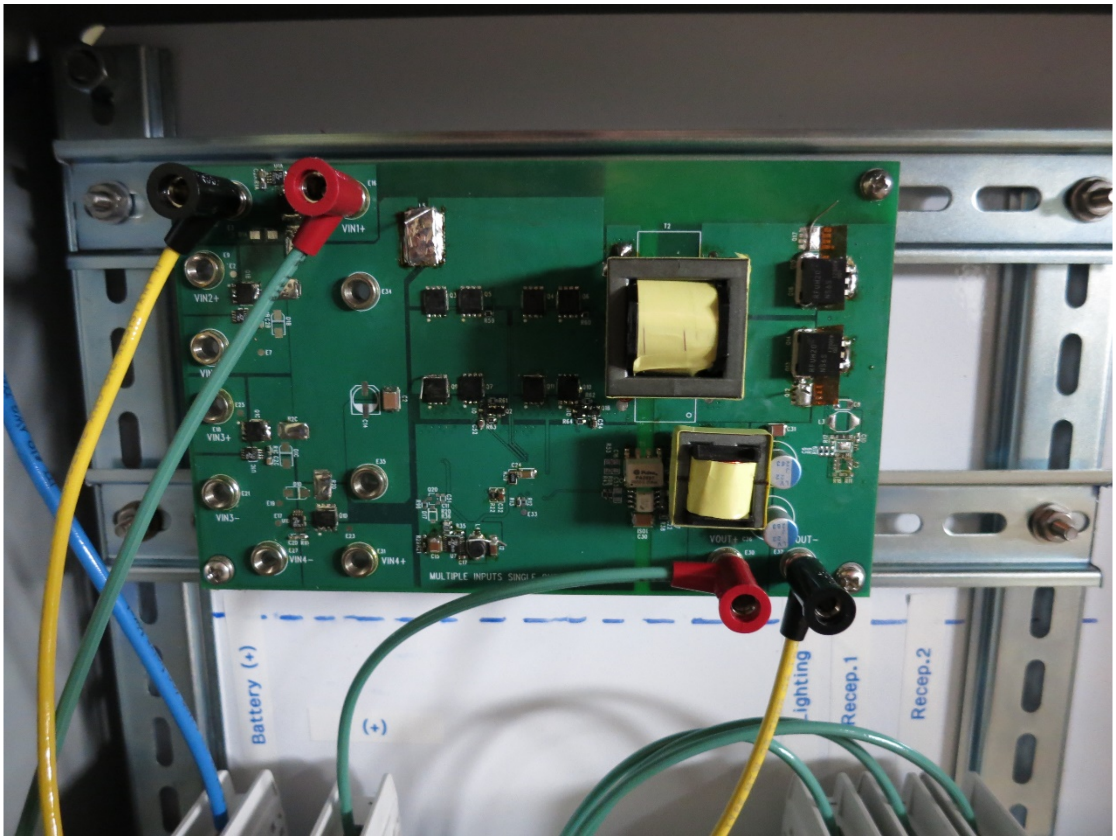

Figure 5-2: MISO mounting and electrical connections.

After the MISO was mounted and its wiring was finished, the circuit breakers below it were mounted onto the din rail channels. Only five circuit breakers were used for this assembly: one to control the battery input to the MISO, one to disconnect the MISO output from the load branches, and the remaining three to provide disconnect points for each of the individual load branches for lighting and receptacles. These circuit breakers are shown in Figure 5-3.

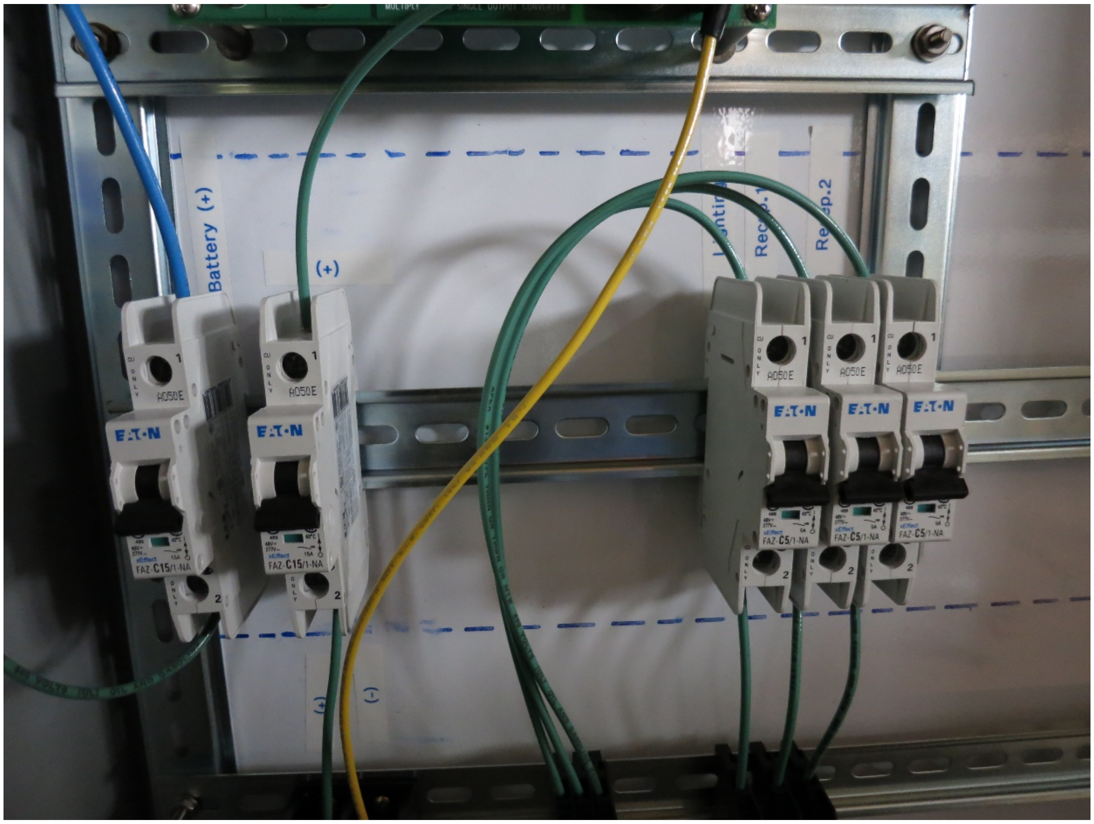

Figure 5-3: Panel Enclosure Circuit Breakers

The output of the Vout(+) terminal from the MISO feeds into circuit breaker, and then into a 2-pole power distribution block (PDB). This PDB feeds the power input on a single line and splits it into 3 separate branches. These wires are fed from the PDB into terminal blocks for wire management. These terminal blocks then feed into each of the load branch breakers labelled “Lighting”, “Recep. 1”, and “Recep. 2”. The outputs of the breakers are fed into another set of terminal blocks which are then distributed to the DC House loads via AWG #14 wire.

5.2 Solar Panel Mount Construction

The solar panel mount was constructed mainly of unistrut channels connected at corner joints by metal angle brackets and flat brackets. Unistrut bars are ideal for this application since they possess a large number of 5/8” diameter holes along the channel which can easily be fastened together using nuts, bolts and flat washers. This mount was assembled atop the donated trailer shown in Figure 4-6. In order to achieve the 35° tilt detailed in Chapter 4.2, the mount will be assembled in a shape similar to two right triangles connected by three 4’ unistrut channels to comprise the width of the frame. The hypotenuse of this triangle must match or exceed the length of the solar panel at 81.36”, and the width of the frame must match the 41.18” width of the solar panel.

Figure 5-4: Solar Panel Mount Construction

Firstly, two 6’ channels of unistrut were bolted along the length of the trailer. At the ends of these channels facing towards the battery enclosure, a 4 hole 90° angle bracket is bolted into the channel. From here, a 4’ strut channel is laid atop the two 6’ channels, and bolted to the angle brackets near the battery enclosure. Two more 4’ channels are then bolted perpendicular to the trailer plane, and are attached and reinforced to the first 4’ strut channel using flat 2-hole connecting plates. At the top of the structure, another 4’ channel attaches to the two perpendicular channels. This forms the shape of a square. The corners of this structure are reinforced as shown in Figure 5-5.

Figure 5-5: Solar Panel Frame Corner Connection

Following this, two more angle brackets are bolted to topmost corners of the strut square. These brackets connect to two 8’ strut channels which form the hypotenuse of this frame. At the base of these 8’ channels, angle brackets from the 6’ channels are attached to further reinforce the frame. Below this, another 4’ strut channel is connected between the two 8’ branches. This strut channel located at the base of the frame forms a foot that the solar panel can rest on while it is clamped to the frame. Figure 5-6 shows the assembled result.

Figure 5-6: Solar panel resting foot

With the frame in place, the solar panel is laid atop the 8’ strut channels and clamped at four points to the channels using the angle bracket and bolt connection shown in Figure 5-7.

Figure 5-7: Solar panel clamp connection

5.3 Battery Enclosure

The battery enclosure contains 2 Werker WKA12-100C batteries connected in series, the Xantrex C40 charge controller, and two circuit breakers which control the input from the solar panels to the charge controller, and from the battery to the panel enclosure. Since the batteries are lead acid sealed, they do not emit corrosive gases

which may damage the electronics within the Xantrex charge controller. As a result, all the components listed above can be placed together in the same enclosure.

The enclosure used was the metal box which came attached to the trailer used for the solar panel frame. Firstly, the 12V batteries were placed within the enclosure and connected in series. Following this, a wooden frame was assembled to mount the 2 circuit breakers and the Xantrex charge controller to. The resulting assembly is shown in Figure 5-8. The electrical connections were made based on the wiring diagram shown in Figure 4-11.

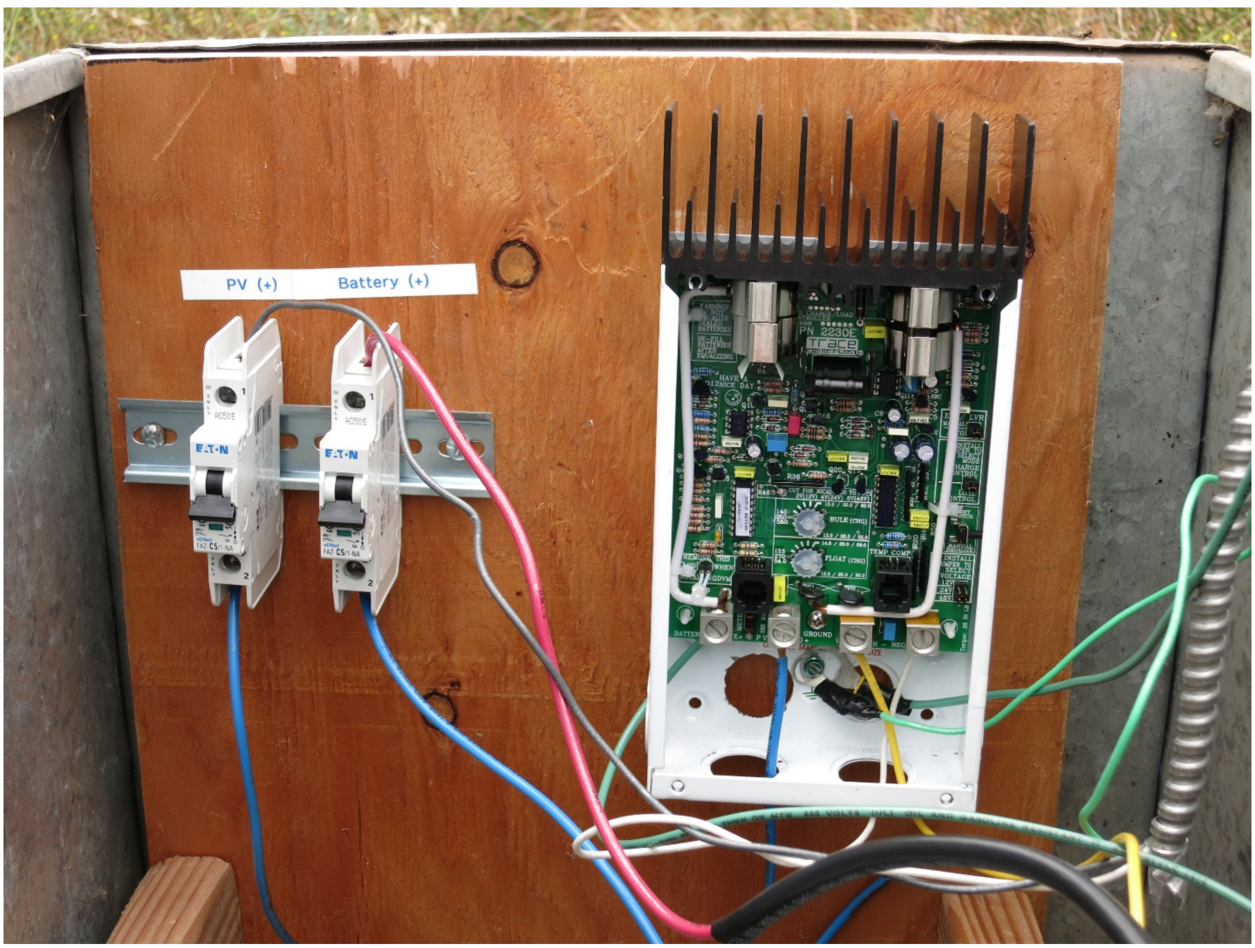

Figure 5-8: Charge Controller and Circuit breaker mounting plane

As shown above, the output of the solar panel in input into a 5A breaker labelled PV(+). A 5A breaker was selected in order to keep the maximum current output of the solar charge controller and batteries close to the recommended 15A for AWG #10 wire (Table 4-2). The output of this breaker feeds into terminal 2 of the solar charge controller. A close-up view of the terminals is shown in Figure 5-9.

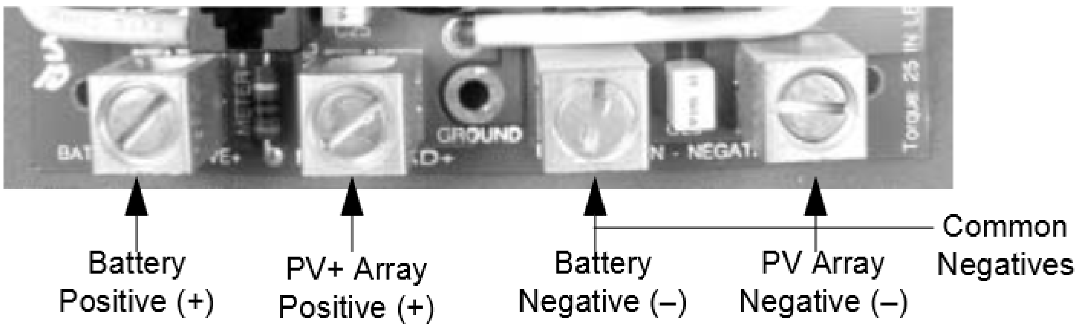

Figure 5-9: Close-up of Xantrex wiring terminals

The positive terminal of the battery, shown as the red wire Figure 5-8, connects to a 15A circuit breaker. In this case, a 15A breaker was chosen to allow the solar charge controller to vary the current feeding into the batteries during its high current "Bulk" stage. This breaker also allows for a manual disconnect between the charge controller and the battery. The output of this breaker connects to terminal one of the charge controller labelled "Battery Positive (+)". To complete the circuit, the negative PV line and Battery negative line connect to the remaining common negative terminals of the charge controller. The completed battery enclosure is shown in Figure 5-10.

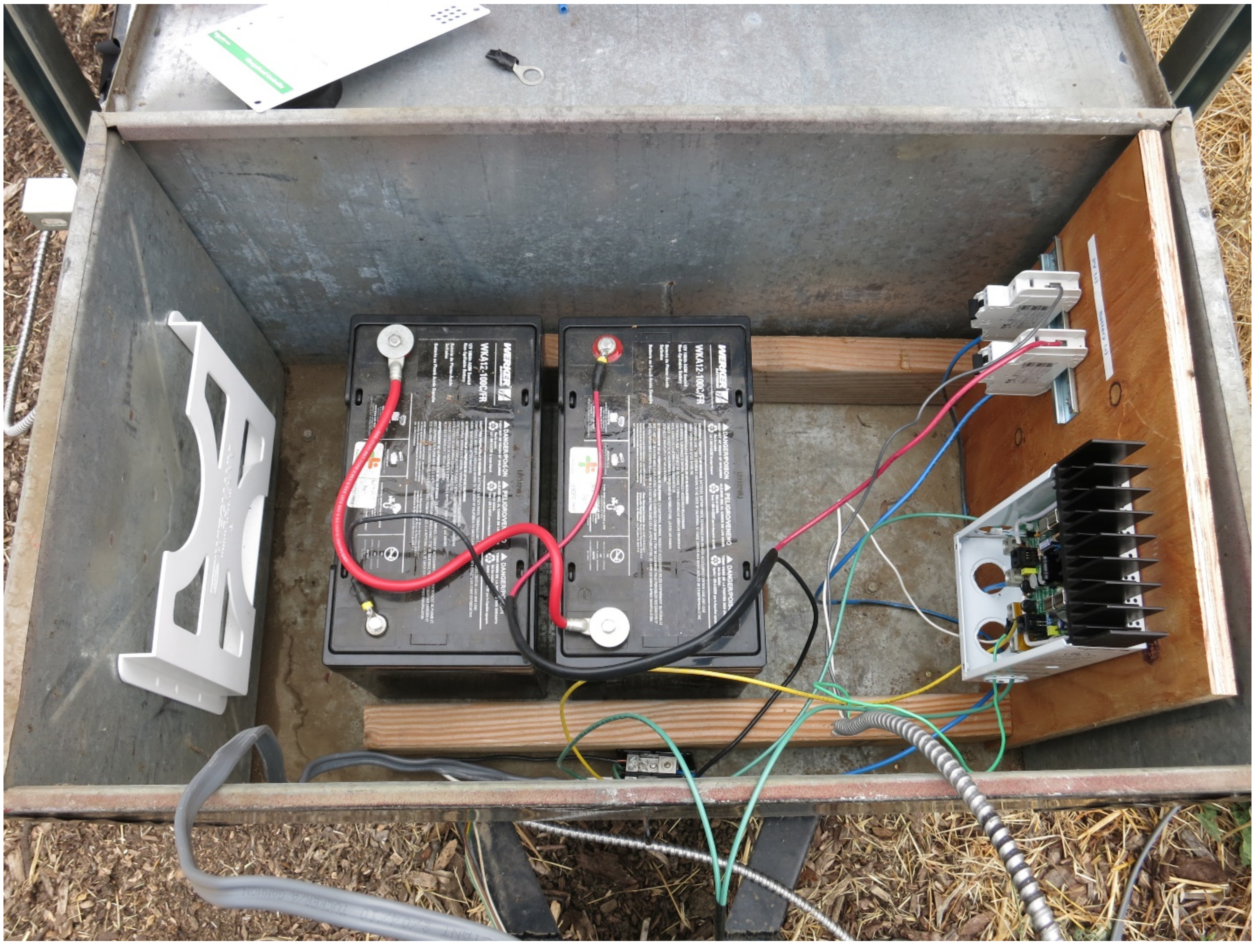

Figure 5-10: Top-Down view of Battery Enclosure

The final terminal of the Xantrex charge controller is the ground. This connects the chassis charge controller to the ground terminal of the solar panel, and to the negative line of the batteries via PDB. The grounding system is then connected to an 8ft copper grounding rod shown in Figure 5-11.

Figure 5-11: Grounding rod connection

As discussed earlier in Chapter 3, the entirety of the grounding rod cannot be a permanent installation at the SEF site. In order to test the electrical system for continuity however, the grounding rod was pounded 1’ into the ground, and then removed once testing was finished.

5.4 Continuity Testing & Results

In order to evaluate whether or not the electrical system operates correctly, voltage measurements were made at the battery terminals, MISO input, MISO output, and across a 10 ohm power resistor shown in Figure 5-12 below.

Figure 5-12: 10 ohm power resistor

Firstly, the batteries were allowed to charge for 1 day. The following day, the voltage input of the batteries was measured. Table 5-1 lists the results of these measurements.

Table 5-1: Battery Voltage

Trial #	Measured Voltage (V)
1	22.56
2	22.57
3	22.58
4	22.59
5	22.58

Next, in order to observe the amount of power transmitted to the load, the 10 ohm power resistor was connected to battery input breaker located in the panel enclosure. Once connected, both the voltage and current were measured across and through the resistor. The results are shown in Table 5-2.

Table 5-2: 10 ohm Resistor VI measurements

Voltage V_R	21.61 V
Current I_R	1.95 A
Power	42.1395

The power dissipated across the resistor was shown to be well below the 150W limit initially imposed at the start of this project. This is most likely due to the possibility that the batteries were not fully charged after 1 day, and would thus require more time before performing a full load test. At this wattage however, the MISO inputs and outputs can be measured to verify correct operation. The results of these measurements are shown below in Table 5-3.

Table 5-3: MISO input and output voltage

Trial #	Vin	Vout
1	22.47	48.2
2	22.49	48.2
3	22.51	48.2

Despite the low power capacity at this point, the MISO still operates correctly, reading nearly 24V at the input terminals from the batteries, and nearly 48V at the

output terminals feeding to the load branches. This concludes the Construction and Testing of the assembled electrical system for the DC House.

6. Conclusion

This project covered the design and construction of the electrical system for the newest rendition of the DC House. The purpose of this project was to assemble the initial electrical system in order to provide the necessary framework for future senior projects to modify it with ease. The main components resulting from this project include a solar panel mount, a panel enclosure for the MISO and load branch circuit breakers, and a battery enclosure. Due to the dynamic nature of the DC House project with new project ideas constantly being proposed and modifying older designs, the panel enclosure will provide a good starting point for future projects to modify by the inclusion of additional MISO converters, circuit breakers, power distribution blocks, and field terminal blocks. The solar panel can be moved to different locations if needed, and will operate as the primary source of power for the DC House until more power generation sources can be added. The battery enclosure provides a convenient location to store energy from the solar panel, and contains the Xantrex C40 charge Controller which can track and maintain the charge of the batteries. Each of these components were all constructed throughout the duration of this project and moved to the Student Experimental Farm for testing. The power measured did not exceed the 150W limit imposed in Chapter 3, however this may have been due to the incomplete charging of the batteries over the time span of 1 day.

6.1 Recommendations

The inclusion of additional power sources should be the next step as the project progresses forward. In particular, the inclusion of a wind turbine is entirely feasible, although it should not be mounted directly onto the house since it may damage its structural integrity due to the mechanical motion. Additionally, the testing of a human powered generator such as the swing generator or the merry-go round generator could also take place at this site of the DC House. If additional power sources are added to the framework of this project, the inclusion of an additional MISO, or one which is rated for higher power intake is also suggested. Once enough power generation capacity is present, DC receptacles should be outfitted to the house and used to power loads throughout to complete the proof of concept.

7. Bibliography

[1] Taufik, NFN. "The DC House Project." *The DC House Project*. N.p., n.d. Web. June 2015.

[2] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." *What Is U.S. Electricity Generation by Energy Source?* N.p., 31 Mar. 2015. Web. June 2015. <http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3>

[3] "Advantages and Disadvantages of Renewable Energy - Conserve Energy Future." *Conserve Energy Future*. CEF, 20 May 2014. Web. June 2015. <http://www.conserve-energy-future.com/advantages-and-disadvantages-of-renewable-energy.php>.

[4] "Energy Poverty." *IEA*. Internatl Energy Agency, n.d. Web. June 2015. <http://www.iea.org/topics/energypoverty/>.

[5] "GEF Agencies | Global Environment Facility." *GEF Agencies | Global Environment Facility*. Global Environment Facility, n.d. Web. 11 June 2015. <http://www.thegef.org/gef/gef_agencies>.

[6] "About the Climate Investment Funds." *About the Climate Investment Funds*. Climate Investment Funds, n.d. Web. June 2015. <http://www.climateinvestmentfunds.org/cif/aboutus>.

[7] "Student Experimental Farm." *Student Experimantal Farm*. Cal Poly Land, n.d. Web. June 2015. <http%3A%2F%2Fwww.polyland.calpoly.edu%2Ftopics%2Fagriculture%2Fstudentsites%2F2004a%2Findex.html>.

[8] Lund, Mark W. "Wire Gauge and Current Limits Including Skin Depth and Strength." *American Wire Gauge Table and AWG Electrical Current Load Limits with Skin Depth Frequencies and Wire Breaking Strength*. Lund Instrument Engineering, Inc., n.d. Web. June 2015. <http://www.powerstream.com/Wire_Size.htm>.

[9] Schneider Electric, Xantrex Charge Controller Information Manual, 2003 http://pdf.wholesalesolar.com/controller%20pdf%20folder/XantrexCSeriesManual.pdf?_ga=1.137909168.1213787092.1432060409

[10] Masters, Gilbert M. *Renewable and Efficient Electric Power Systems*. Hoboken, NJ: John Wiley & Sons, 2004. Print.

Appendix A – Bill of Materials

Photo Voltaic					
Item#	**Product**	**Manufacturer**	**QTY**	**Price Per Unit**	**Total Cost**
1	10 ft. 12-Gauge Strut Channel	Unistrut, Superstrut	5	19.62	98.1
2	UniStrut Hardware 1/2" Zing-Plated Hex Bolts	Home Depot	50	0.48	24
3	1/2 in. Zinc-Plated Coarse Threaded Hex Nut	Home Depot	50	0.2	10
4	UniStrut Hardware 1/2" Flat Washers	Home Depot	50	0.18	9
5	Superstrut 90-Degree 4-Hole Channel Bracket	Superstrut	12	2.25	27
6	Superstrut 2 Hole Flat Straight Bracket	Superstrut	10	2.71	27.1
7	Superstrut 3 Hole Flat Right Angle Bracket	Superstrut	8	2.71	21.68
8	1/2" Diameter 5.5" Length Bolts	Home Depot	4	1.28	5.12
9	Ground Rod 8 foot	ERITECH	1	11.28	11.28
10	#10 AWG Solid Core Wire	Home Depot	50	1.28	64
11	C40 Xantrex Charge Controller	Schneider Electric	1	111	111
					408.28

Miso Enclosure					
Item#	**Product**	**Manufacturer**	**QTY**	**Price Per Unit**	**Total Cost**
1	Enclosure W/ Viewing Window (24"x24"x8")	Wiegmann	1	739.17	739.17
2	Back Panel	Wiegmann	1	101.64	101.64
3	2 Pole Power Distribution Block - PB1042	Edison	2	19	38
4	Field Terminal Blocks 100 Pack - KN-T12BLK	Konnect-It	1	30	30
5	Grounding Terminal Block 10 pack - KN-G12SP-10	Konnect-It	1	15	15
6	Field Terminal Block End Cover - KN-ECT6BLK	Konnect-It	1	2	2
7	Field Terminal Block Seperator - KN-ST1BLK	Konnect-It	5	3	15
8	Din Rail 2-pack - DN-R35S1-2	Automation Direct	2	9	18
9	5A Circuit Breaker - FAZ-C5-1-NA-SP	Eaton	10	18	180
10	15A Circuit Breaker - FAZ-C15-1-NA-SP	Eaton	6	18	108
					1246.81

Appendix B – Analysis of Senior Project Design

Analysis of Senior Project Design

Please provide the following information regarding your Senior Project and submit to your advisor along with your final report. Attach additional sheets, for your response to the questions below.

Project Title **The DC House Project: Electrical System Design and Construction**

Student's Name: **John Bradley** **Student's Signature:** ______________________

Advisor's Name: **Ahmad Nafisi, Taufik** **Advisor's Initials:** ___________

- **Summary of Functional Requirements**

  This project provides the electrical framework necessary for future senior projects to easily modify and add to this rendition of the DC House project. This includes providing solar power to the DC House, and controlling source and load branches with appropriately sized circuit breakers in a weather-proof panel enclosure box.

- **Primary Constraints**

  Several constraints limited the final design of the electrical system. One major issue that arose during the construction phase, was the limited power capacity of the Multi Input Single Output (MISO) DC-DC converter, a device which formed the backbone of the DC House design. Traditionally, this device combines the input from several different power generation sources, and outputs the combined DC power to a load. However, the current MISO converter is only rated for 150W. This limited the number of sources that could be used and also required undersized circuit breakers to be placed throughout the electrical system in order to adequately protect the MISO. Additionally, the site at which the electrical system was installed did not permit for permanent fixtures, meaning that permanent grounding rods or concrete mounts for a solar panel frame could not be used.

- **Economic**

  The final cost of the materials purchased used to create the electrical system amounted to $1655.09. This is slightly lower than the estimated cost of the project components which was $1890. However, this gap between the estimated cost and the actual cost is due to a variety of reasons. For example, the biggest contributors to the initial electrical system cost were solar panels, wind turbines, and batteries, each of which were either initially provided for or unused in this project. With these left out however, the initial system cost failed to include the cost of wiring, solar panel mount components, and panel enclosure components such as circuit breakers or power distribution blocks.

- **Environmental**

  Since the DC House will only uses renewable energy sources to power its loads, it will not contribute to carbon emissions which often plague the air. The increased use of renewable energy solutions such as the DC House in highly industrious areas with high population density such as Asia will provide energy will also limiting the carbon footprint.

- **Manufacturability**

  While an electrical system for the current rendition of the DC House can be created and evaluated for its development and labor costs, it is difficult to create a “one size fits all” solution to provide for the electrical needs of those living in energy poverty due to the vast variation in housing size, location, and number of tenants to service.

- **Sustainability**

  A DC House electrical system is designed so that it may draw power from the environment it is placed in. Due to this fact, the variation for sustainability of the DC House depends heavily on such an environment, and therefore cannot be accurately evaluated for all cases. For example, a location which has low annual solar access but heavy winds may employ the use of more wind turbines which cause mechanical or structural damage to the location they are mounted due to the rotary motion of the turbine and the force of the wind. Conversely, a location which has high solar access and no winds will use solar panels which may last up to 20 years with little to no maintenance during such lifetime.

- **Ethical**

  While the DC House design is intended for use by those who live in energy poverty, there still remains the possibility that the design for these renewable energy houses could be used for illegal operations in remote locations which are untraceable to a utility grid. From a utilitarian standpoint however, where one would seek to maximize good for the greatest number of people, the DC House could be used to improve the lives of a large number of people sorely in need of energy, which outweighs the hypothetical possibility that such a design will be employed for illegal misuse.

- **Health and Safety**

  Construction of the DC House could pose a possible safety risk, handling electrical components and power generation tools which can cause burns or electrocution. The completed DC House project should seek to minimize exposed wiring to prevent potential fire hazards, and apply effective grounding systems to prevent electrocution.

- **Social and Political**

  The DC House uses no fossil fuels, petroleum, or natural gasses to produce its energy. Organizations such as the Global Environmental Facility (GEF) and Climate Investment Fund (CIF) seek projects and distribute grants to renewable energy projects that help those in energy poverty. However, from a political standpoint, while the DC House offers an off-grid alternative energy solution to alleviate the energy needs in underdeveloped countries, it does not directly contribute to the development of energy infrastructure within these countries, which is ultimately the goal of many countries struggling with energy distribution. This may discourage the use of the DC house in the interest of searching for more permanent energy solutions.

- **Development**

  While the concept has been introduced many times throughout the coursework at Cal Poly, effectively grounding an electrical system to comply with NEC requirements is a rather involved process. Rather than simply using a connection to ground or eliminating the use of a grounding system entirely, NEC code requires the use of two 8 foot grounding rods when using a solar panel to power an electrical load for a house. Additionally, the majority of these grounding rods must be pounded into the ground with the use of a device such as an auger. Prior to pounding these rods into the ground however, one must check with an underground excavation service such as DigAlert to verify that services lines such as oil pipes are not present beneath the land which the grounding rods may be installed.