Residential Grid-Tied Photovoltaic (PV) System With Battery Backup

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2012

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Acknowledgements:

Many people helped me in nearly every stage of this project. First and most important, I wish to thank my Senior Project Advisor, Dr. Nafisi, for helping me develop my project and help it become feasible. I also appreciate his guidance and availability to answer my many questions and emails. He was very flexible and supportive with my ideas and very patient in dealing with my procrastination. I would like to thank Tim Townsend from Behnke, Erdman, and Whitaker (BEW) Engineering for his informative presentation on Photovoltaic (PV) Site Analysis and System Sizing, presented by PG&E's Energy Training Center. Without Tim's presentation, I may not have chosen this project. His real-world knowledge of Photovoltaic Systems, guidance, and helpful tips aided me to move forward in brainstorming and executing my project as well as providing information to access further resources. I would like to take this chance to thank my parents, without whom I would lack support and people to bounce ideas off of. This project serves as a culmination of my higher education and I could not have been as successful without my parents' patience and encouragement while I finished my education . Also, the owners of the house I used as a model deserve thanks. Without their home, I would have not been able to collect adequate quantifiable data and apply it to creating a PV system for a home like theirs. I would like to thank PG&E's Pacific Energy Center's (PEC) Tool Lending Library. Access to their tools provided real world, industry level experience, as their tools are used by industry professionals to create residential and commercial solar systems. Tool lending is also free, which made it feasible for me. Finally, I would like to thank the Students and Faculty of the EE department who graciously voted and awarded me with third prize for my project display Figure 1. It is validating to be recognized and I appreciate the recognition. Without the assistance of these people and PG&E, I would not have been able to successfully develop and execute this project. Thank you.

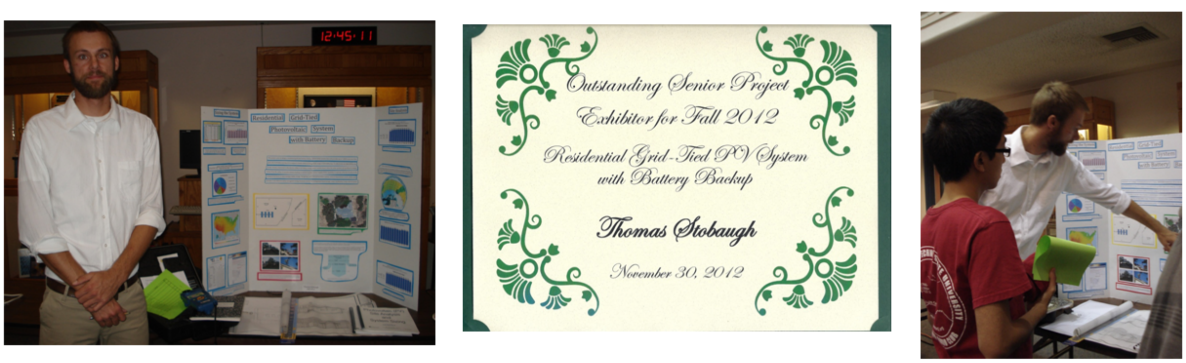


Figure 1: Senior Project Expo Fall 2012

Abstract:

When power outages occur, many homes are left without power for some time as they are dependent on the power grid. This project aims to design a residential grid tied battery backup photovoltaic system that will provide up to 7.2kW in an area that gets 5.36-5.49 kWh/m2/day [1] to support a home with an average daily usage of 28.4 kWh/day. To effectively use this system the house remains connected to the electric utility at all times, so any power needed above what the solar system can produce is simply drawn from the utility. It includes battery backup or uninterruptible power supply (UPS) capability to operate selected circuits in the residence for hours or days during a utility outage. Designing a grid tied photovoltaic system reduces dependence on the utility and provides a cost effective safety net against losing necessary power for refrigerated food storage, water facilitation, crops, and livestock.

I. Introduction

Photovoltaics is a method of generating electrical power by converting solar radiation into direct current (DC) electricity using semiconductors that exhibit the photovoltaic effect. The photovoltaic effect is the creation of voltage in a material upon exposure to light and occurs when electrons are transferred between different bands within a material, resulting in the buildup of voltage between two electrodes [2] [3].

Solar photovoltaics are growing rapidly, albeit from a small base, to a total global capacity of 67,400 megawatts at the end of 2011, representing 0.5% of worldwide electricity demand [3]. More than 100 countries use solar PV [3]. Installations may be ground-mounted or built into the roof or walls of a building.

A residential PV power system enables a homeowner to generate some or all of their daily electrical energy demand and "the customer obtains the full retail electricity rate—rather than the much lower wholesale rate—for kilowatt-hours of PV- produced electricity sent to the utility power grid." [4]. There are three main types of PV systems: grid-tied systems, grid-tied with battery backup, and stand alone systems. In a grid –tied system the house remains connected to the electric utility at all times, so any power needed above what the solar system can produce is simply drawn from the utility. PV systems can also include battery backup or uninterruptible power supply capability to operate selected circuits in the residence for hours or days during a utility outage. By designing a grid tied photovoltaic system, dependence on the utility is reduced and many environmental and socio-economic benefits are gained. These include reduced dependence on the utility, diminished electricity costs, and reliable, renewable, clean energy [4]. This is the main drive behind this design project. This project aims to alleviate the financial burden and powerlessness of relying solely on the utility to provide a reliable power service, and specifically to provide a cost effective safety net to keep refrigerated food storage, water facilities, crops, and livestock fresh and thriving. All one needs to do to discover an interest in these systems is to spend a week or two after a hurricane, an ice storm, or some other natural disaster without electric power. Those who have purchased fossile-fuled generators for backup power generally appreciate the idea of a quiet reliable, non-fuel consuming source of electricity. Rather than wait in long lines for gasoline for their generator, they can sit by the pool drinking a cold beer. Often , those interested in battery-backup PV systems expect the systems to pay for themselves, even though no fossil standby generator ever paid for itself with the electricity it generated . The payback from a battery backup system must be measured in terms of food not spoiled after a utility outage and the comfort level knowing that power will be available after a utility outage [2].

The steps to design such a system are briefly discussed. The first step to design is to understand the system requirements both from an engineering perspective and marketing perspective. Next sizing the system based on load demand, roof space, and site analysis are vital for developing a foundation for the rest of the design. Continuing this process, once a thorough assessment of the sit and system sizing are complete selection of the major components can begin. For a battery backup system it is easiest to begin by selecting the modules to design the array. Next the charge controller and inverter can be sized and selected fallowing up with the design completion and Balance of System (BOS) components. Fallowing this outline this report documents the design process for designing a residential grid-tied with battery backup photovoltaic system.

II. Requirements and Specifications

Below is a table representing the engineering specifications and marketing requirements of a grid-tied with battery backup PV system that meets the needs of the customer. The engineering requirements below are short statements that address the technical need of the design specifying what the system will do, not how it will be implemented. Each engineering spec. is associated with at least one marketing requirement pertaining to the inputs of the customer.

Grid-Tied With Battery Backup Photovoltaic System	
Your Name: Thomas Stobaugh **EE 460-01**	**EE 463/464 Ahmad Nafisi a.n.** **1. I agree to supervise this senior project. a.n.** **2. The specifications are [2] [3]:** ☒ Abstract—Describes what project should do, not how. ☒ Bounded—Identify project boundaries, scope, and context ☒ Complete—Include all the requirements identified by the customer, as well as those needed to define the project. ☒ Unambiguous—Concisely state one clear meaning. ☒ Verifiable—A test can prove if system meets specification. ☒ Traceable—Each engineering specification serves at least one marketing requirement.
ADVISORS: Please initial above, if you agree to supervise this senior project. Also, please check applicable boxes above. Comment below, if requirements or specifications require revision.	

Table 1: Grid Interactive With Battery Backup PV System Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1,2,3,8	The PV array must produce at least 7.1kW	Based on chart sizing for a PV system [5]
1,2,3,8	The System must provide ≥ 28.4 kWh/Day energy output	Average daily power consumption of household, which is based on Electric Utility data for a 12 month duration.
3,5,8	PV array must be ≥ 710 ft^2	General output for the average PV panel produces 1kW/100ft^2 [6]. *Ex:* $(710ft^2)(.01)(kW/ft^2) = 7.1kW$
1,2,3,4,7,8	Should have an efficiency (η) ≥ 64%	For PV systems containing battery systems - calculated by taking into account the modulation factor, wiring losses, charge controller losses, and Inverter Efficiency Factor [6] [7].
1,2,3,4,6,7,8	The backup battery system must provide ≥ 1557.3Ah over 20 hour discharge rate for 2 days without recharging.	This exceeds the average time it takes to repair a utility outage and provides a safety net for long periods of time without sunlight to the PV array.
2,3,4,6,7	The system must be automated to disconnect from the grid when there is a utility outage, and reconnect to the grid when the utility power is restored.	This is part of the fundamental design of the grid-tied PV system with battery backup. It allows the system to still produce power during a utility outage. It also provides safety to line workers repairing utility lines during a utility outage.

Marketing Requirements
1. The System should have minimal electrical loss.
2. The System should reduce or eliminate a dependence on the Electrical Utility Company.
3. The System must meet the house hold energy needs.
4. Outdoor equipment must be weather resistant.
5. The System should be aesthetically pleasing.
6. The System should be able to supply power in low sunlight conditions during a Utility outage
7. The System needs to meet the *IEEE 1547 and UL 1741 standards* [8] [9].
8. The System must be within the customers price range[i]

[i] Customer has not provided a specified budget for system yet.

III. Functional Decomposition

The below figures and tables provide the overall description of the system and its functions by using the recursive process of functional decomposition. The functional decomposition reflects the inputs, outputs, and the functionality through block diagrams. Figure 1 is a level 0 functionality block diagram of the grid-tied with battery backup PV system. It displays the definition of the highest level of system function. Table II gives a detailed breakdown of the inputs, outputs, and functionality of the overall system.

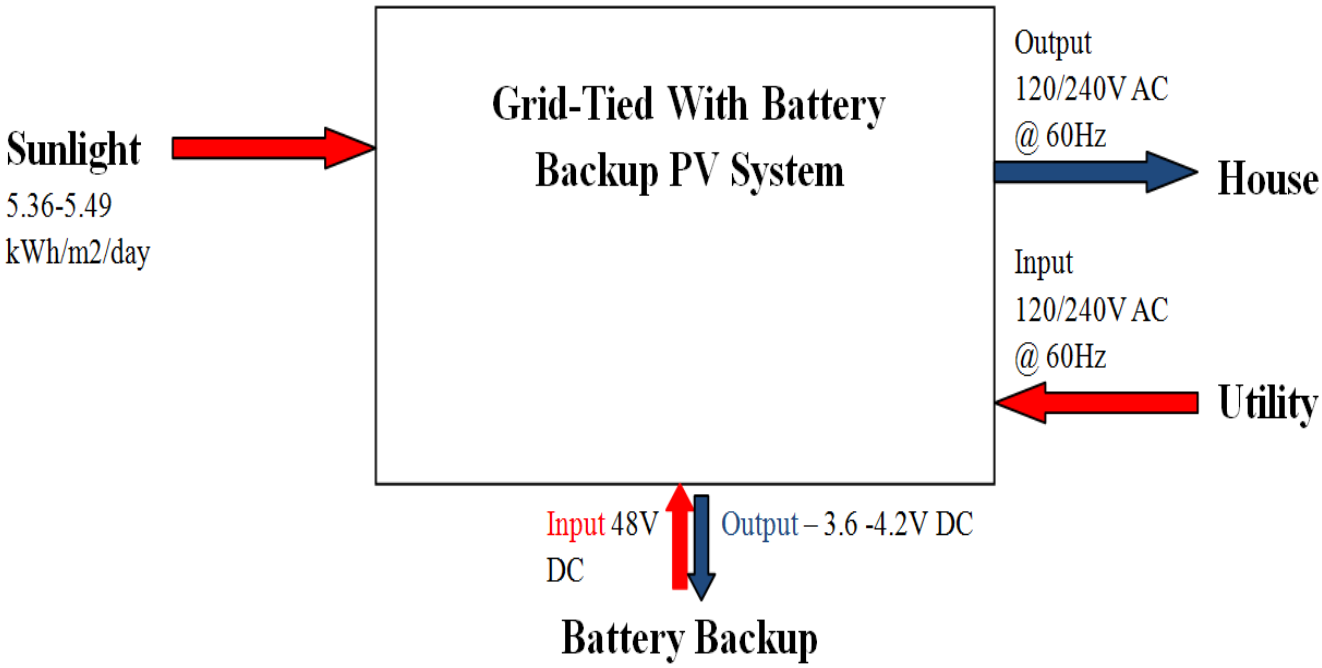


Figure 2: LEVEL 0 FUNCTIONALITY BLOCK DIAGRAM FOR GRID-TIED WITH BATTERY BACKUP PV SYSTEM

Table 2: System Functionality Requirements

Module	Grid-Tied With Battery Backup PV System
Input	- Sunlight: Variable light from the Sun depending on weather conditions, time of day, and altitude in the sky. Average annual solar irradiation of 5.36-5.49 kWh/m2/day [1] - Utility: 120/240V AC rms, 60Hz - Battery Backup: 48V DC supplied from battery system at 778.6Ah/day (assuming losses) [10]
Output	- House:120/ 240V AC rms, 60Hz at up to 28.4kWh/day to the residence - Battery Backup: 3.6-4.2V varying to the batteries depending on state of charge of each individual battery.
Functionality	Convert Sunlight into DC power, then into 120/240V AC rms at 60Hz to provide up to 28.4kWh/day. If the household demand exceeds the maximum daily output power (28.4 kWh/day) the system should also supply 120/240V AC rms at 60Hz from the Utility. It should also supply 3.6-4.2V DC to charge the batteries, varying the voltage depending on the state of charge of each battery. Should the Utility be unable to provide power and there should be insufficient light to meet the household power demand the system should be able to supply 48V at 778.6Ah/day (taking into account losses) for up to 2 days to meet the household power demand of 28.4 kWh/day.

Figure 3 is a level 1 functionality block diagram. It expresses the main design architecture of the system displaying the organization and interconnections between modules. The following Table 3through Table 8further presents a detailed breakdown of the inputs, outputs, and functionality of the individual modules within the system.

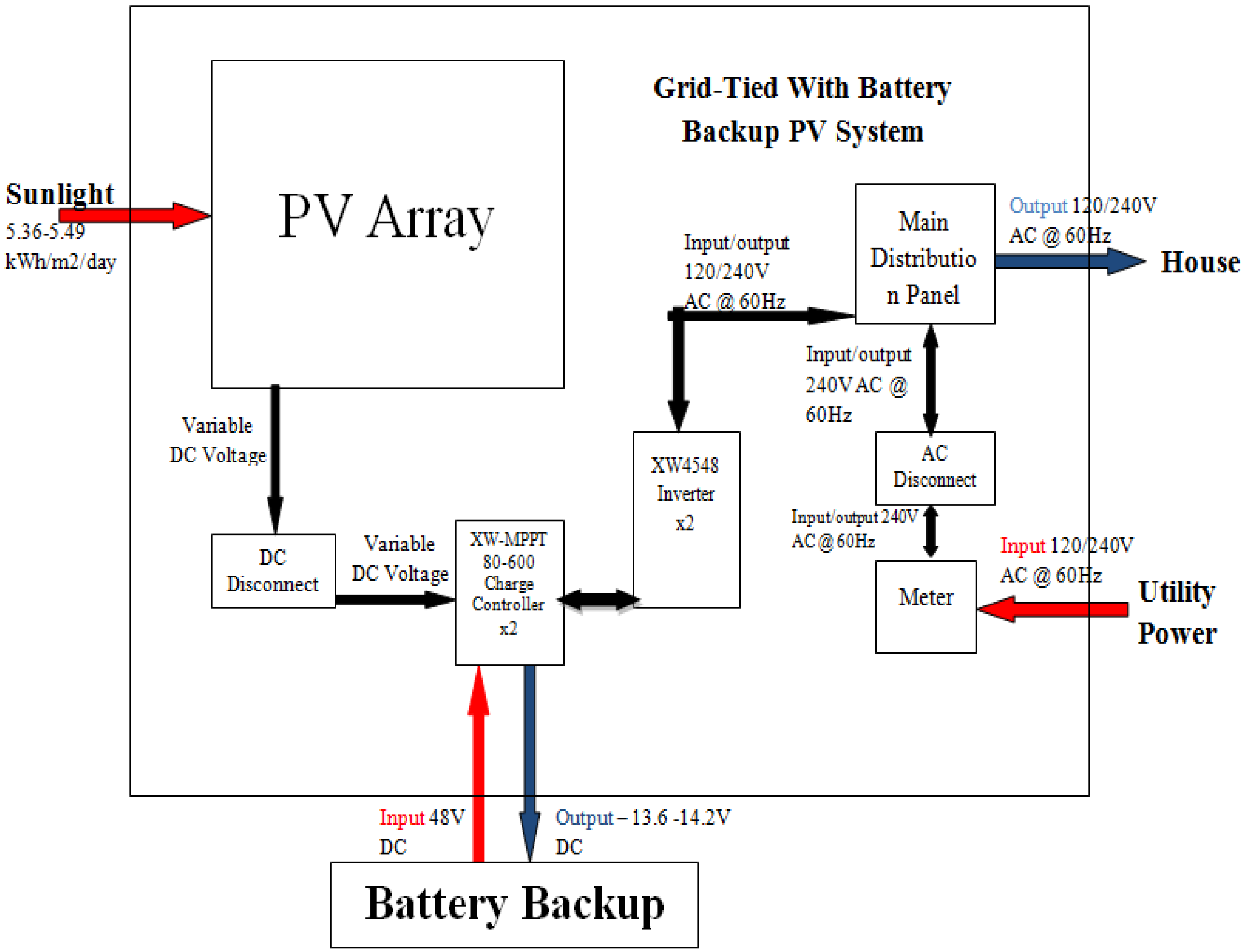


Figure 3: LEVEL 1 FUNCTIONALITY BLOCK DIAGRAM FOR GRID--TIED WITH BATTERY BACKUP PV SYSTEM

Table 3: PV Array Functionality Requirements

Module	PV Array
Input	- Sunlight: Variable light from the Sun depending on weather conditions, time of day, and altitude in the sky. Average annual solar irradiation of 5.36-5.49 kWh/m2/day [1]
Output	- Variable DC voltages ranging from 0 volts to maximum output voltage of the individual panels; dependent upon many factors such as weather conditions, shading factor, orientation/tilt factors, soiling factors, etc.
Functionality	The PV array accepts incoming sunlight and converts the energy of light into a DC voltage through the photovoltaic effect.

Table 4: DC Disconnect Functionality Requirements

Module	DC Disconnect
Input	- DC voltage varying from 0 to max output of PV array.
Output	- DC voltage varying from 0 to max output of PV array.
Functionality	Serves as a switch to safely disconnect the PV array from the rest of the system.

Table 5: Inverter/Charge Controller Functionality Requirements

Module	Inverter/Charge Controller x2
Input	- Variable DC voltages generated by the PV array. - Battery Backup: 48V DC supplied from battery system at 778.6Ah/day (assuming losses) [10] - Utility: 240V AC rms, 60Hz
Output	- Battery Backup: 3.6-4.2V varying to the batteries depending on state of charge of each individual battery. - Utility: 120/240V AC rms, 60Hz
Functionality	Accepts DC voltages generated by the PV array and converts the DC voltages into 120/240V. The **Inverter must have anti-islanding protection** [8] [9] and is designed to draw energy from the battery system at 48V and 778.6Ah. Manage the battery charge via a MPPT charge controller separate from the inverter, supplying 3.6-4.2V DC varying the voltage depending on the state of charge of each battery

Table 6: Meter Functionality Requirements

Module	Meter
Input	- Utility: 120/240V AC rms, 60Hz - Inverter: 120/240V AC rms, 60Hz
Output	- 120/240V AC rms, 60Hz
Functionality	Measures the amount of electric energy consumed or produced by the residence. Depending on if the residence is consuming more power than the PV system can produce the meter will read the energy consumed by the residence. If the residence produces more energy than is consumed or stored by the PV system it will measure the energy fed into the utility grid.

Table 7: AC Breaker Panel Functionality Requirement

Module	AC Breaker Panel
Input	- Utility: 120/240V AC rms, 60Hz - Inverter: 120/240V AC rms, 60Hz
Output	- House: 120/240V AC rms, 60Hz - Inverter: 120/240V AC rms, 60Hz
Functionality	To pass the 120/240V AC rms, 60Hz signal from the inverter and or the utility to residence household. Also to detect a fault condition and, by interrupting continuity, will immediately discontinue electrical flow.

Table 8: AC Disconnect Functionality Requirements

Module	AC Disconnect
Input	- Utility: 120/240V AC rms, 60Hz - Inverter: 120/240V AC rms, 60Hz
Output	- House: 120/240V AC rms, 60Hz - Inverter: 120/240V AC rms, 60Hz - Utility: 120/240 V AC rms, 60Hz
Functionality	Serves as a switch to safely disconnect the system from the utility when a fault condition is detected by the inverter.

IV. System Sizing

Energy Usage Data

The most important and complex stage in sizing any residential PV system is providing a breakdown of the daily electrical consumption. A determination of the loads and daily electrical demand provides a baseline for correct sizing of the PV array. For this project the system is to provide 100% of the household demand, therefore a comprehensive collection of energy usage data is collected from the customer's utility provider, which in this case is Pacific Gas & Electric (PG&E). Table 9 displays the energy usage history of the residence for the years of 2010 and 2011. It provides the average kilowatt-hour per day (kWh/day) for each month and then an average daily usage (kWh/day) for the year. It also presents the total energy usage for each year. In 2010 the average energy usage is 28.0 kWh/day with an annual consumption of 10241 kWh/yr. In 2011the average energy usage is approximately 28.4 kWh/day with an annual consumption of 10380 kWh/yr. The data gives a consistent average daily usage between the two years for the household. Therefore based on the provided data the system will be sized according to an average daily demand of 28.4 kWh/day. This data is used in determining the size that the PV array needs to be to meet the average daily energy demand of the house hold.

Table 9: PG&E Energy usage History for 2010 and 2011

	PG&E Energy Usage History Rate Schedule: E1 SB Residential Service Meter #1004821807									
	2010					2011				
	Date	Days Billed	Usage (kWh)	kWh/Day	Charge ($)	Date	Days Billed	Usage (kWh)	kWh/Day	Charge ($)
Jan	12/29-1/28	31	871	28.1	$172.00	12/30-1/28	30	787	26.2	147.00
February	1/29 - 3/1	32	843	26.3	$155.00	1/29 - 3/1	32	819	25.6	149.14
March	3/2-3/31	29	876	30.2	$185.00	3/2-3/30	29	737	25.4	136.00
April	4/1-4/29	30	819	27.3	$167.00	3/31-4/29	30	729	24.3	131.00
May	4/30-5/28	29	701	24.2	$99.72	4/30-5/31	32	764	23.9	110.00
June	5/29-6/29	32	923	28.8	$152.00	6/1-6/29	30	832	27.7	143.00
July	6/30-7/29	30	1062	35.4	$208.00	6/30-7/29	31	1021	32.9	207.00
August	7/30-8/30	32	966	30.2	$165.00	7/30-8/29	31	1053	34.0	214.01
Septembe	8/31 - 9/29	30	805	26.8	$125.00	8/30 - 9/28	30	1010	33.7	204.01
October	9/30 - 10/28	29	744	25.7	$111.00	9/29 - 10/27	29	851	29.3	155.79
Novembe	10/29 - 11/30	33	810	24.5	$141.00	10/28 - 11/29	33	928	28.1	188.42
Decembe	12/1-12/29	29	821	28.3	$167.00	11/30-12/28	29	849	29.3	179.57
	Average		853	28.0		Average		865	28.4	
	Total (kWh/yr)		10241			Total (kWh/yr)		10380		

Figure 4 and Figure 5are graphical representations of Table 9 displaying the average daily energy usage for each month compared to the annual average daily energy usage in kWh/day. This is useful for understanding which months of the year the demand is greatest to better prepare and adjust energy needs and habits for the customer. From the charts it is observed that the summer months June through August are generally the highest demand throughout the year. This is most likely due to the increased usage of the well for watering crops and livestock.

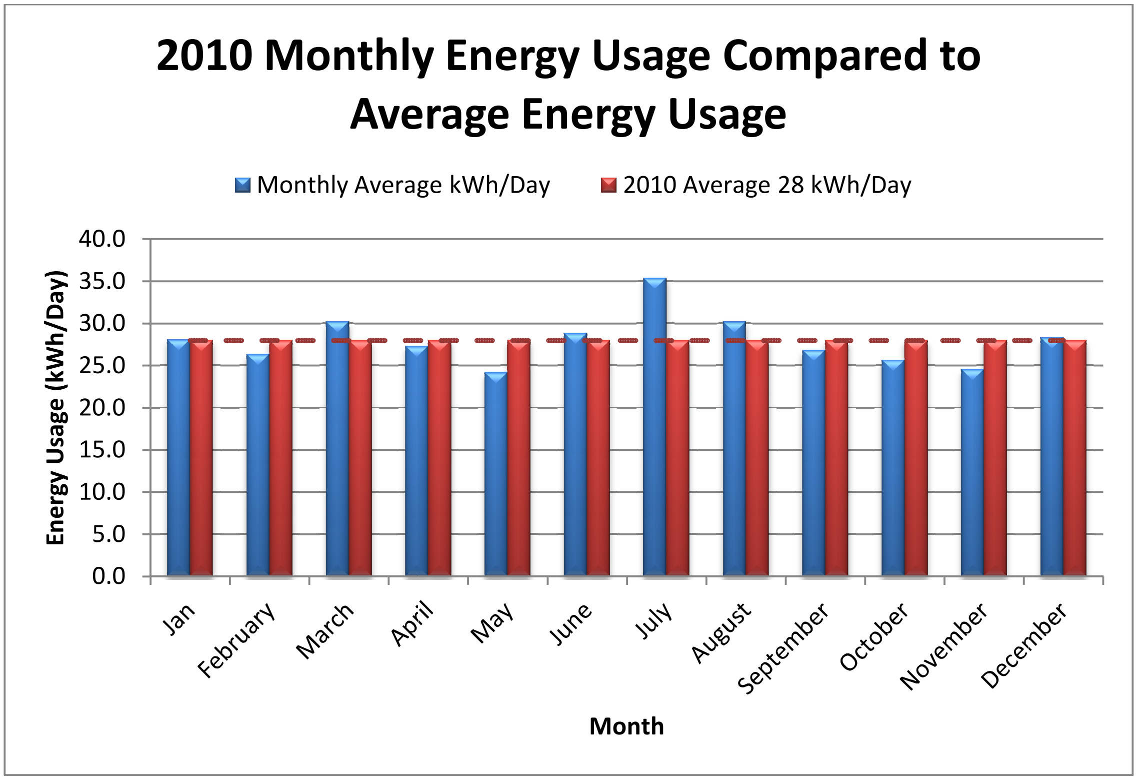


Figure 4: 2010 Monthly Energy usage Compared to the Average Energy Usage for Each Month

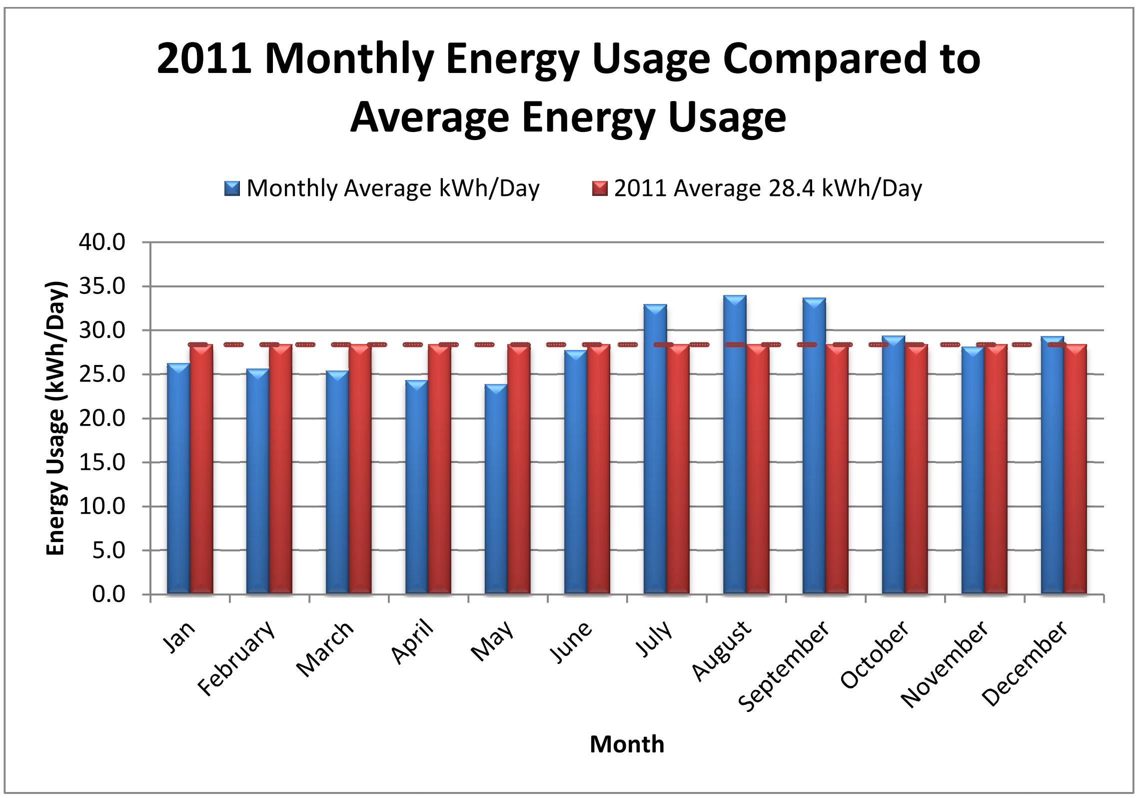


Figure 5:2010 Monthly Energy usage Compared to the Average Energy Usage for Each Month

Array Sizing

After the daily electrical demand is ascertained, the correct size of the PV is determined. It is designed to provide sufficient daily energy to operate the residence when grid power is lost. Proper sizing of the array must account for loss mechanisms encountered in charging and discharging of batteries, array temperature and module mismatch losses, system wiring losses, inverter losses, and charge controller losses. Figure 6 exhibits the general loss mechanisms for worst-case scenarios. Using these loss factors, the worst-case dc:ac conversion efficiency is estimated using:

$$Efficiency\ Factor = (.88)x(.96)x(.94)x(.90)x(.96) = .7$$

The industry standard efficiency factor of .77 or 77% is generally used [2]. Because this is a battery backup system there are more losses attributed to the battery system, therefore an efficiency factor of .7 or 70% is used assuming worst-case scenario to size the system appropriately.

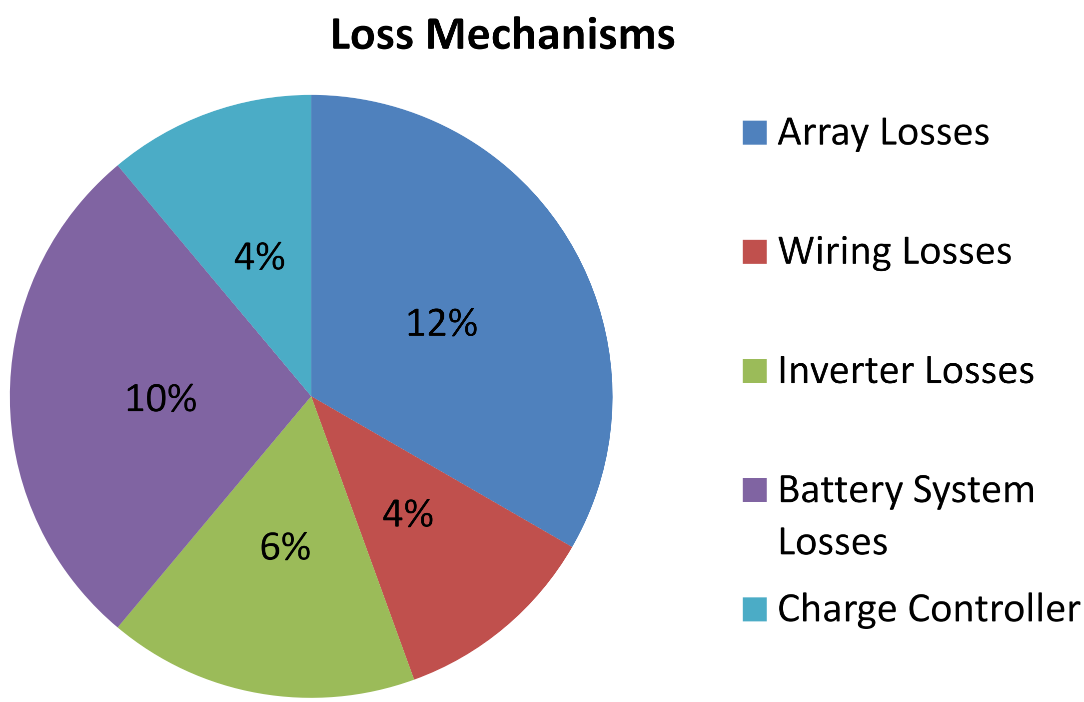


Figure 6: Worst-Case Loss Mechanism for a Grid-Tied Battery Backup PV System

Calculation Based on Energy Usage and Sun Hours

There are different methods applied when determining the yields of the diverse solar module types available. These include differing methods of calculations and photovoltaic software. Sizing programs and simulators enable the checking and simulating of threshold values and operating systems. For this project multiple approaches including hand calculations and simulation software are employed to utilize consistency and verify the appropriate system

size. Exercising one calculation method the daily energy requirements and peak sun-hours per day at the location are taken into account using:

$$Array\ Size = \left[\frac{daily\ energy\ requirement}{Sun\ hours\ per\ day}\right] x\ efficiency\ factor$$

$$Array\ Size = \left[\frac{28.4\ kWh/day}{5.36\ to\ 5.49\ hr/day}\right] x\ efficiency\ factor$$

Using data from the Solar Resource Map in Figure 10 the peak sun hours of 5.36 – 5.49 hr/day are input into the above equation. This results in an array size of 6.70 – 6.88 kW @ .77 efficiency factor and 7.37 – 7.56 kW @ .70 efficiency factor.

Software - PVWatts Version 1

Using PVWatts version 1simmulation software a city is selected closest to the project site (either Sacramento, CA or Fresno, CA) and site parameters such as azimuth, tilt, and efficiency factor are input into the program [11]. The array size is varied through trial and error until the desired daily kWh for the loads is produced. Figure 7 shows an example of the PVWatts GUI (Graphical User Interface). It is noted that the actual site location for this project receives slightly different solar irradiation than the two options provided in the software. Therefore the results are for an overestimation for the size.

PVWatts AC Energy & Cost Savings Cautions for Interpreting the Results

(Type comments here to appear on printout; maximum 1 row of 80

Station Identification	
City:	Fresno
State:	California
Latitude:	36.77° N
Longitude:	119.72° W
Elevation:	100 m
PV System Specifications	
DC Rating:	7.2 kW
DC to AC Derate Factor:	0.770
AC Rating:	5.5 kW
Array Type:	Fixed Tilt
Array Tilt:	22.6°
Array Azimuth:	166.0°
Energy Specifications	
Cost of Electricity:	12.5 ¢/kWh

Results			
Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
1	2.73	441	55.12
2	4.18	616	77.00
3	5.65	907	113.38
4	6.88	1055	131.88
5	7.51	1149	143.62
6	7.86	1130	141.25
7	7.97	1164	145.50
8	7.69	1120	140.00
9	6.75	975	121.88
10	5.61	863	107.88
11	3.93	613	76.62
12	2.48	407	50.88
Year	5.78	10440	1305.00

Figure 7: GUI of PVWatts Outputting Data for Fresno CA for a 7.2 kW System @ .77 Efficiency Factor, Fixed Tilt, 22.6° Array Tilt, 166° Azimuth, and Outputting 10440 kWh/yr [11].

Software – Wholesale Solar (Private)

Using private software from Wholesale Solar the monthly household energy usage is input into the calculator fallowed by
into the calculator fallowed by the percentage of generation to be provided by the PV system, and using the solar resource
and using the solar resource zone map provided the peak sun hours per day are entered into the calculator [12]. Inputting
the calculator [12]. Inputting the average monthly usage of 865 kWh from 2011, 100% generation, and 5.0-5.5 peak sun
generation, and 5.0-5.5 peak sun hours per day calculates a system of between 6.8 to 7.5 kW. Using this method of
Using this method of calculation generates a system before taking into account the efficiency factor and loss mechanisms.
factor and loss mechanisms. An example of the Wholesale Solar calculator is displayed in

Figure 8 with the solar resource zoning map.

Figure 8: GUI of Wholesale Solar calculating the system size without taking into account an efficiency factor; Monthly Usage of 865 kWh, 100% Solar Generation, and 5.5 Peak Sun Hours

Calculation Based on Available Roof Space

Sizing the system based on available roof space is the final method taken into account for determining an appropriate array size. Using roof measurements taken form Figure 13 in the next section (**SunEye Site Analysis: *Roof Measurements***) the square footage of the south facing roof and west facing roof are calculated and added together:

$$Roof\ Area = South\ Facing + West\ Facing$$
$$Roof\ Area = 545ft^2 + 198ft^2$$
$$Roof\ Area = 743ft^2$$

Using the industry standard conversion of $1\ kW \approx 10m^2 PV\ area$ [2] the system can be sized based on available roof space:

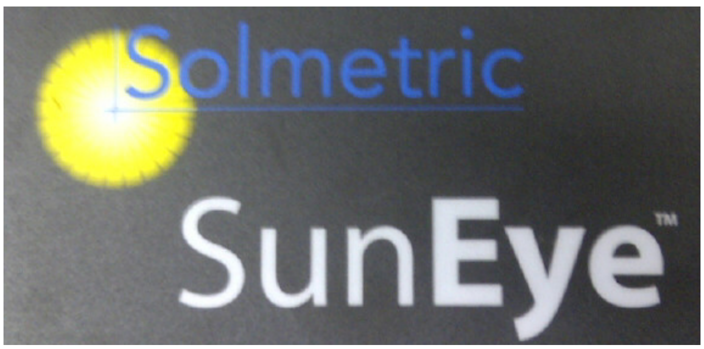
$$743ft^2 (\frac{1m}{3.28ft})^2 = 6.91m^2 \left(\frac{1kW}{10m^2}\right) = 6.91kW$$

Sizing Summary

Based on the multiple sources employed and worst-case dc:ac conversion a 7.1 kW system will be designed taking into account available roof space, location, sun hours (solar irradiation), and efficiency factors.

V. SunEye Site Analysis

Site analysis is a critical step in the design process of any photovoltaic project. The main issue to analyze and overcome is shading. Even small amounts of shade on a PV module can significantly reduce the module output. It is therefore imperative to gather appropriate data such as irradiance and irradiation measurements, solar access, sun path, and daylight hours. There are various tools and methods used for site analysis of a future PV system. For this project a comprehensive site analysis for a roof mounted system is completed using the Solometric SunEye 210 Shade Tool. The SunEye 210 Shad Toole observed in figure 9 is an integrated Shade Analysis Tool for solar site assessment. It includes a fisheye camera and a dedicated on-board processor to perform digital image processing and analysis to compute shading and solar access percentages. It includes an electronic compass and inclinometer enabled to measure roof pitch and azimuth [13].The SunEye 210 is obtained through the PG&E PEC Tool Lending Program [14].



(a)

(b)

Pacific Energy Center Tool Signout Form

Project: Grid-Tied with Battery Backup Resid
Address: 10541 Shawmut Rd
City: Chinese Camp
State: CA
Zip: 95309

Start Date: 5/14/2012
Intended Use:
This project aims to design a residential grid tied battery backup photovoltaic system that will provide up to 5.64kW in an area that gets 5.36-5.49

Accessories:
Suneye hard case, manual,AC adaptor, data cable, lens cap

Tools On This Loan:

BarCode	Tool	Type	Borrowed	Due
17832	SUNEYE.210	Suneye 210 with GPS	5/14/2012	5/24/2012

(c)

Figure 9:(a) (b) Solometric SunEye 210 Shade Tool. (c) Receipt for Tool Lending Program

Location

The residential site is located in Chinese Camp California at approximate coordinates of 37.9°N, 120.4°W with a magnetic declination of about 13.8°E. Using the appropriate GPS coordinates a US photovoltaic solar resource map observed in Figure 10is used to estimate the Irradiation. The map in Figure 10 displays the average annual solar irradiation with data taken continuously of a seven year period between 1998 – 2005 [1].

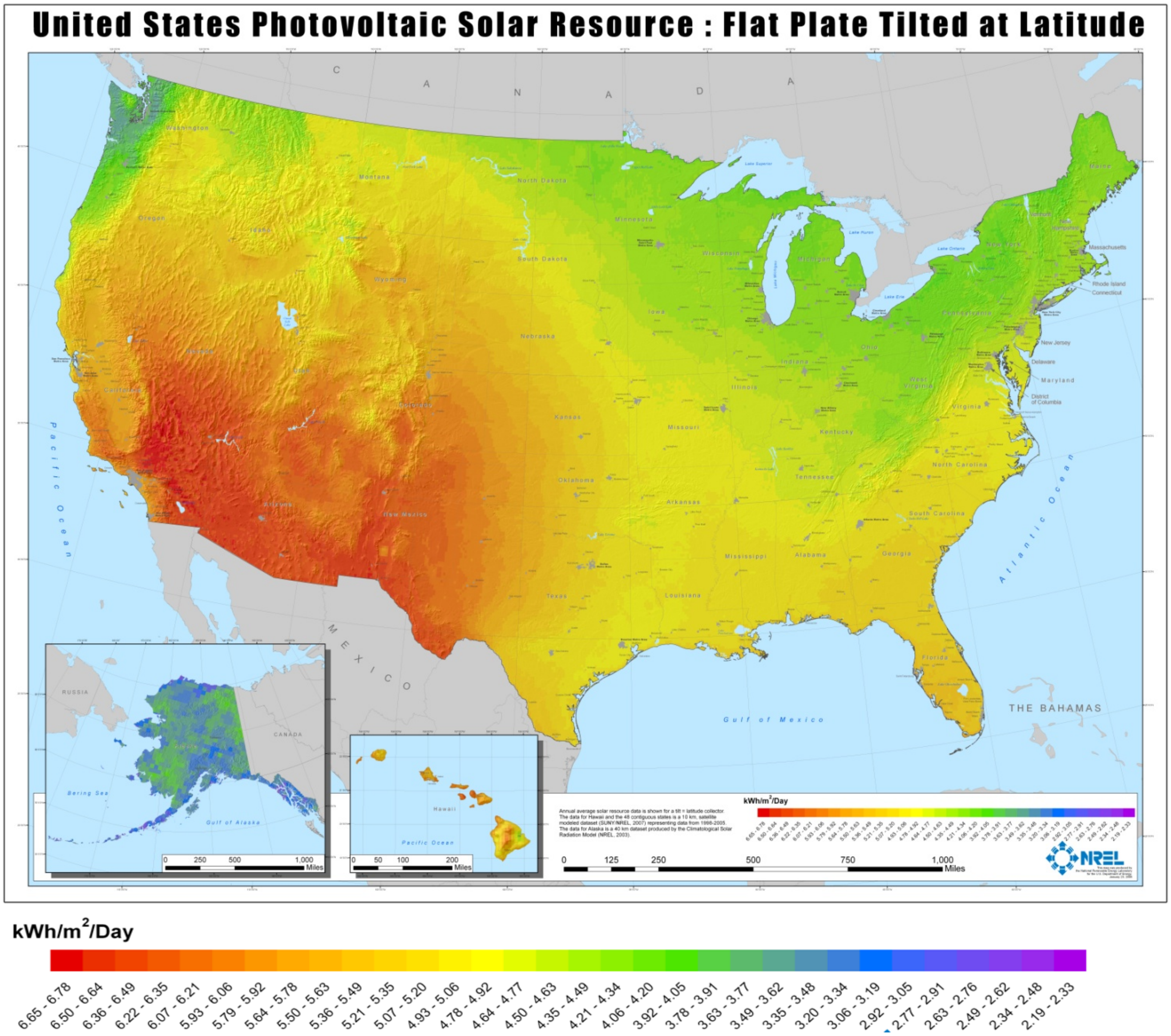


Figure 10: National Renewable Energy Laboratory (NREL) High Resolution PV Resource Map

Roof Measurement

Figure 11(a), (b), (c), and (d) show roof measurements being taken to accurately determine the available area for panels and irradiance calculations. Also recording measurements of skylight locations for later consideration of roof mounting issues. Figure 11 and Figure 13 display the floor plans of the residence and a sketch with the dimensions of the roof. The compass displays magnetic north showing the 13.8°E magnetic declination.

(a) (c)

(b) (d)

Figure 11: (a) Author and Homeowner using SunEye (b) Author and Homeowner (c) Measurement of top peak of south facing roof (d) Measurement of skylights on south facing roof

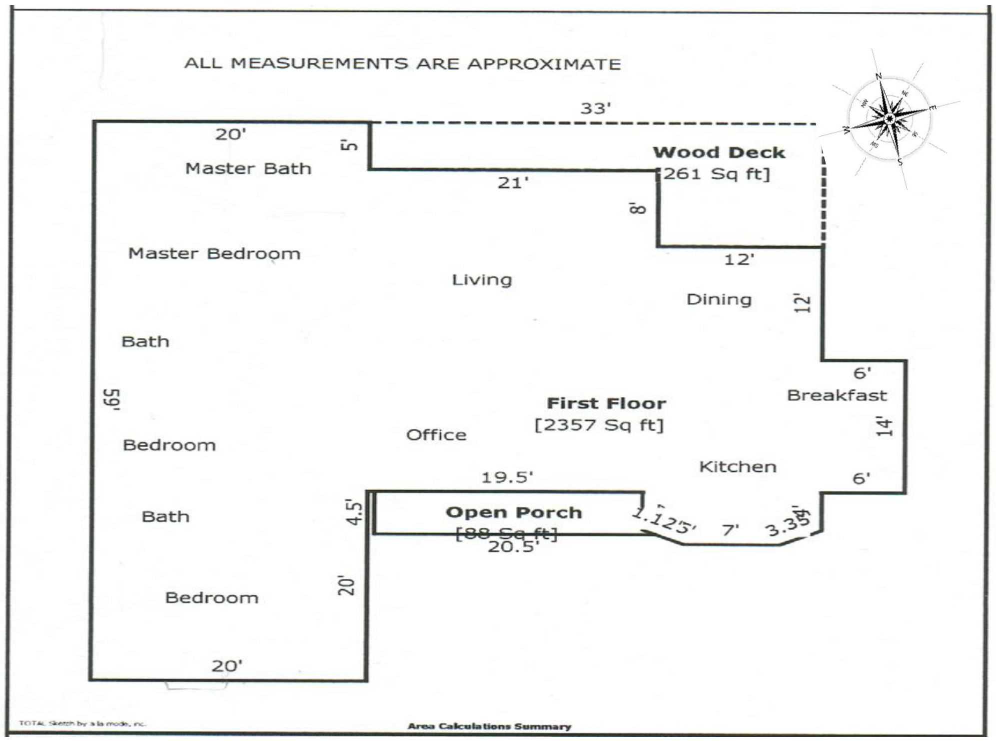


Figure 12: Floor Plan of the Household

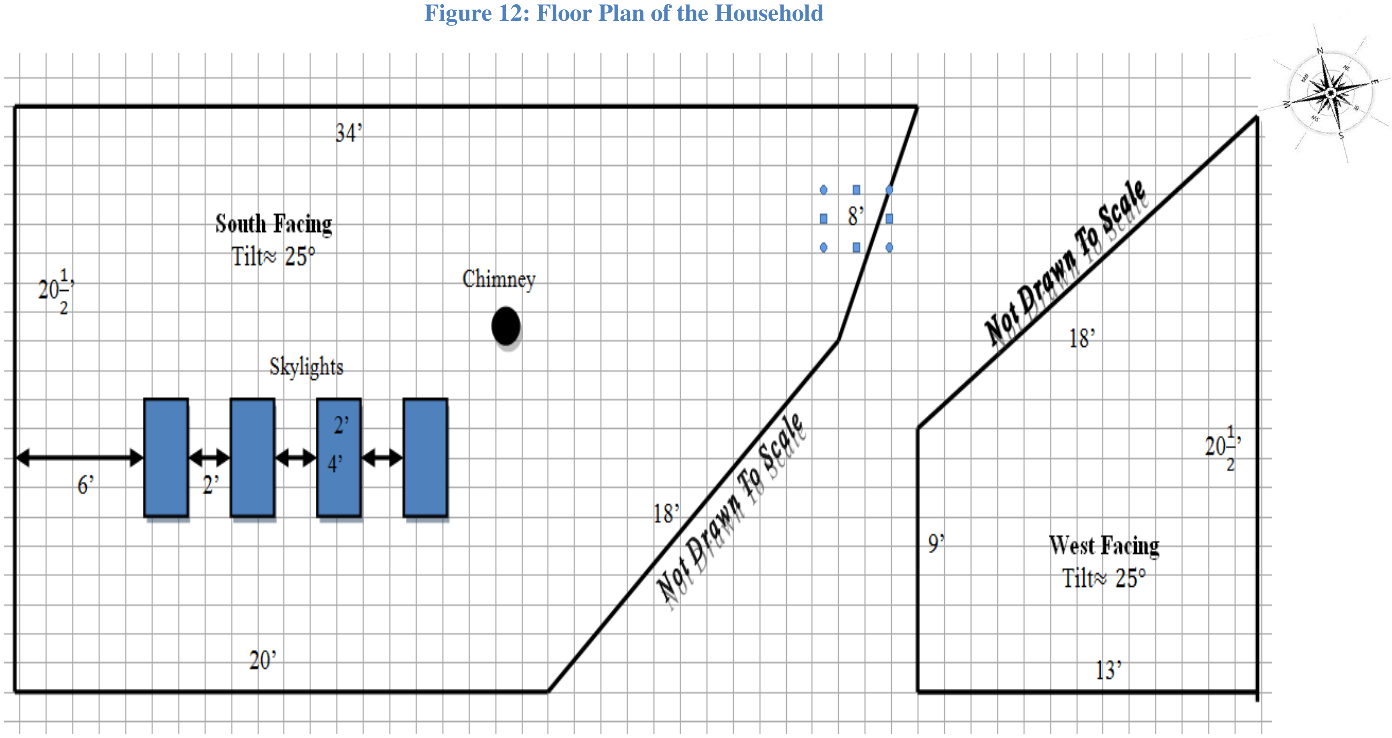


Figure 13:Diagram Showing Actual Measurements with Skylights and Chimney

Figure 14 presents a satellite image of the site using Google maps and showing the roof with the skylights and the chimney [15].

Figure 14: Satellite Image of Project Site

South Facing Roof

Using the SunEye 210 Shade Tool, 360° images of the skyline are captured at various locations on the roof to obtain accurate sky line images of assumed panel locations. The sun plots are overlaid to show the yearly sun path with any obstructions that potentially cause shading of panels. Figure 15Shows the summery of the site based on the four SunEye images captured at the four corners of the south facing roof. The chart shows the proportion of total solar energy available at this site for each month.This indicates that the site has acceptable to very good solar resource with minimal month to month variation for March through October. The acceptations are for November through January when the sun is at a lower angle in the sky. Shading issues are worse in winter because elevations angles are lower, shadows are longer, and the daylight hours are less.

Skylines Averaged: Sky01, Sky05, Sky06, Sky10

TSRF averages of 4 skylines in this session: 95% (*See Appendix C)*

Annual	May-Oct	Nov-Apr
96%	98%	92%

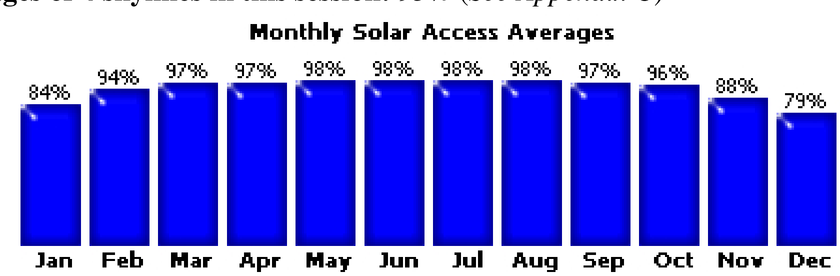
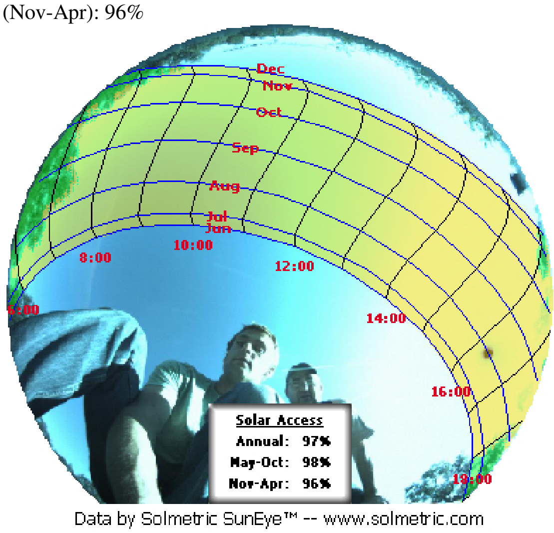


Figure 15: Solar access averages of 4 skylines in this session

Figure 17 (a), (b), (c), and (d) show skyline captures at the four corners of the south facing roof. Notice the obstructions caused by the trees in figure X (d) resulting in the low solar access for November through January. These obstacles cause little concern as the homeowner has expressed that the trees will be trimmed back so as to alleviate the shading issues. This will therefore improve the solar access throughout the winter months.

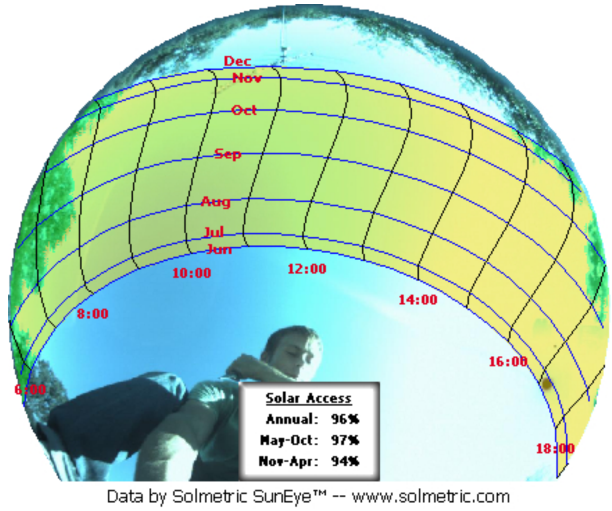
Panel Orientation: Tilt=25° -- Azimuth=166° -- **Skyline Heading=159°**
GPS Location: Latitude=37.86610°N -- Longitude=120.41447°W
Solar Access: Annual: 97% -- Summer (May-Oct): 98% -- Winter (Nov-Apr): 96%



TSRF: 97% -- **TOF:** 99%

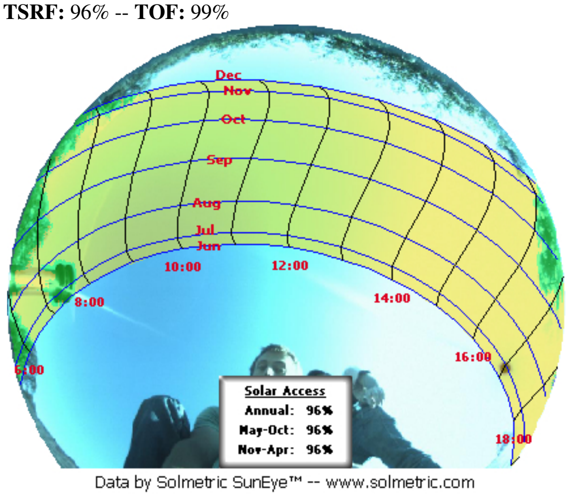
(a) Sky01 -- 5/19/2012 17:35 -- Top East Corner

Panel Orientation: Tilt=25° -- Azimuth=166° -- **Skyline Heading=173°**
GPS Location: Latitude=37.86604°N -- Longitude=120.41452°W
Solar Access: Annual: 96% -- Summer (May-Oct): 97% -- Winter (Nov-Apr): 94%
TSRF: 95% -- **TOF:** 99%



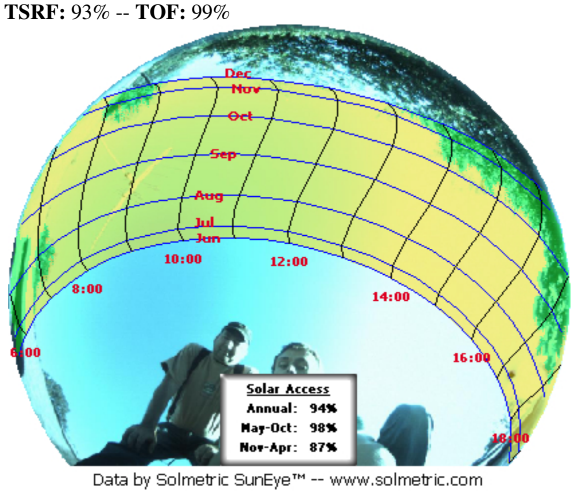
(c) Sky06 -- 5/19/2012 18:01 – Bottom East

Panel Orientation: Tilt=25° -- Azimuth=166° -- **Skyline Heading=171°**
GPS Location: Latitude=37.86608°N -- Longitude=120.41454°W
Solar Access: Annual: 96% -- Summer (May-Oct): 96% -- Winter (Nov-Apr): 96%
TSRF: 96% -- **TOF:** 99%



(b) Sky05 -- 5/19/2012 17:53 – Top West

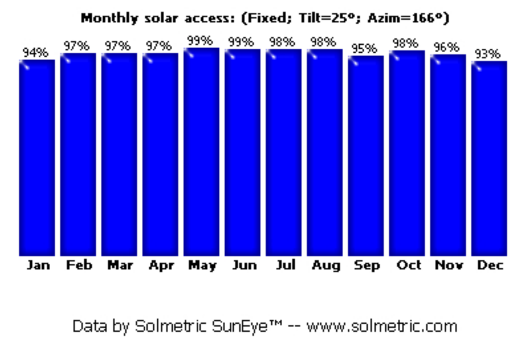
Panel Orientation: Tilt=25° -- Azimuth=166° -- **Skyline Heading=169°**
GPS Location: Latitude=37.86610°N -- Longitude=120.41452°W
Solar Access: Annual: 94% -- Summer (May-Oct): 98% -- Winter (Nov-Apr): 87%
TSRF: 93% -- **TOF:** 99%



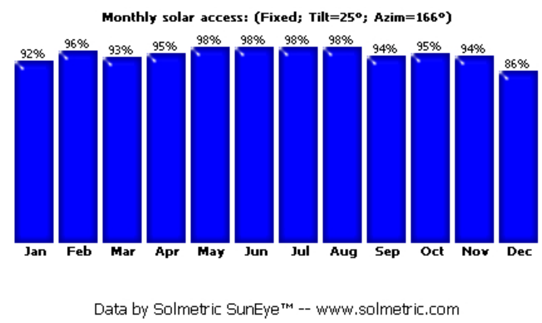
(d) Sky10 -- 5/19/2012 18:12 –Bottom West

Figure 16: Skyline Captures of South Facing Roof

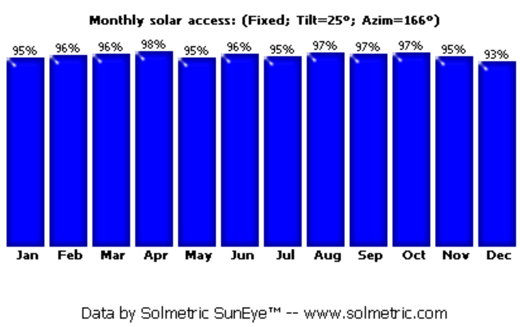
Figure 17 (a), (b), (c), and (d) show the monthly solar access for the four corners of the south facing roof. All values are above 90% indicating good solar access accept for Figure 17 (d) on the months of November through January for the bottom West corner of the roof. As stated above shading issues are worse in winter because elevation angles are lower, shadows are longer, and the daylight hours are less. These obstacles cause little concern as the homeowner has expressed that the trees will be trimmed back and the antenna will be removed so as to alleviate the shading issues. This will therefore improve the solar access throughout the winter months.



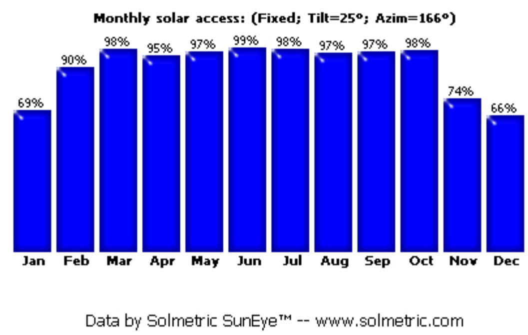
(a) Top East



(c) Bottom East



(b) Top West



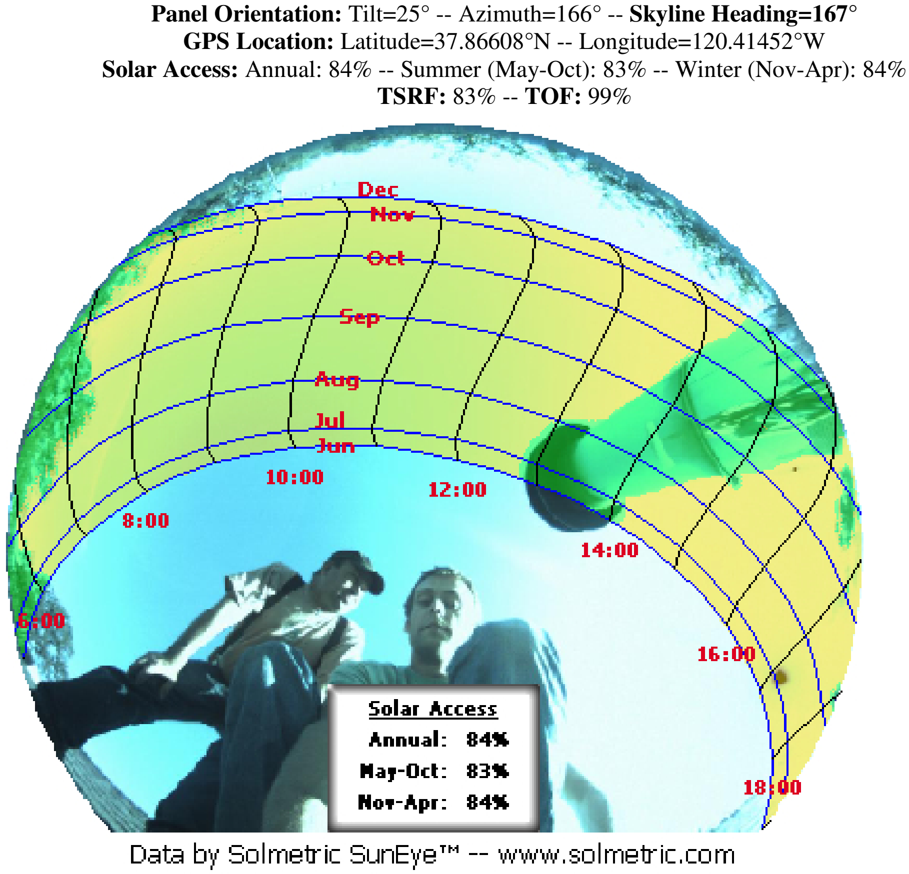
(d) Bottom West

Figure 17: Monthly Solar Access for the Four Corners of the South Facing Roof

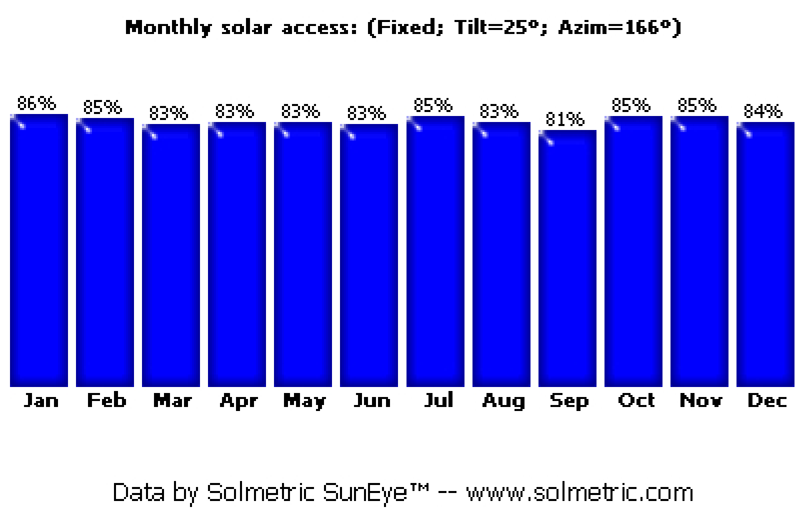
Chimney

A common challenge in PV system design is to fit as much power on the roof as possible. Odd roof shapes, shading, and roof protrusions all influence the placement of PV modules, which intern affect the power produced. For this project the south facing roof unfortunately has a chimney. The effects of the chimney on solar access are taken into consideration using the SunEye. Figure 18(a) shows the skyline capture of the area of the roof that will be affected by the chimney. Notice in the image the chimney will have the greatest impact for approximately two hours between 12:00 and 4:00PM depending on the months throughout the year. Figure 18(b) shows the monthly solar access of the area of the roof affected by the chimney. All values are between 80% to 86% showing the chimney will have a marginal affect on the solar access. To compensate, panels will be placed on the west facing roof

which will receive maximum sun exposure during the afternoon hours. This will help make up the loss acquired by the chimney.



(a) Sky08 -- 5/19/2012 18:07 -- chimney 1



(b) Monthly Solar Access for Area Affected by the Chimney

Figure 18: Skyline Capture and Monthly Solar Access for the Area Affected by the Chimney

West Facing Roof

To compensate for shading issues caused by the chimney, site analysis is again performed using the SunEye 210 Shade Tool on the West facing roof. As mentioned above, 360° images of the skyline are captured at various locations on the roof to obtain accurate sky line images of assumed panel locations. The sun plots are overlaid to show the yearly sun path with any obstructions that potentially cause shading of panels. Figure 19 below shows the summery of the west facing roof based on the three SunEye images captured on the west facing roof. This indicates that the site has acceptable to very good solar resource with minimal month to month variation for January through November. The only acceptation is December when the sun is at a lower angle in the sky.

Skylines Averaged: Sky02, Sky03, Sky04

TSRF averages of 3 skylines in this session: 95% (*See Appendix C)*

Annual	May-Oct	Nov-Apr
96%	97%	95%

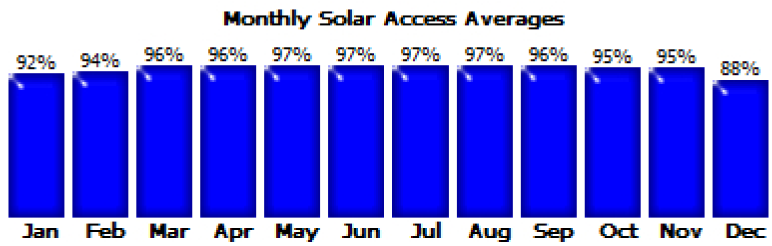
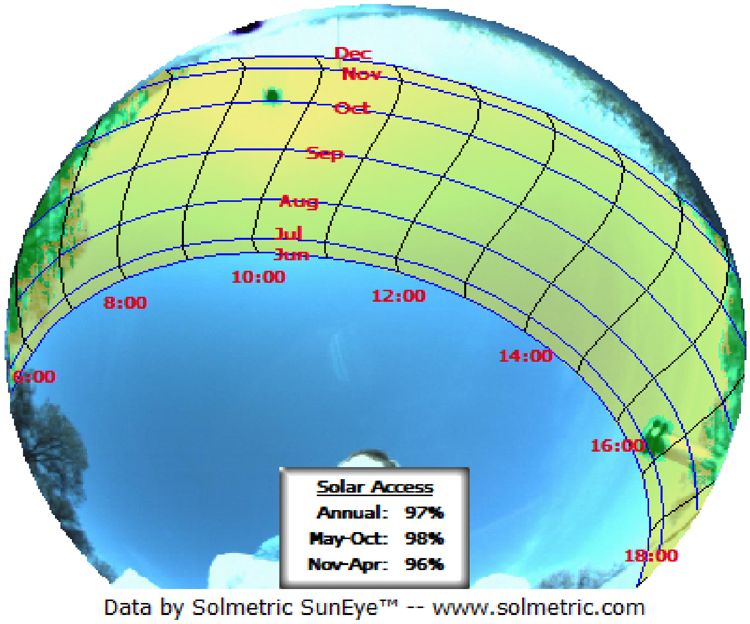


Figure 19: Solar access averages of 3 skylines for West Facing Roof

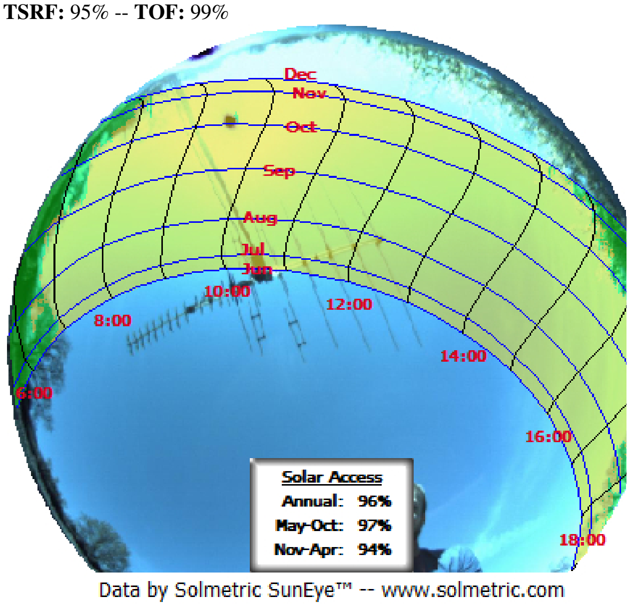
Figure 20(a), (b), and (c) show skyline captures at three locations on the west facing roof. Notice the chimney in Figure 20(a). Observing it only interferes after 3:30PM during the summer months results in a negligible effect on overall performance due to the high irradiance during this time of year. The antenna in Figure 20 (b) and (c) will be removed and will have no effect on performance. Also notice the roof shading effects and bathroom ventilation pipe in Figure 20(c) resulting in the low solar access throughout the year for the early morning hours. These obstacles cause little concern as the homeowner has expressed that the pipe height can be reduced or relocated all together. Also the shading effects of the roof only occur during the early morning hours when there is little energy demand and low irradiance due to the sun angle.

Panel Orientation: Tilt=25° -- Azimuth=166° -- **Skyline Heading=162°**
Solar Access: Annual: 97% -- Summer (May-Oct): 98% -- Winter (Nov-Apr): 96%
TSRF: 96% -- **TOF:** 99%



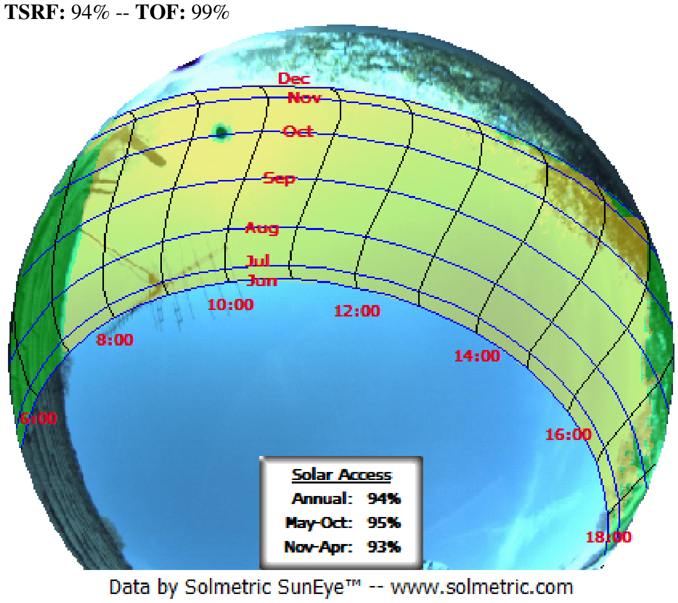
(a) Sky02 -- 11/4/2012 10:54 – Northern End of West Facing Peak

Panel Orientation: Tilt=25° -- Azimuth=166° -- **Skyline Heading=165°**
Solar Access: Annual: 96% -- Summer (May-Oct): 97% -- Winter (Nov-Apr): 94%
TSRF: 95% -- **TOF:** 99%



(b) Sky03 -- 11/4/2012 10:56 –Southern End of West Facing Peak

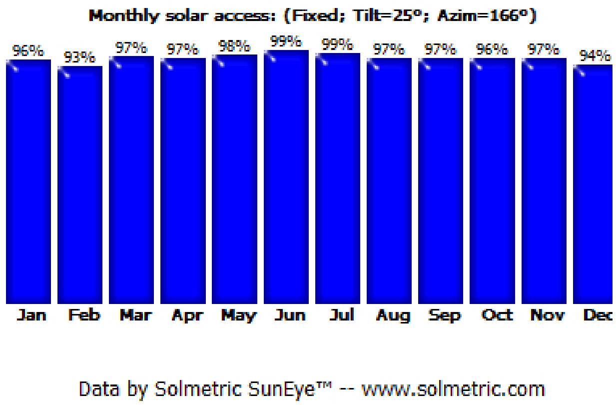
Panel Orientation: Tilt=25° -- Azimuth=166° -- **Skyline Heading=168°**
Solar Access: Annual: 94% -- Summer (May-Oct): 95% -- Winter (Nov-Apr): 93%
TSRF: 94% -- **TOF:** 99%



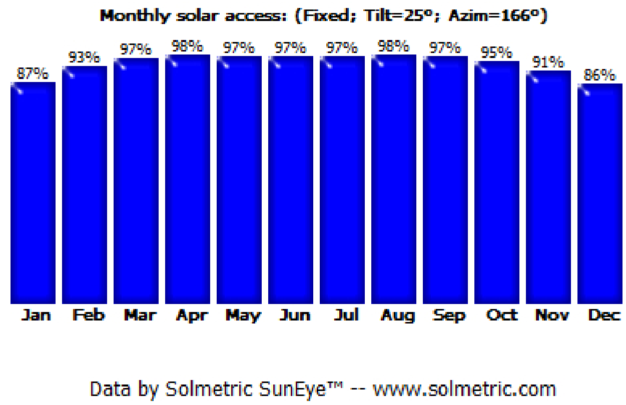
(c)Sky04 -- 11/4/2012 10:59 – Bottom of West Facing Roof

Figure 20: Skyline Captures of West Facing Roof

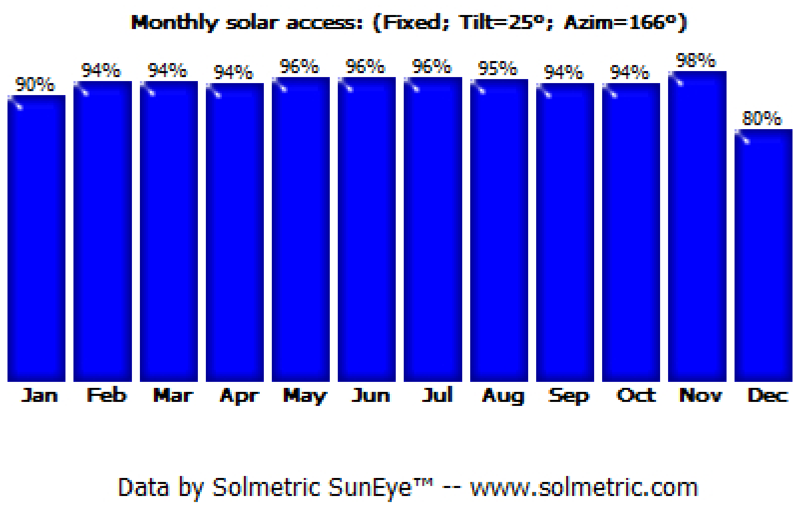
Figure 21(a), (b), and (c) show the monthly solar access for the three skyline captures of the west facing roof. All values are above 90% indicating good solar access accept for Figure 21(b) and (c) on the months of December through January. As stated above shading issues are worse in winter because elevation angles are lower, shadows are longer, and the daylight hours are less. These obstacles cause little concern as the homeowner has expressed that the trees will be trimmed back and the antenna will be removed so as to alleviate the shading issues. This will therefore improve the solar access throughout the winter months.



(a) Northern End of West Facing Peak



(b) Southern End of West Facing Peak



(c) Bottom of West Facing Roof

Figure 21: (a), (b), and (c): Monthly Solar access of the three points taken on the West Facing Roof

VI. Module Selection

Since a battery-backup grid-connected system essentially uses the utility grid to store/use any excess PV power generation, there is no reason to limit the size of the array to the exact size needed to keep the batteries charged. It is at the owner's digression on whether or not the array should be large enough to supplement 50% of the energy or 150% of the energy used. As stated previously this project is limited to the amount of roof space available and is sized accordingly. The type of module selected for this project will be able to meet the energy requirements to supplement 100% of the average energy needs for the household. Through extensive research the Solarworld Sunmodule SW255 Mono is selected providing 255W. The SW255 in Figure 22 consist of monocrystalline cells which offer 15%-18% efficiency, which is on the higher end for consumer photovoltaic panels [2]. These modules are compatible for "top-down" or "bottom-up" mounting methods which employ the rooftrack support rail and clamping system displayed in Figure 23. Refer to Appendix E for product specifications.

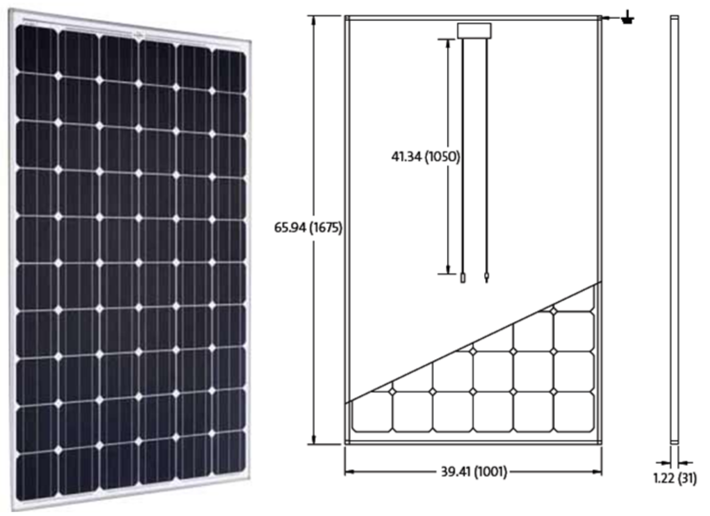


Figure 22: Solarsunworld Sunmodule SW255

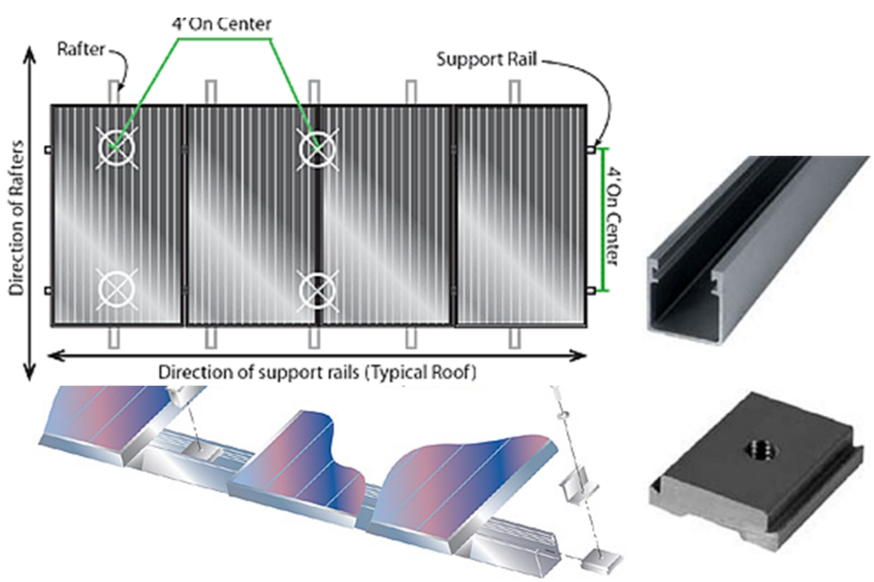


Figure 23: Rooftrack Support Rail and Clamping System for SW255 PV Module

In order to design the array and determine the number of strings the operating temperature range of the module must first be calculated to account for minimum and maximum array temperature. The module temperature can have an effect on the performance of the array and is inversely proportional to the module open circuit voltage (V_{OC}). The specifications needed are taken from Appendix E along with the minimum and maximum recorded temperatures for the site [16]. This data is input into the fallowing equations:

$$V_{OC}(max) = V_{OC}[1 + (T_{min} - 25℃)(\Delta V_{OC}/\Delta T)]$$
$$= 37.8V[1 + (-13℃ - 25℃)(-.3(\%/℃)) = 42.12V$$

$$Max\ Cell\ Temp = T_A + \frac{NOCT - 20}{.8}(G) = 45℃ + \frac{46℃ - 20}{.8}(1) = 77.5℃$$

NOTC ≡ Nominal Operating Cell Temperature
T_A ≡ Maximum Temperature for Site Location
G ≡1kW/m^2 @ Full Sun. Corresponds to Air Mass (AM) rating of 1. AM rating ranges from 1kW/m^2 at sea level to 1367 kW/m^2 at the top of the atmosphere

$$V_{mp}(min) = V_{mp}[1 + (T_{max} - 25℃)(\Delta V_{OC}/\Delta T)]$$
$$= 31.4V[1 + (77.5℃ - 25℃)(-.45(\%/℃)) = 23.89V$$

Taking the system size and dividing it by the module's wattage gives the total number of panels needed:

$$\#\ of Panles = \frac{System\ Size}{Module\ Wattage} = \frac{7.1kW}{255W} = 27.84\ panels$$

Rounding up gives a total of 28 panels providing 7.14kW, which meets the requirements calculated in the previous section. All components and modules are certified to the safety and design requirements of UL-1741 and IEEE 1547 standards [12].

VII. Charge Controller

In nearly all systems with battery backup a charge controller is an essential component. The main responsibility of a charge controller is to regulate the charging state of the batteries and shut down the PV array when the batteries are fully charged. It also must shut down the load if the batteries reach a predetermined state of discharge. Since the PV array is not always operating at the maximum power point (MPP) a maximum power point tracking (MPPT) charge controller is employed. The energy losses associated with series and shunt charge controllers are between 10%-40% depending on battery voltage, irradiance, and temperature. These are avoided by using an MPPT tracker. The MPPT tracker passes along the current/voltage characteristic curve of the PV array about every 5 min and determines the MPP. The DC/DC converter within the MPPT tracker is set to take the optimum power from the array and adjust it to the charging voltage of the batteries [2]. Since the battery system is a 48V system the available current is approximately:

Figure 24: XW-MPPT 80-600 Charge Controller

$$\frac{7100W}{48V} = 147.92A \approx 150A$$

This suggests that two 80A MPPT charge controllers be used. For this system the Schneider Electronic Xantrex XW-MPPT 80-600 Charge Controller in Figure 24 is used . This MPPT charge controller is selected because it can accept DC input voltages of up to 600V, which allows for longer strings of modules simplifying the design and BOS components. For example, using the Solarworld SW255 module:

$$V_{OC} < 600V \therefore \frac{600V}{42.12} = 14.25\, modules$$

Rounding down gives a maximum of 14 modules in a string. Based on the calculations with the Solarworld modules, 2 strings of 14 modules are used equaling the 28 modules. Based on the $V_{mp}(min)$in the previous section:

$$V_{mp}(min) = 14 * (23.98V) = 335.72V$$

This falls within the acceptable operating range of the XW-MPPT 80-600 indicating that on the hottest day on record the minimum voltage for the array with a string of 14 Solarworld SW255 modules is 335.72V, well above the minimum operating voltage of 195V of the XW-MPPT charge controller, See Appendix F. Since there is two source circuits the system is nicely balanced feeding one source circuit to each MPPT charge controller. Below displays a simple example of the PV array wired into the charge controller Figure 25 with two source circuits similar to this design. The XW-MPPT 80-600 meets all safety and design requirements of UL-1741 and IEEE 1547 standards.

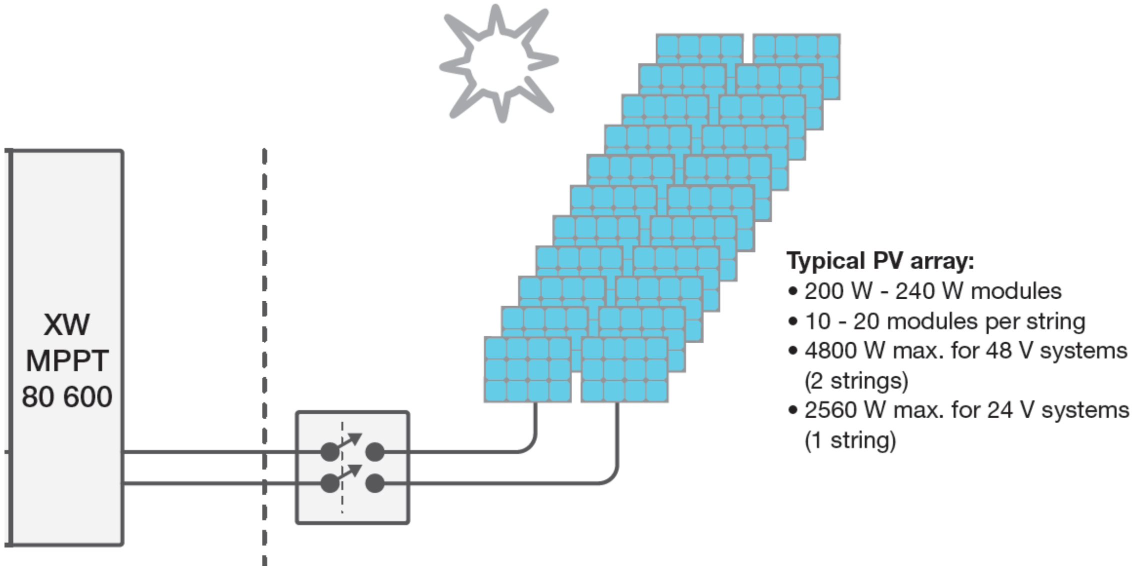


Figure 25: Example of Two String Array Connected to XW- MPPT 80-600 Charge Controller

VIII. Inverter

Depending on which system is being designed there are a number of different types of inverters available. Selection of the proper inverter for a particular application depends on the waveform requirements of the load. In addition, all inverters must comply with safety standards and electrical codes of UL 1741 and IEEE 1547. The inverter will serve as a multipurpose device supplying power to the gird as a current source that continuously monitors the gird and acts as an alternate means of charging the system batteries in the event that the PV system for any reason has not kept them charged. Finally it acts as a stand –alone voltage source to powering the occupancy while the utility is not available [2]. For this system two Xantrex XW 4548 Grid-tie/Off-Grid Solar Inverters are "stacked" to provide 7100W of 120/240V power; Figure 26. Appendix G gives detailed product specification. The XW4548 is a hybrid inverter/charger, single phase, 60Hz true sign wave inverter. It supplies 4500W (up to 9000W with two, which meet the minimum system requirement of 7100W) of continuous power with an operating range of 44-64V accepting the 48V from the battery system. This inverter is selected because it meets the specifications and size of the system while also integrating well with the XW MPPT charge controller. Selecting components from the same company allows for smoother integration and implementation along with less complicated maintenance in the future. Figure 27 below displays a simple example of the PV array and MPPT charge controller wired into the inverter with two source circuits similar to this design.

Figure 26: XW4548 Inverter

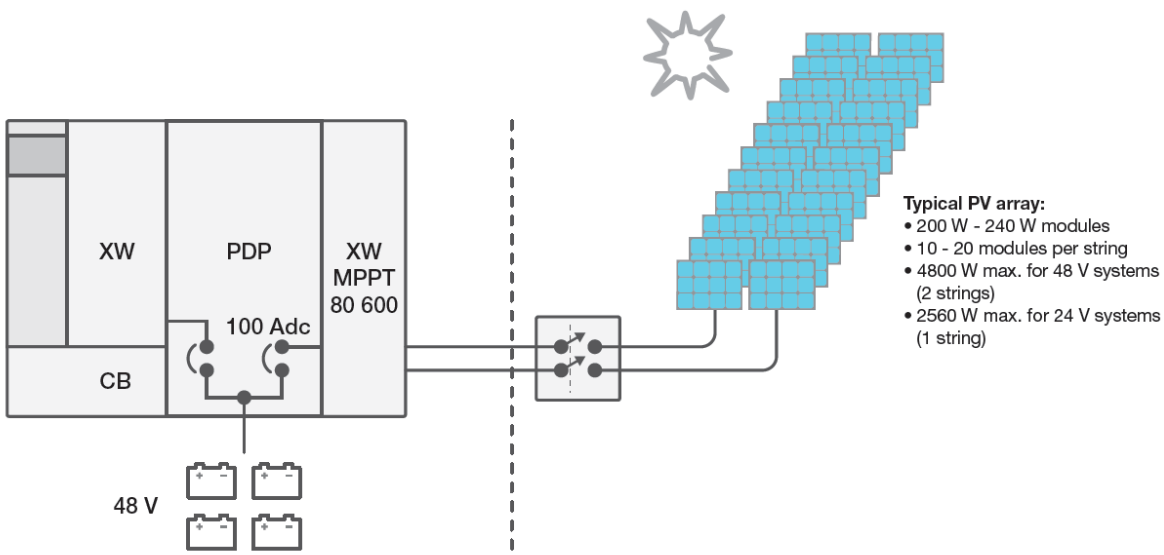


Figure 27: Inverter Wired into MPPT Charge Controller and Array

IX. Battery System

The sizing of batteries will depend on the daily kWh consumption of the loads and how many days of storage or autonomy are desired. The other deciding factor is financial cost as the batteries are often the most expensive components. For this system a flooded lead-acid battery will be utilized as they are the most common and cheapest battery to manufacture while still meeting the minimum requirements. A typical lead-acid battery will offer approximately 400 cycles at a 50% discharge rate in its lifetime [2]. Batteries in a grid-tied system will rarely cycle (usually no more than 10 times per year [10]) and require far less maintenance. To begin, the total energy is divided by the inverter efficiency, which is obtained from Appendix H:

$$DC\,\frac{Wh}{Day} = \frac{Total\ Wh/Day}{Inverter\ Efficiency} = \frac{28.4kWh/day}{.95} = 29894.74\ DC\ Wh/Day$$
$$\approx 29900\ DC\ Wh/Day$$

Then divide by the battery system voltage to obtain DC Ah/Day:

$$DC\,\frac{Ah}{Day} = \frac{DC\ Wh/Day}{Battery\ Voltage} = \frac{29.9kWh/day}{48V} = 622.9DC\ Ah/Day$$

Then multiply by 1.25 to assume 80% discharge:

$$DC\ Total\,\frac{Ah}{Day} = 622.9DC\ Ah/Day * 1.25 = 778.6\ DC\ Total\ Ah/Day$$

Then multiply by the number of days of desired autonomy. For this system and site the desired days of autonomy are 2. This means that in the event of grid failure and no source for recharging from the grid or PV array, the batteries should maintain system operation providing power to the loads for a minimum of 48 hours assuming a 20h discharge rate. Therefore the size of the batter system is:

$$778.6\ \ Ah/Day * (2days) = 1557.3Ah$$

1557.3Ah is therefore the minimum size battery needed. Once suitable batteries have been researched, dividing the battery size (1557.3Ah) by the Ah capacity rating of the chosen battery will give the number of parallel battery strings needed. Table 10 below displays a sample of suitable batteries obtained

Table 10: Data for Suitable Batteries Obtained for 48V, 1557Ah System

Data for 48V, 1557Ah Battery System							
Battery	**Volts**	**Multiplier (48V)**	**Ah Rating**	**# of Strings**	**Total Ah**	**Price ($)**	**Total ($)**
Surrette L/A	2	x24	1766	1	1766	836.36	20064
Surrette L/A	6	x8	820	2	1640	1261	20176
Trojan	6	x8	897	2	1794	1228	19648
Surrette L/A	8	x6	820	2	1640	1595.47	19140
Trojan	4	x12	1570	1	1570	1410	16920
Surrette L/A	6	x8	400	4	1600	---	11556

When decided the number of parallel battery strings other factors outside of cost also come into play. Since batteries age and deteriorate at different rates one or more individual batteries in a string will have a lower capacity compared to the other batteries in the string. When the batteries are called to supply power the string with the reduced capacity battery will provide a lower output voltage compared to the other parallel strings. These imbalances in charging current between batteries are overcharged in the attempt to fully charge all batteries resulting in possible damage to the system [17]. Because of the sensitivity and tolerances required in PV systems for charging/discharging it is recommended that the fewest number of parallel battery strings be used when possible for PV systems. Taking this into consideration the Trojan IND29-4V Flooded Lead-Acid Battery (Appendix H) highlighted in green in Table 10 will be used in the design of the battery system since it offers a 4V battery at 1570Ah. Therefore only one string of 12 batteries is required to meet the 48V, 1557Ah requirement of the system. Figure 28 Shows an example of the battery system wired up in one series string:

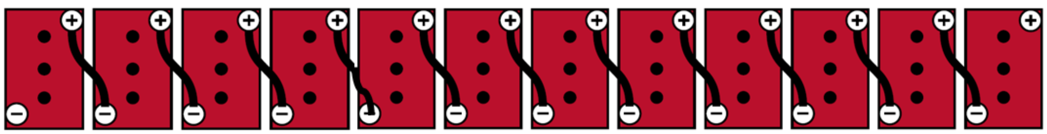


Figure 28: Schematic of 48V, 1557Ah Battery System

X. BOS Selection and Completion of Design

Figure 29Display the schematic for the wiring of DC portion of a 7100W battery backup system. Figure 30Displays the AC wiring diagram of the schematic for the completed system with the inverters being the components couple the two schematics together.

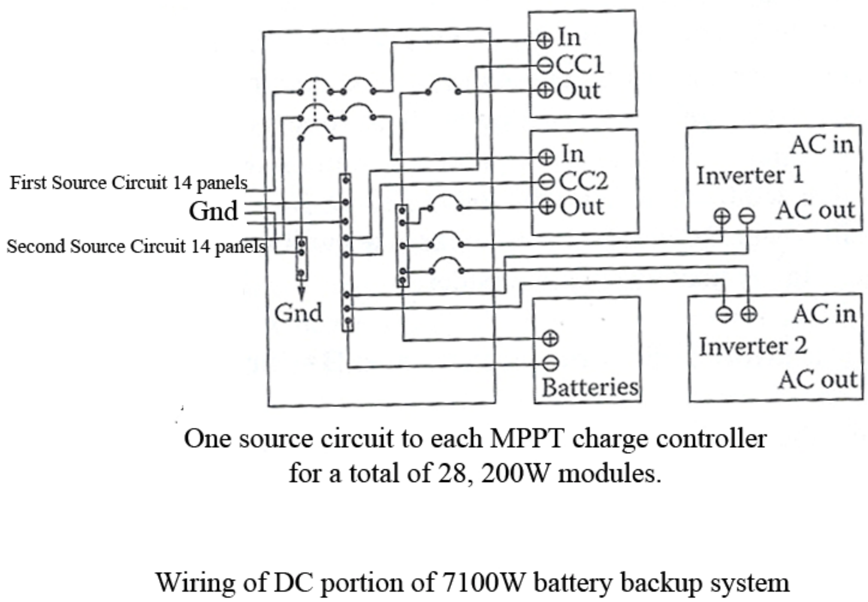


Figure 29: Wiring of DC Portion of 7100W Battery Backup System

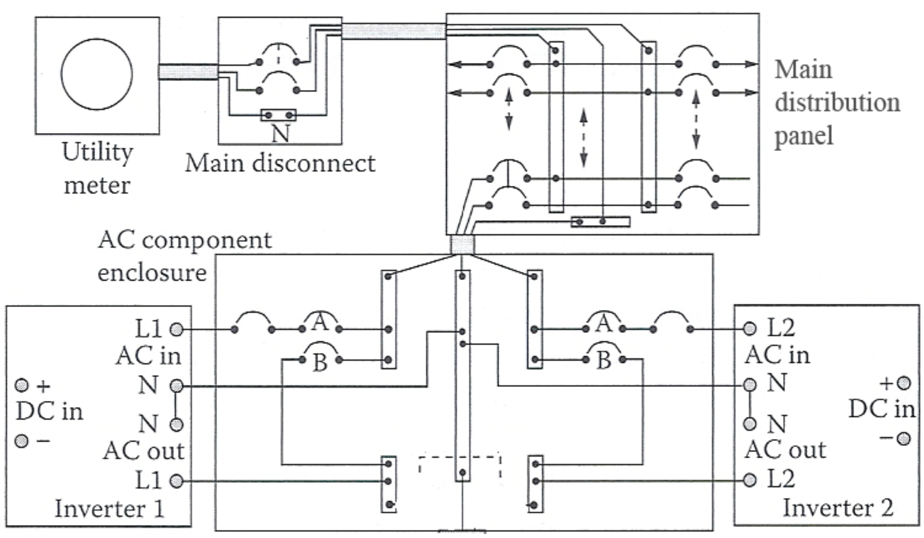


Figure 30: Wiring of AC Portion of 7100W Battery Backup System

Balance of System (BOS) components describe all other components aside from the major components of a PV system, that is, PV modules, charge controller, batteries, and inverters. BOS components may include extension cables for array wiring, a rooftop junction box, input and output disconnects for the inverters and charge controllers, battery cables, battery

enclosure, inverter input and output disconnects, circuit breakers, the equipment for connecting to the utility, and all conduit and wire for the system. As mentioned before with the inverter, designing a system with components produced from the same company has many added benefits. Another one of these benefits is that many of the BOS components come with the purchase of other key system components such as the inverter and charge controller. Since the Xantrex line of inverter and charge controller are designed for this system they also come with a Power Distribution Panel, Conduit Box, System Control Panel, and Connection Kit for the second inverter all shown in Figure 31

Figure 31: BOS Components Included with Xantrex Inverter

BOS components are numerous other smaller/less expensive components used to complete the implementation of a system and go beyond the scope of this project.

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APPENDIX A — Schedule and Time Estimates

Figure 32on the below represents a hierarchical breakdown of the tasks and deliverables that need to be completed to accomplish the project objectives. It is displayed as bar graph representation of activities and project goals effectively showing the work breakdown structure and the timeline for completion. A rough estimate of the timeline breakdown is calculated using the PERT technique represented by equation 2 below [18].

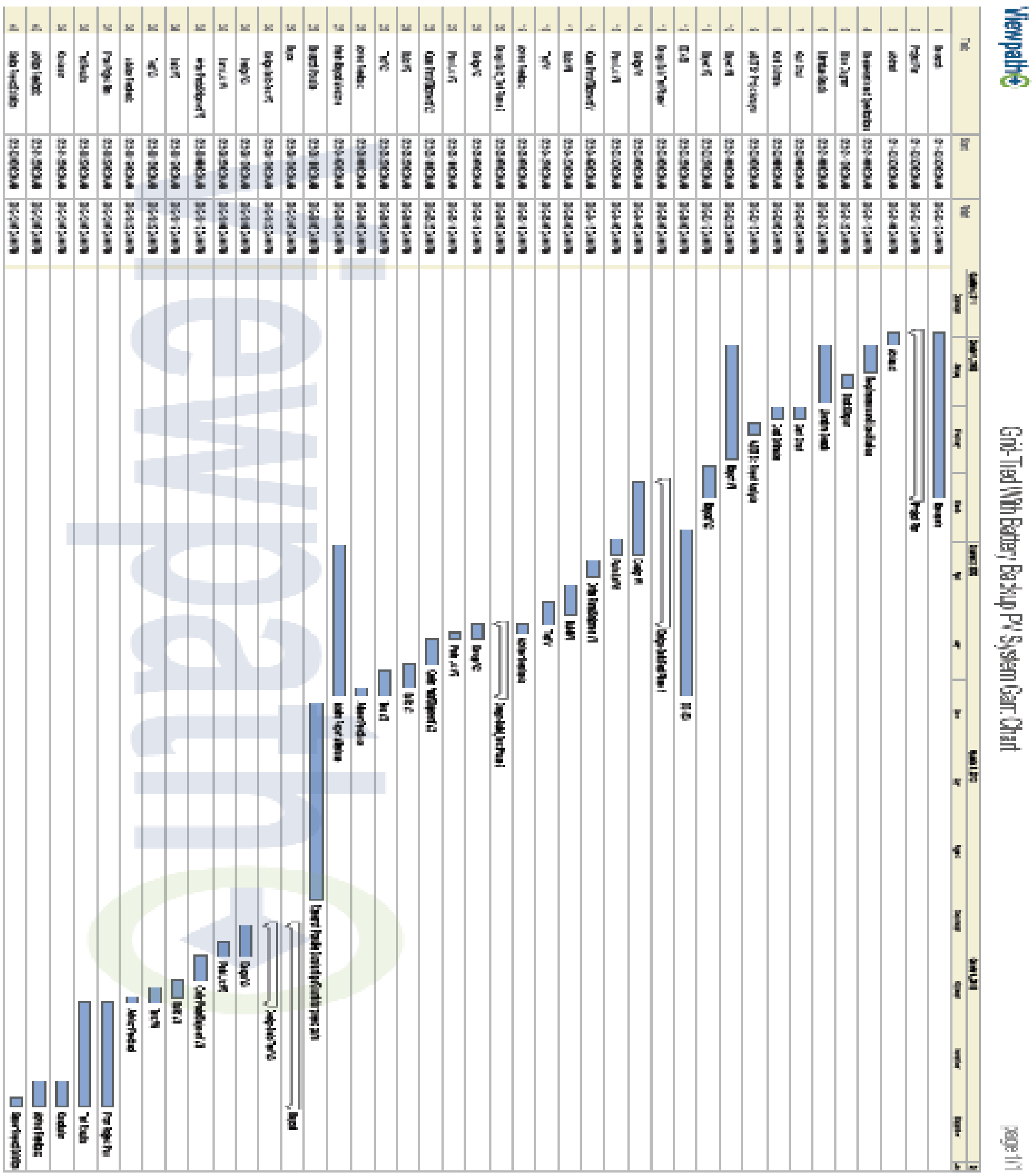


Figure 32: Gantt chart showing breakdown of the tasks and deliverables in the project timeline using the PERT technique to derive expected time estimates

APPENDIX B — Financial Cost Analysis

Table 11 is a preliminary summary of cost estimates. It discusses estimated costs associated with the design, development, and implemention of the PV system. A grid-tied with battery backup PV system includes both fixed costs and variable costs. Fixed costs are those that are constant and do not change due to a process or activity. These include design and development, market research, and permits. Variable costs depend upon the process and fluctuate directgly with the number of units produced. Examples include materials, inventory, labor, and shipping. The cost estimates in table IX were calculated using equation 1 below.

Table 11: Cost Estimates

Expenses	Price Estimate (U.S. Dollar)	Actual Price (U.S. Dollars)[i]	Justification for Estimates
PV Array	$12,223.00		**$cost_a$** →25.7 ≈ 26 panels @ $360.00/panel = $ 9360.00 **$cost_m$** →33.3 ≈ 34 panels @ $350.00/panel = $11900.00 **$cost_b$** → 25.5 ≈ 26 panels @ $630.00/panel = $16380.00 Estimates obtained from various parts pricing for PV panels. The number of panels is a rough calculation based on the available square footage to produce ≈ 5.64kW of power and the power output rating of the individual panels, which varies from brand to brand [6].
MPPT Charge Controller	$920.95		**$cost_a$** →Outback 80 Amp 12/24/48/60 Volt MPPT Charge Controller @ $591.95 **$cost_m$** →2x MorningStar Tristar 45 Amp 12/24/48 Volt MPPT Charge Controller @ $ $471.94 ea. **$cost_b$** → Xantrex XW 80 Amp 12-60 Volt MPPT Charge Controller @ $1158.95 Estimates obtained from various parts pricing for charge controllers [19], [20].
Inverter	$2308.22		**$cost_a$** → SolarEdge Tech SE 6000 (240V) @ $1813.95 **$cost_m$** → Schneider TX 5000 (240V) @ $2291.00 **$cost_b$** → Power One PVI-6000 (240V) @ $2871.36 Pricing of Inverters that meet the required DC power output of the PV and Battery Systems. Also grid-tied capabilities [20], [21], [22], [23].
Battery System	$31538.00		**$cost_a$** → The Rolls Surrette S600 6V at 600 Ahr ≈ 30 @ $467.00 ea. **$cost_m$** → The Rolls Surrette 8CS25PS 8V at 1156 Ahr ≈ 18 @ $1699.00 ea. **$cost_b$** → **The** Rolls Surrette 6CS21PS 6V at 963 Ahr ≈32 @ $1130.00 ea. These are based on rough calculations for battery system [24]
Misc. Parts (Wire, Mounting Supplies, Nuts, Bolts, shipping, ect…)	$1250.00		**$cost_a$** → $500.00 **$cost_m$** →$1000.00 **$cost_b$** →$2000.00 These are just preliminary estimates. More precise numbers will be provided as the design process continues [2].
			$cost_a$ →$24840.00/yr = $12.42/hr @ 150hrs = $1863.00

Labor	$4119.00		**$cost_m$** →$53107.00/yr = $26.55/hr @ 150hrs = $3983.00 **$cost_b$** →$83320.00/yr = $41.66/hr @ 150hrs = $6294.00 Time estimated using eq. 2. Salary estimates based on national salary data for a solar energy/solar engineer [25].

[i] Actual Price to be filled in at purchase which will likely be after Senior Project Completion.

$$\text{Cost} = \frac{cost_a + 4cost_m + cost_b}{6}$$

$cost_a$ = the most optimistic estimate
$cost_m$ = the most realistic estimate
$cost_b$ = the most pessimistic estimate

$$\text{Time} = \frac{time_a + 4time_m + time_b}{6}$$

$time_a$ = the most optimistic estimate
$time_m$ = the most realistic estimate
$time_b$ = the most pessimistic estimate

APPENDIX C — Solar Resource Terms

Tilt and Orientation Factor (TOF): TOF is the solar irradiation (Wh/m^2) at the actual tilt and orientation divided by the irradiation at the optimum tilt and orientation, expressed in percent [26].

Total Solar Resource Fraction (TSRF): TSRF is the ratio of irradiation (Wh/m^2) available accounting for both shading and TOF, compared to the total irradiation available at a given location at the optimum tilt and orientation and with no shading. TSRF is also expressed in percent, according to the following equation: TSRF = (Solar Access) *(TOF) [26].

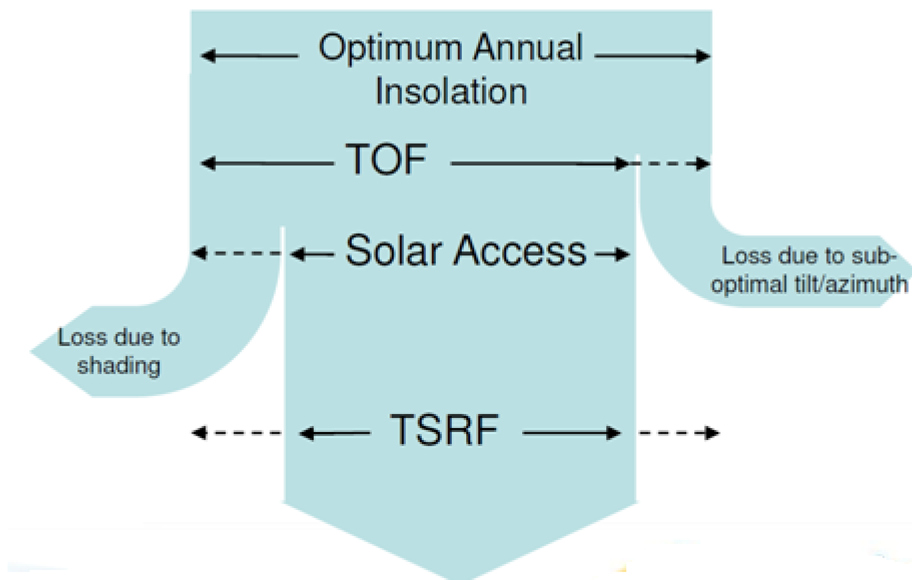


Figure 33: Displays the definition of the TOF and TSRF ratios discussed in above.

APPENDIX D — ANALYSIS OF SENIOR PROJECT DESIGN

Grid-Tied with Battery Backup Photovoltaic System

Thomas Stobaugh:

Ahmad Nafisi: Date:

• Summary of Functional Requirements

This project aims to design a residential grid tied battery backup photovoltaic system that will provide up to 5.64kW converting sunlight into DC power, then into 240V AC rms at 60Hz in an area that gets 5.36-5.49 kWh/m2/day to support a home with an average daily usage of 28.1 kWh/day [1]. To effectively use this system the house remains connected to the electric utility at all times, so that any power needed above what the solar system can produce is simply drawn from the utility. The system also includes battery backup or uninterruptible power supply (UPS) capability to operate selected circuits in the residence supplying 48V at 861Ah/day (taking into account losses) for up to 3 days during a utility outage [10]. The system supplies 13.6-14.2V DC to charge the batteries, varying the voltage depending on the state of charge of each battery. It is automated to disconnect from the grid when there is a utility outage, and reconnect to the grid when the utility power is restored to provide a safety measure to line workers repairing utility lines during a utility outage. Designing a grid tied photovoltaic system reduces dependence and provide a cost effective safety net against losing necessary power for refrigerated food storage, water facilitation, crops, and livestock.

• Primary Constraints

With every project comes challenges and difficulties associated with implementation. This project will undoubtedly encounter many issues and overcome several constraints. Many of these include financial, logistical, and design and will occur throughout the various stages. One constraint is limited square footage of roof space for the PV array. The general output for the average PV panel produces $100ft^2/k$ [6]. The array must produce at least 5.64 kW [5]; therefore the PV array must be $\geq 550\ ft^2$ requiring enough roof space to safely install the panels and produce the desired energy output. If there is not enough space extra design steps must be taken for mounting the PV array. One obvious issue associated with implementation of this project is financial cost to the client. As observed from preliminary cost estimates the PV array and the battery system are proven to be the most costly. Other challenges to consider are distance to the project site and applying for the appropriate building permits. The house for which the system is designed is a 4-5 hour commute; also in order to implement the project, building permits must be obtained.

• Economic

This project contains numerous economic capital impacts relating to human, financial, manufacturing, and natural. The human capital takes into account what people do and involves the design and build phases of the project. Beyond this there is little human capital. The system is mostly autonomous and only requires periodic maintenance and repair. The financial capitol involves the monetary instruments. This includes U.S. currency in the form of cash, coins, and credit cards. The manufactured, real capital relates to the things made by people and their tools. This includes all of the parts and materials (PV panels,

charge controller, inverter, batteries, wiring, utility, design software, permits, etc…) along with tools used to manufacture, design, and build the system. The natural capital involves the Earth's resources and bio-capacity. This project greatly impacts the natural capital by reducing the dependence on utility supplied power. It produces the energy required without any direct negative impacts on the environment. The possible negative impacts on the natural capital result from the resources required to manufacture the parts (PV panels, electronics for the inverter, and charge controller, batteries, etc). Other economic factors that relate this project include the cost and benefits. These occur throughout the duration and at many stages in the project. For example, during the beginning stages the initial costs incurred mainly include time spent researching and designing. During this time the benefits include the knowledge gained both in meeting the project goals and in the knowledge gained in the overall subject matter. The most obvious costs include the monetary capitol in the purchasing of the equipment, parts, tools and labor. Provided the client accepts the final design he/she covers the financial costs of the project, which from preliminary estimates may be as high as $55,000. The arguable benefits resulting from this include a functional completed PV system that meets the energy needs of the residence reducing or eliminating dependence on the electric utility that in the long run will begin to generate revenue; also providing a cost effective safety net against losing necessary power for refrigerated food storage, water facilitation, crops, and livestock.

• If manufactured on a commercial basis:
If the resulting system of this project were to be manufactured on a commercial basis many factors would need to be considered such as number of systems sold per year, cost per system, purchase price per system, profit per year, and estimated cost to operate device for the duration of its desired life cycle. The most difficult thing facing these questions is the fact that each system is circumstantial and there are no two PV systems exactly the same. Therefore there is no way of considering these questions without first determining the size of the system. The size of the system directly affects the number of systems sold per year, the manufacturing cost of each system, the price, and the profit. The size of each system directly relates to each client's requirements, which no two will be exactly the same. Therefore there is no assembly line approach for this project. For example one large system could take the entire year depending on its size while in the same time frame 20 small systems could be produced. To better analyze manufacturing on a commercial basis, one must consider the average or typical system size of a PV system at approximately 5 to 6 kW [27]. Using this as a foundation, it now becomes possible to estimate the cost, purchase price, profit and estimated cost to operate the system per year. Using the average size of 5kW for a system and using its location, it is possible to project the cost of a system. For example a rough estimate of the cost of a typical system in California would be $23,751 after rebates and tax credits [27]. However, one consideration is as the cost of solar panels and other system equipment decreases, larger systems become an option for homeowners.

• Environmental
When considering the environmental aspects of this project the one natural resource that directly affects this project is the <u>sun</u>. The sun is the defining source behind this project. It is where the energy for the project and household are derived from. It is widely accepted that conventional generating options can damage air, climate, water, land and wildlife. Renewable technologies, which include PV systems, are substantially safer offering a solution to many environmental and social problems associated with fossil and nuclear fuels [28]. The potential environmental burdens of PV systems are regularly site specific and dependent on the size and nature of the project. These burdens are usually associated with the loss of

amenity (e.g. visual impact or noise—during the installation phases) and the impacts can be minimized. Photovoltaics on a residential scope are seen to be generally of benign environmental impact generating no noise or chemical pollutants during use. The impact of land use on natural ecosystems is dependent upon specific factors such as the topography of the landscape, the area of land covered by the PV system, the type of the land, and the biodiversity. The impacts and the modification on the landscape are likely to come up during the construction stage, however long term effects must be considered. For example, the Topaz Solar Farm is a 550MW PV power plant project being constructed in San Luis Obispo County California and is expected to have a lifespan of at least 25 years. Arguments for environmental impacts include using ground mounted panels versus roof mounted panels, sensitive species occupying the area such as the San Joachin kit fox, enough power for 160,000 average homes, and displacement of 377,000 tons of CO_2 annually [29]. Many groups question the long term environmental effects this project will have on the habitat and its species but the costs and benefits have yet to be weighed [29].

This senior project has no direct impact on the surrounding environment as it makes use of the existing residential structure with the surrounding ecosystem and species already adapted to the residence. The production of current generation PV systems is rather energy intensive (especially the poly crystalline and the mono-crystalline modules) and large quantities of bulk materials are needed [28]. Small quantities of scarce materials (In/ Te/Ga) are required. Also limited quantities of the toxic Cd from which the emissions attributed to CdTe production amount to 0.001% of Cd used [28]. The environmental performance of the system depends heavily on the energy efficiency of the system manufacturing and production. The emissions associated with transport of PV modules and other systems equipment are insignificant in comparison with those associated with manufacture. Transport emissions are estimated at only 0.1– 1% of manufacturing related emissions [28]. In the case of poly- and mono-crystalline modules, the estimated emissions are 2.757–3.845 kg CO2/kWp, 5.049– 5.524 kg SO2/kWp and 4.507–5.273 NOx/kWp [20]. Another important environmental aspect of this project includes the effects of chemical substances within the batteries. The batteries are responsible for most of the environmental impacts, due to their relatively short life span and their heavy metal content. Furthermore a large amount of energy and raw materials are required for their production [24].

- **Manufacturability**

When considering the manufacturability of this project many challenges arise. To first understand these challenges, the prototyping process must be considered. Challenges that would face prototyping of this project would mainly include financial and system size. Understanding that each system is unique to each residence makes it difficult to prototype. The cost of parts, equipment, and modifications to residential structures is far too great for most clients to invest in equipment for prototypes. Larger solar system/install companies may consider using/developing software to help model and aid in the prototyping process. To proceed with manufacturability on a commercialized scale other issues are taken into account such as design/engineering processes, outsourcing, and supply and demand. Since each PV project is exceedingly variable and dependent upon sizing factors and site analysis, generating a solid, well rounded engineering team would be highly valuable. It would also make sense to create contracts with multiple manufactures to create a wide range of accessible resources given the amount of subsystems that go into each PV system. The benefits of outsourcing would need to be weighed considering the high costs of manufacturing of PV panels, batteries, and inverters. Larger commercialized companies would

also consider financial incentives from all sources (government, private, or corporate) to invest in possible sub contracts with manufacturers.

• Sustainability

Sustainability is the capacity to endure, the long-term maintenance of responsibility, which has environmental, economic, and social dimensions, and encompasses the concept of responsible management of resource use. The overall design process of a PV system is heavily influenced by the concept of sustainability and the challenges associated with designing a low maintenance device. There are three main types of PV systems, each increasing in the level of maintenance required for preservation: Grid-Tied (requiring the least maintenance), Grid-Tied with Battery Backup, and Stand Alone systems (requiring the most maintenance) [30]. This project combines the benefit of being independent of the utility grid while requiring relatively low maintenance to keep the system performing optimally. Some of the challenges associated with the maintenance of the completed system include replacing the batteries as they degrade, cleaning the PV panels to optimize efficiency, and upgrading the components of the system as technologies improve. Upgrades that could improve the design include advancement in PV panel design, improvement in battery technology, and more efficient inverters requiring less power to operate, in turn resulting in fewer losses of the overall system [31]. The main issues associated with upgrading would require staying up to date with the current PV technologies making sure the newer technologies are adaptable and compatible with the current system, along with checking that new technologies meet the IEEE 1547 and UL 1741 standards. Other challenges to consider are increasing or decreasing the system output if the household energy demand were to change. This would include altering the PV array, battery system, and resulting components such as a charge controller and inverter. This would be the most sustainable option as the overall design would remain constant, only the components would need to be resized to meet the new ratings of the system.

• Ethical

Ethics, also known as moral philosophy, is a branch of philosophy that involves systemizing, defending, and recommending concepts of right and wrong behavior. It is also recognized as rules or standards governing conduct, especially those of a profession [18]. Systems are developed for use by other people, beyond issues in the technical aspects of design there are professional ethics that govern the broad scope of integrations between technology and people. Ethical frameworks that people can associate with are rule-based ethics, conditional rule based ethics, treating others with fairness and respect, honesty and trustworthiness, professional competence, and utilitarian ethics [18]. From these ethical frameworks an ethical statement can be developed for this project: *This system accepts the responsibility of making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the environment. By being honest and realistic in stating claims or estimates based on available data, this system aims to help sustain planetary resources by promoting solar energy research, development, education and practice at home, and in the community*. The utilitarian ethical implications relating to this can be associated with the design, manufacture, and use of this project in many ways. For example, when designing the PV system the engineer will design with the customer needs in mind being honest and forthright to the client, expecting the same in return so as to understand the needs and demands of the client. This will produce an efficient product. Another ethical framework widely accepted is the IEEE Code of Ethics. It has many ethical implications relating to the design, manufacture, and use of the project. For example, being honest and realistic in stating claims or estimates

based on available data. This is a key concept in achieving a top quality system. Overstating estimates such as financial cost or energy output would create mistrust between the designer and the client discrediting results of the design. Also not taking responsibility in "making engineering decisions consistent with the safety, health, and welfare of the public" [18] can have deadly consequences when dealing with a project that involves high voltages and currents, especially when connecting to a public utility grid. Another key aspect of this project relating to this ethical framework is designing with components that meet government codes, and accepted standardizations, such as the IEEE 1547 and UL 1741 standards.

• Health and Safety

A main responsibility and concern of every project is health and safety. These two components exist in all phases of development throughout the project and contain many aspects. Beginning with design the system is fashioned to have self protecting measures such as switches, fuses, and breakers to protect the system in the event that there is a problem. On the opposite side during the manufacturing process precautions must be taken to protect the health of plant workers producing PV panels since small amounts of toxic cadmium are used in the manufacturing of PV panels and some batteries [28]. Other safety concerns associated with manufacture or use of the project include construction (system installation) and operation of the system. As with any construction site the necessary safety precautions must be taken to prevent injury of workers during installation of the system. Also, the storage of the battery system must be well ventilated to prevent the buildup of hydrogen gas produced through electrolysis of some batteries. If the batteries require periodic maintenance safety measures must also be taken to prevent chemical burns. Since the project involves high voltages and currents of both DC and AC many safety precautions must be taken to prevent serious injury during construction as well as once the system is online and producing power. Also, precautions must be taken to protect the existing infrastructure in the house and associated circuits (including devices such as appliances, computers, TV's, etc).

• Social and Political

When considering social and political issues relating to this project it is important to consider the stake holders, or who the project will directly and indirectly impact. The most obvious direct stakeholders are the residents of the household that the system will provide power to. On a broader scheme this would include anyone directly receiving power from a PV system. Indirect stakeholders include the manufacturers of the components (PV panels, batteries, inverters, etc) of the system and the workers involved in the transportation of the components, hardware, and tools. Other indirect stakeholders are the employees of the utility company and the rest of the community. The project will benefit all of the stakeholders (both direct and indirect) in various ways such as the obvious environmental benefits as stated in the environmental section. Also the benefits of reduced dependence and cost effective safety net against losing necessary power for refrigerated food storage, water facilitation, crops, and livestock affecting the residence of the household. Other benefits relating to the indirect stakeholders include jobs created for manufacturing, shipping, and construction of the PV system along with the financial gain to the community from fees acquired in permits. Some harm caused to the indirect stakeholders of the project includes loss of revenue resulting in possible jobs lost to the utility company due to fewer customers. However, a resulting benefit might include more available power in an ever increasing demand for energy for residence of the electric utility. Other political issues associated with this project that have a broad effect on the community, town, and state include emissions laws and taxes.

• Development
The following include the sources for all tools and techniques, used for development and analysis during the course of the project.

Literature Search

[1] National Renewable Energy laboratory, "Dymanic Maps,GIS Data, & Analysis Tools," 20 Jan 2012. [Online]. Available: http://www.nrel.gov/gis/solar.html.

[2] The German Engineering Society, Planning & Installing Phontovoltaic Systems 2nd ed., London: Earthscan, 2009.

- This book provides in-depth information detailing every subject necessary for successful project implementation, from the technical design to the legal and marketing issues of PV installation. It also provides resource assessment and an outline of the core components, and covers system design, economic analysis, installation, operation and maintenance of PV systems.
- This book is recommended as a reliable and valuable source from Tim Townsend of BEW Engineering. Tim Townsend is a senior Engineer and was the instructor for PG&E's course in PV site analysis and system sizing. The book is the "most up-to-date and comprehensive guide to solar PV systems."

[3] Wkipedia, "Photovoltaics," 25 Feb. 2012. [Online]. Available: http://en.wikipedia.

[4] S. Direct, "How Solar Electric Technolty Works," 2011. [Online]. Available: http://www.solardirect.com/pv/pvbasics/pvbasics.htm.

[5] The Solar Energy Company, "How Solar Electric Technologies Work," 2003. [Online]. Available: http://www.thesolarenergycompany.com/solarelectric6.html.

- This article provides information and charts for proper sizing of this project's PV system based on the average power demand of the residence. It provides a starting point for feasibility and design of the overall system.
- The Solar Energy Company Inc. is one of the oldest and largest solar contractors in California operating since 1976. They provide sales and installation with experience in solar electric systems for both residential and commercial applications.

[6] T. Townsend, "Photovoltaic (PV) Site Analysis and System Sizing," in *PG&E's ETC Energy Eduaction Course*, Cal Poly Advanced Technology Laboratory, Oct. 22, 2011.

- This 8 hr lecture class offered by PG&E provided information on PV System design and how to access further resources. It provided demonstrations on site analysis and proper use of available tools.
- PG&E is a leading utility company that produces 16% of its power from renewable energy sources. Tim Townsend is a senior Engineer at BEW and instructed the course in PV site analysis and system sizing. BEW is an internationally recognized firm of a multi-discipline team of engineers, designers, and technicians providing engineering consulting services, and performing research and development in electrical power systems for emerging energy resources. BEW specializes in distributed generation, renewable energy systems (primarily wind and photovoltaics), power electronics and power system

planning. The projects range from distributed energy resources connected at the distribution level to bulk power generation interconnected at transmission voltages.

[7] G. Lijun, R. Dougal and A. Jotova, "Parallel-Connected Solar PV System to Address Partial and Rapidly Fluctuating Shadow Consitions," *J. IEEE Trans. On Indust. Elect.,* vol. 56, pp. 1548 - 1556, Jan. 2009.

- This IEEE Journal article discusses photovoltaic (PV) arrays that are often subject to partial shading. Residual energy generated by partially shaded cells either cannot be collected or impedes collection of power from the remaining fully illuminated cells. In this paper a system is capable of simultaneously maximizing the power generated by every PV cell in the PV panel. Study results demonstrate that, under complex irradiance conditions, the power generated by the new configuration is approximately twice that of the traditional configuration. This Article will provide useful information relating to shading effects on PV arrays and how to optimize maximum power output when shading could become a problem.
- The IEEE Industrial Electronics Society is part of IEEE and promotes the engineering process of creating, developing, integrating, sharing, and knowledge of electronic information technologies for the benefit of humanity and the profession. IEEE is internally recognized for its credibility. **Lijun Gao** received a Ph.D. degree in electrical engineering from the University of South Carolina, Columbia, in 2003. He is currently an Electrical Design and Analysis Engineer with the Boeing Company, Seattle, WA. **Roger A. Dougal** received a Ph.D. degree from Texas Tech University, Lubbock, in 1983. He is currently the Thomas Gregory Professor of Electrical Engineering at the University of South Carolina, Columbia. He directs the Virtual Test Bed project that aims to advance the technologies for simulation-based design and virtual prototyping of dynamic multidisciplinary systems. **Shengyi Liu** received a Ph.D. degree in electrical engineering from the University of South Carolina, Columbia, in 1995. He is specialized in high power and high energy density power and energy system design and integration for space, ground, surface, and subsurface vehicle applications. Dr. Liu is a member of the American Institute of Aeronautics and Astronautics and the Society of Automotive Engineers. He is a Licensed Professional Engineer in the State of Washington.

[8] *IEEE 1547 Standard for Interconnecting distributed Resources with Electric Power Systems,* IEEE std. 1547, Jul. 28, 2003.

- This source provides a uniform standard for interconnection of distributed resources with electric power systems. It provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection. As this project is intended to be connected to the electric utility it must be designed to meet the safety requirements and laws set forth in order to be economically feasible.
- IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems was approved by the IEEE Standards Board in June 2003. It was approved as an American National Standard in October 2003. IEEE standard 1547 has the potential to be used in federal legislation and rule making and state public utilities commission (PUC) - interconnection agreements for distributed generators powering the electric grid.

[9] *Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Resources,* Underwriters Laboratories (UL) 1741, Jan. 17, 2000.

- These requirements cover inverters, converters, charge controllers, and interconnection system equipment (ISE) intended for use in stand-alone (not grid-connected) or utility-interactive (grid-connected) power systems. As this project is intended to be connected to

the electric utility and have the ability to stand alone it must be designed to meet the safety requirements and laws set forth in order to be economically feasible.

- Underwriters Laboratories Inc. (UL) is an independent product safety certification organization established in 1894. UL develops standards and test procedures for products, materials, components, assemblies, tools and equipment, chiefly dealing with product safety. UL is one of several companies approved for such testing by the U.S. federal agency Occupational Safety and Health Administration (OSHA).

[10] F. Richter, "Sizing a Grid-Tied PV System With battery Backup," *Mag. Home Power,* vol. 139, pp. 66-72, Nov. 2010.

- This article provides very detailed information on grid-tied systems with battery backup along with providing examples of equipment that will meet a wide range of system demands.
- Home Power is a Magazine that has been published since 1987. Solar, wind, and hydro systems information is covered at a homeowner's do-it-yourself level with expert advice and examples. Home Power also promotes and presents information on energy efficient building and design practices. Flint Richter is currently project manager at Rocky Grove Sun Company and is NABCEP certified with over 35 years of experience in PV stand alone and grid-tied, wind and hydro systems.

[11] N. R. E. L. (NREL), "PVWatts Version 1," Office of Efficiency and Renewable Energy, 10 March 2009. [Online]. Available: http://rredc.nrel.gov/solar/calculators/pvwatts/version1/. [Accessed 26 November 2012].

[12] W. Solar, "Wholesale Solar," Wholesale Solar, 2011. [Online]. Available: http://www.wholesalesolar.com/StartHere/OFFGRID/OFFGRIDCalculator.html. [Accessed 26 November 2012].

[13] Solometric, "SunEye 210 Shade Tool," 2011. [Online]. Available: http://www.solmetric.com/buy210.html.

[14] Pacific Gas & Electric (PG&E), "PEC Tool Lending Library (TLL)," 2012. [Online]. Available: http://www.pge.com/pec/tll/.

[15] Google , "Google Maps," 2012. [Online]. Available: https://maps.google.com/maps?hl=en. [Accessed 6 June 2012].

[16] R. M. Ford and C. S. Coulston, Design for Electrical and Computer Engineers, NY: McGraw Hill, 2008.

[17] Northern Arizona Wind and Sun, "What is a Solar Charger," [Online]. Available: http://www.windsun.com/ChargeControls/ChargeCont.htm.

- This online article defines what a charge controller is and describes its purpose in a PV system. This article will help in choosing the proper charge controller to meet the specifications of the projects PV system.
- Northern Arizona Wind & Sun, Inc. is one of the largest solar retailers in the U.S. and has been selling and installing solar electric systems and components full time since 1979. They have installed and sold thousands of PV power systems for communications, remote home sites, water pumping, telemetry, and RV and battery maintenance systems. They carry photovoltaic equipment for industrial and home systems.

[18] Go Solar CA, "Eligible Equipment Selection," 2012. [Online]. Available: http://www.gosolarcalifornia.org/equipment/index.php.

[19] Schneider Electronics, *Xantrex XW - Hybrid Inverter Charger,* XW6048 datasheet, Nov. 2011.

- This datasheet describes the characteristics of an inverter that may be used in the design of this project. It is a grid-tied with battery backup, sine wave inverter that offers split-phase (120/240 AC) voltage output, and a 200% surge capacity for 10 seconds. It can accept two AC inputs – the first from the utility grid; the second to provide the option for backup engine generators (if desired).
- Schneider Electronics is a well established energy management company with over 170 years of operation. They produce products that specialize in power and control systems with the majority of their markets in renewable energy.

[20] Shop Akari, "Shneider Ele. Context TX 5000 Grid-Tied Inverter, 878-5001," 2012. [Online]. Available: http://www.akarienergy.biz/Schneider-Electric-Conext-TX-5000-Grid-Tied-Inverter-878-5001-878-5001.htm.

[21] Solar Edge, *Solar Edge Single Phase Inverters,* SE3000A-US/SE3800A-US/SE5000A-US/SE6000A-US/SE7000A datasheet, Jan. 2012.

[20] DC Battery Specialist, "Solar Panel Batteries (Photovoltaic PV Batteries)," 2012. [Online]. Available: http://www.dcbattery.com/solar.html.

[22] No Author, "Salary for Solar Energy/Solar Power Engineer Jobs," Jan. 31, 2012. [Online]. Available: http://www.payscale.com/research/US/Job=Solar_Energy_%2F_Solar_Power_Engineer/Salary.

[23] GetSolar, "Size of US Solar Home PV Systems Growing, IREC Industry Report Says," 30 June 2011. [Online]. Available: http://www.getsolar.com/blog/size-of-u-s-solar-home-pv-systems-growing-irec-industry-report-says/18107/.

[24] T. Tsoutsos, N. Frantzeskakib and V. Gekas, "Enviromental Impacts from the Solar Energy Technologies," *Energy Policy,* no. 33, pp. 289-296, 2005.

- This source provides detailed information on solar energy providing significant environmental benefits in comparison to the conventional energy sources, thus contributing to the sustainable development of human activities. The analysis provides the potential burdens to the environment, which include—during the construction, the installation and the demolition phases, as well as the case of the central solar technologies—noise and visual intrusion, greenhouse gas emissions, water and soil pollution, energy consumption, labor accidents, impact on archaeological sites or on sensitive ecosystems, negative and positive socio-economic effects.
- **T. Tsoutsos** is an Associate Professor in the Environmental Engineering Dept (Technical University of Crete) Head of the Renewable and Sustainable Energy Laboratory (ReSEL) Chemical Engineer (National Technical University of Athens, 1984) and Economist (Kapodistrian and National University of Athens, 1990). He has a PhD in the National Technical University of Athens (1990), is Adjunct Associate Professor in the Technical University of Crete (Environmental Engineering Dept, 1999 – Feb 2005), Scientific Collaborator in the Centre of Renewable Energy Sources (CRES), and Head of the Marketing & Development Department (1992- Feb 2005). **Niki Frantzeskaki** was born in Chania, Crete-Greece in 1980 and graduated Environmental Engineering at TU Crete (Greece) in 2003. Her master studies were realized at TU Delft (The Netherlands) where she graduated a Master of Science on Engineering and Policy Analysis. From 2006 until present, she is a PhD candidate on research of transition dynamics. **Vassilis Gekas** is currently a Components Engineer at Intracom Telecom **.**

[25] First Solar, "Topaz Solar Farm," 2012. [Online]. Available: http://www.topazsolar.com/Overview.

[26] Endecon Engineering, "A Guide to Photovoltaic (PV) System Design and Instillation 1st ed.," San Ramon, CA, 2001.

- This is a report prepared for the California Energy Commission to provide tools and guidelines to help ensure that residential photovoltaic power systems are properly specified and installed. It describes a quality system, and key design and installation considerations that should be met. This document deals with systems located on residences that are connected to utility power, and will provide valuable information relating to government standards for a residential PV system.
- Endecon Engineering, which is part of BEW generated this report. BEW is an internationally recognized firm of a multi-discipline team of engineers, designers, and technicians providing engineering consulting services and performing research and development in electrical power systems for emerging energy resources. BEW specializes in distributed generation, renewable energy systems (primarily wind and photovoltaics), power electronics and power system planning.

[27] T. Tsoutsos, N. Frantzeskakib and V. Gekas, "Enviromental Impacts from the Solar Energy Technologies," *Energy Policy,* no. 33, pp. 289-296, 2005.

[28] First Solar, "Topaz Solar Farm," 2012. [Online]. Available: http://www.topazsolar.com/Overview.

[29] Endecon Engineering, "A Guide to Photovoltaic (PV) System Design and Instillation 1st ed.," San Ramon, CA, 2001.

[30] M. Andrew, J. Stanley and R. de, "High Efficiency Multi-Source Photovoltaic Inverter". U.S. Patent Patent 7,929,325, 19 Apr. 2011.

- This Patent discusses the design features of high efficiency PV inverter. It is vital to design a PV system with maximum efficiency to achieve maximum power transfer. The higher the efficiency of the inverter, the less power is lost when converting from DC to AC.
- The inventors of the device patented are engineers of the General Electric Company which is well known for its quality inventions applicable to all fields of electronics

[31] Cutler-Hammer, *Improving Life of Parallel Connected Battery Strings,* EATON, 2002.

APPENDIX E — Solarworld Sunmodule SW255

Sunmodule

SW 255 mono / Version 2.0 and 2.5 Frame

World-class quality
Fully-automated production lines and seamless monitoring of the process and material ensure the quality that the company sets as its benchmark for its sites worldwide.

SolarWorld Plus-Sorting
Plus-Sorting guarantees highest system efficiency. SolarWorld only delivers modules that have greater than or equal to the nameplate rated power.

25 years linear performance guarantee and extension of product warranty to 10 years
SolarWorld guarantees a maximum performance degression of 0.7% p.a. in the course of 25 years, a significant added value compared to the two-phase warranties common in the industry. In addition, SolarWorld is offering a product warranty, which has been extended to 10 years.*

*in accordance with the applicable SolarWorld Limited Warranty at purchase.
www.solarworld.com/warranty

1)

- Qualified, IEC 61215
- Safety tested, IEC 61730
- Periodic Inspection

ISO 9001
ISO 14001
Certified

Intertek

US LISTED
Photovoltaic Module / Panel

Made in USA

SOLARWORLD

We turn sunlight into power.

www.solarworld.com

SW-02-5070US 07-2012

Sunmodule Plus™

SW 255 mono / Version 2.0 and 2.5 Frame

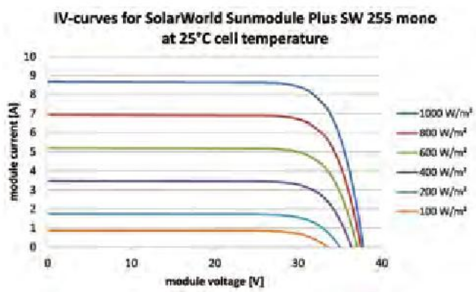
PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

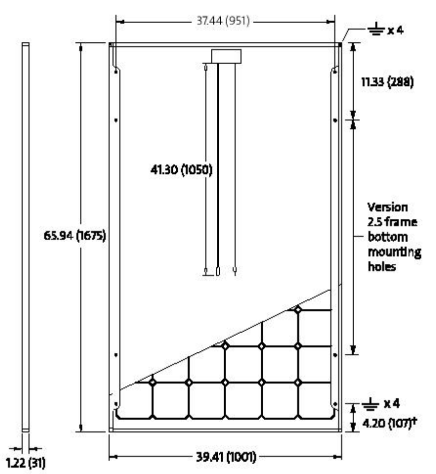
		SW 255
Maximum power	P_{max}	255 Wp
Open circuit voltage	V_{oc}	37.8 V
Maximum power point voltage	V_{mpp}	31.4 V
Short circuit current	I_{sc}	8.66 A
Maximum power point current	I_{mpp}	8.15 A

*STC: 1000W/m², 25°C, AM 1.5

THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.004 %/K
TC $_{Voc}$	-0.30 %/K
TC P_{mpp}	-0.45 %/K
Operating temperature	-40°C to 85°C





PERFORMANCE AT 800 W/m², NOCT, AM 1.5

		SW 255
Maximum power	P_{max}	184.1 Wp
Open circuit voltage	V_{oc}	34.0 V
Maximum power point voltage	V_{mpp}	28.3 V
Short circuit current	I_{sc}	6.99 A
Maximum power point current	I_{mpp}	6.52 A

Minor reduction in efficiency under partial load conditions at 25°C: at 200W/m², 95% (+/-3%) of the STC efficiency (1000 W/m²) is achieved.

COMPONENT MATERIALS

Cells per module	60
Cell type	Mono crystalline
Cell dimensions	6.14 in x 6.14 in (156 mm x 156 mm)
Front	tempered glass (EN 12150)
Frame	Clear anodized aluminum
Weight	46.7 lbs (21.2 kg)

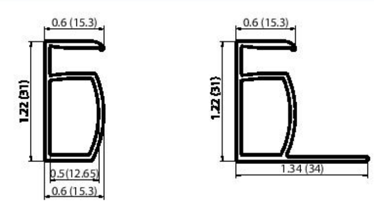
SYSTEM INTEGRATION PARAMETERS

Maximum system voltage SC II		1000 V
Max. system voltage USA NEC		600 V
Maximum reverse current		16 A
Number of bypass diodes		3
UL Design Loads*	Two rail system	113 psf downward 64 psf upward
UL Design Loads*	Three rail system	170 psf downward 64 psf upward
IEC Design Loads*	Two rail system	113 psf downward 50 psf upward

*Please refer to the Sunmodule installation instructions for the details associated with these load cases.

ADDITIONAL DATA

Power tolerance[2)]	-0 Wp / +5 Wp
J-Box	IP65
Connector	MC4
Module efficiency	15.21 %
Fire rating (UL 790)	Class C



VERSION 2.0 FRAME
- Compatible with "Top-Down" mounting methods
- Grounding Locations: 4 corners of the frame

VERSION 2.5 FRAME
- Compatible with both "Top-Down" and "Bottom" mounting methods
- Grounding Locations:
  - 4 corners of the frame
  - 4 locations along the length of the module in the extended flange†

1) Sunmodules dedicated for the United States and Canada are tested to UL 1703 Standard and listed by a third party laboratory. The laboratory may vary by product and region. Check with your SolarWorld representative to confirm which laboratory has a listing for the product.
2) Measuring tolerance traceable to TUV Rheinland: +/- 2% (TUV Power Controlled).
3) All units provided are imperial. SI units provided in parentheses.

SolarWorld AG reserves the right to make specification changes without notice.

APPENDIX F — Xantrex XW-MPPT 80-600 Charge Controller

Schneider Electric Xantrex™ XW MPPT 80 600 Solar Charge Controller

The XW MPPT 80 600 is an innovative solar charge controller that offers an industry-first set of features: high PV input voltage (up to 600 Vdc), Maximum Power Point Tracking (MPPT), and 80 A charge current. 600 Vdc PV input voltage delivers lower installation costs through fewer PV strings, longer home runs, smaller wiring and conduit, and virtual elimination of PV combiner boxes and circuit breakers. MPPT technology helps harvest the most energy available from the PV array, regardless of environmental conditions. 80 A battery charge current allows for connection of arrays rated at up to 4800 W (48 V battery bank).

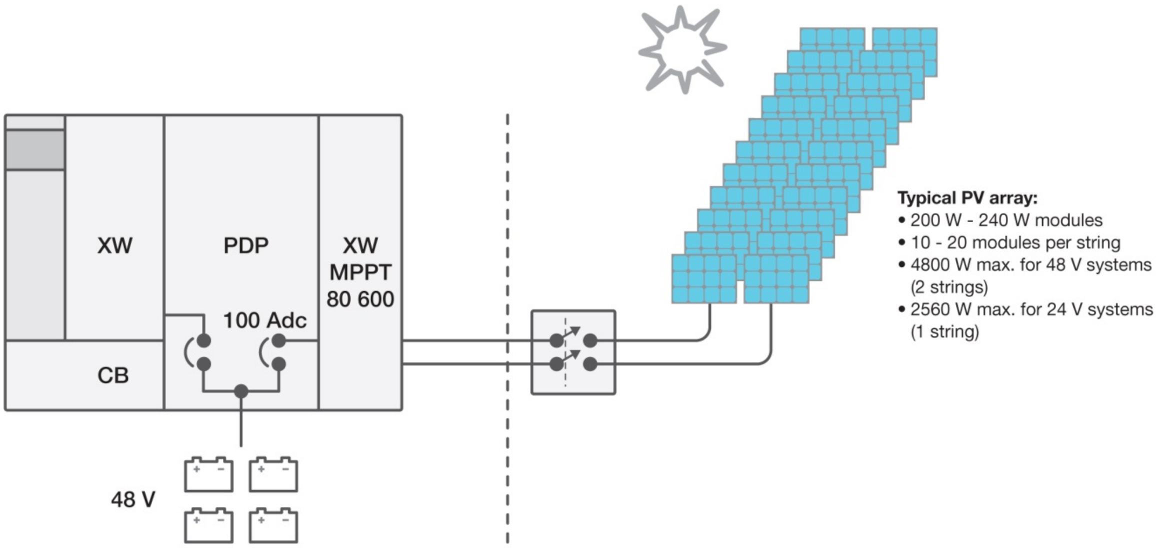
Features

- Up to 600 Vdc input
  - Full Power Range: 230 to 550 Vdc
  - Operating Range: 195 to 550 Vdc
  - MPPT Range: 195 to 510 Vdc
  - PV Array Start Voltage: 230 Vdc
- 80 A Output; 48 V or 24 V Battery (nominal)
- Full Power (4,800 W; 2,560 W) up to 45 C (113 F)
- Fast Sweep MPPT Algorithm
- Two- or Three-stage Battery Charger, Plus EQ
- Battery Type Settings: FLA, AGM, Gel, Custom
- Battery Temperature Compensation
- High Efficiency: 96% nom @ 48 V; 94% nom @ 24 V
- Low Tare Loss (0.5 W; Xanbus Power Supply Off)
- Built-in GFP and Indicator
- Input Over-voltage and Over-current Protection
- Output Over-current and Back-feed Protection
- Over-temperature Protection
- PV Cell Compatibility: Mono, Poly, String, Thin-Film
- Selectable PV Array Grounding: (+), (-), or ungrounded
- Positive or Negative System Ground
- Xanbus Compatible with AGS, Gateway, SCP, and XW
- AUX Output (dry contact, form "C")
- PDP Mounting Compatible (30" x 8.5" x 8.5")
- Variable Speed Cooling Fans

For more information about this product email re.pvsales@schneider-electric.com

Schneider Electric

Typical system configuration



Xantrex™ XW MPPT 80 600

Device short name	XW MPPT 80 600
Electrical specifications	
Nominal battery voltage	24 and 48 V (Default is 48 V)
Max. PV array voltage (operating)	195 to 550 V
Max. PV array open circuit voltage	600 V
Max. PV array input current	35 A
Max. and min. wire size in conduit	#6 AWG to #14 AWG (13.5 to 2.5 mm^2)
Charger regulation method:	Three-stage (bulk, absorption, float) Two-stage (bulk, absorption)
General specifications	
Power consumption, night time	< 1 W
Enclosure material	Indoor, ventilated, aluminum sheet metal chassis with 22.22 mm and 27.76 mm (7/8 in and 1 in) knockouts and aluminum heat sink
Product weight	13.5 kg (29.8 lb)
Shipping weight	17.4 kg (38.3 lb)
Product dimensions (H x W x D)	76 × 22 × 22 cm (30 × 8.625 × 8.625 in)
Shipping dimensions (H x W x D)	87 × 33 × 27 cm (34.3 × 13 × 10.6 in)
Device mounting	Vertical wall mount
Ambient air temperature for operation	-20°C to 65°C (-4°F to 149°F), power derating above 45°C
Storage temperature range	-40°C to 85°C (-40°F to 185°F)
Operating altitude	Sea level to 2000 m (6562 ft)
Warranty	Five-year standard
Part number	865-1032
Regulatory approvals	
Certified to UL1741: 2nd Ed and to CSA 107.1-01; CE	

Specifications are subject to change without notice.

Make the most of your energy

APPENDIX G — Xantrex XW4548 Hybrid Inverter/Charger

Product data sheet
Characteristics

865-1000-01
Xantrex XW - hybrid inverter / charger
XW6048-120/240-60 - input: 130A DC

Main

Range of product	Xantrex XW
Device short name	XW6048-120/240-60
Product or component type	Hybrid inverter / charger
Network number of phases	Single phase
Type of signal	True sine wave
Continuous power	6000 W AC - 120 V) 5752 W AC - 240 V)

Complementary

Feature available	105 A - phase to neutral (L-N) - 15 s 52.5 A - phase to phase (L-L) - 15 s
Network frequency	60 Hz +/- 0.1 Hz (output)
Cos phi	0.98
Harmonic distortion	< 5 %
Input voltage	50.4 V DC 120 V AC (L-N) - bypass/charge mode 240 V AC (L-L) - bypass/charge mode
Input voltage limits	44...64 V DC 80...150 V AC (L-N) - bypass/charge mode 160...270 V AC (L-L) - bypass/charge mode 108...130 V +/- 1.5 V AC (L-N) - sell mode 214...260 V +/- 3.0 V AC (L-L) - sell mode
Input current	130 A DC at rated power
Input frequency	59.4...60.4 Hz +/- 0.05 Hz - sell mode 55...65 Hz - bypass/charge mode (default) 44...70 Hz - bypass/charge mode (allowable)
Charging current	100 A
Efficiency	95 % - low-load 92.5 % CEC weighted 89.4 % - maximum charge rate
Power consumption in W	< 8 W - search mode
Communication network type	Xanbus
Device mounting	Wall mounted
Provided equipment	Battery temperature sensor included for temperature compensation
Height	580 mm
Width	410 mm
Depth	230 mm
Product weight	55.2 kg

Environment

NEMA degree of protection	NEMA Type 1
Ambient air temperature for operation	-25...70 °C
Standards	CSA 107.1 UL 1741
Product certifications	FCC Class B

APPENDIX H — Trojan IND29-4V

Trojan BATTERY COMPANY

IND29-4V DATA SHEET
INDUSTRIAL LINE

MODEL: IND29-4V
DIMENSIONS: inches (mm)
BATTERY: Flooded/wet lead-acid battery
COLOR: Maroon (case/cover)
MATERIAL: Polypropylene (internal cell container)
Polyethylene (outer container)

PRODUCT SPECIFICATION

TYPE	CAPACITY [A] Amp-Hours (AH)							ENERGY (kWh)	VOLTAGE	DIMENSIONS [B] Inches (mm)			WEIGHT lbs. (kg)	
	5-Hr Rate	10-Hr Rate	20-Hr Rate	48-Hr Rate	72-Hr Rate	100-Hr Rate	240-Hr Rate	100-Hr Rate		Length	Width	Height [C]	Dry	Wet
DEEP CYCLE BATTERY														
IND29-4V	1245	1409	1570	1770	1857	1910	1927	7.64	4	26-11/16 (678)	10-1/4 (260)	24 (610)	367 (166)	465 (211)

A. The amount of amp-hours (AH) a battery can deliver when discharged at a constant rate at 80°F (27°C) and maintain a voltage above 1.75 V/cell. Capacities are based on nominal performance.
B. Dimensions are based on nominal size. Dimensions may vary depending on type of handle or terminal.
C. Dimensions taken from bottom of the battery to the highest point on the battery. Heights may vary depending on type of terminal.
Trojan's battery testing procedures adhere to both BCI and IEC test standards.

CAPACITY AMP-HOURS (AH)

Cutoff Voltage	5-Hr	10-Hr	20-Hr	48-Hr	72-Hr	100-Hr	240-Hr
1.75 vpc	1245	1409	1570	1770	1857	1910	1927
1.80 vpc	1121	1324	1507	1735	1822	1868	1899
1.85 vpc	1016	1197	1384	1595	1700	1761	1766
1.90 vpc	743	962	1156	1402	1507	1564	1577

CHARGING INSTRUCTIONS

CHARGER VOLTAGE SETTINGS (AT 77°F/25°C)

	Voltage per cell
Absorption charge	2.35-2.45
Float charge	2.20
Equalize charge	2.58

Do not install or charge batteries in a sealed or non-ventilated compartment. Constant under or overcharging will damage the battery and shorten its life as with any battery.

OPERATIONAL DATA

Operating Temperature	Self Discharge	Specific Gravity
-4°F to 113°F (-20°C to +45°C). At temperatures below 32°F (0°C) maintain a state of charge greater than 60%.	Up to 4% per week	The specific gravity at 100% state-of-charge is 1.260

CHARGING TEMPERATURE COMPENSATION

To the Voltage Reading -- Subtract 0.005 volt per cell (VPC) for every 1°C above 25°C or add 0.005 volt per cell for every 1°C below 25°C.

EXPECTED LIFE VS. TEMPERATURE

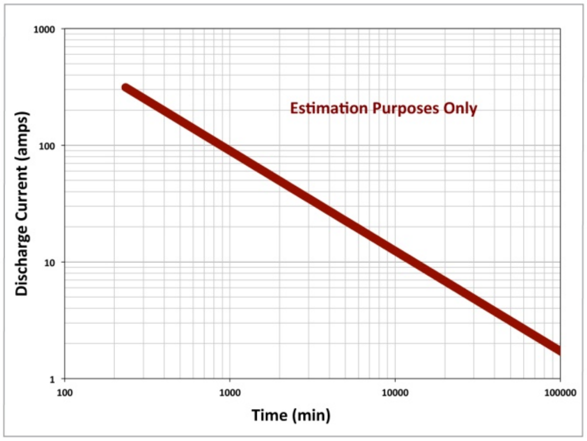
Chemical reactions internal to the battery are driven by voltage and temperature. The higher the battery temperature, the faster chemical reactions will occur. While higher temperatures can provide improved discharge performance the increased rate of chemical reactions will result in a corresponding loss of battery life. As a rule of thumb, for every 10°C increase in temperature the reaction rate doubles. Thus, a month of operation at 35°C is equivalent in battery life to two months at 25°C. Heat is an enemy of all lead acid batteries, FLA, GEL, and AGM alike and even small increases in temperature will have a major influence on battery life.

TRJN_IND29-4V • DS0811

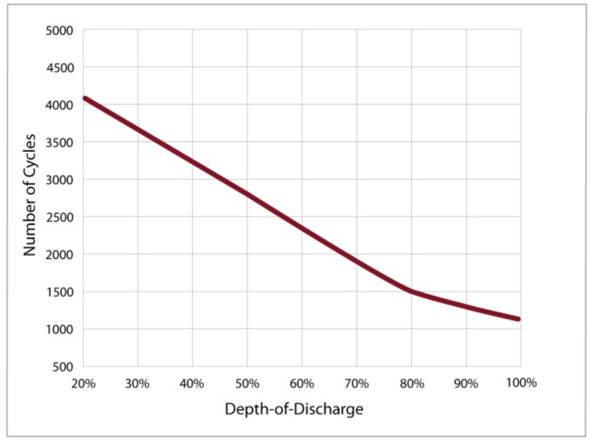
Page 1 of 2

IND29-4V DATA SHEET
INDUSTRIAL LINE

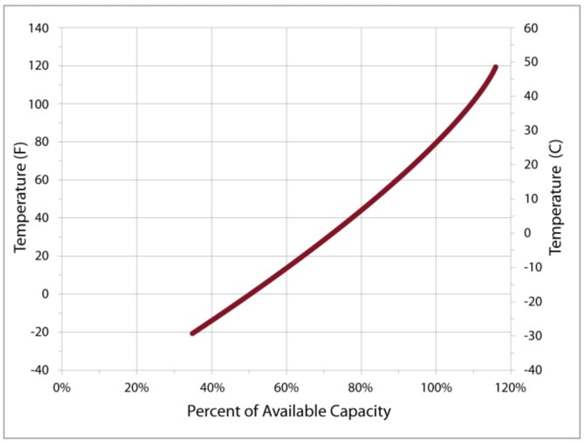
TROJAN IND29-4V PERFORMANCE



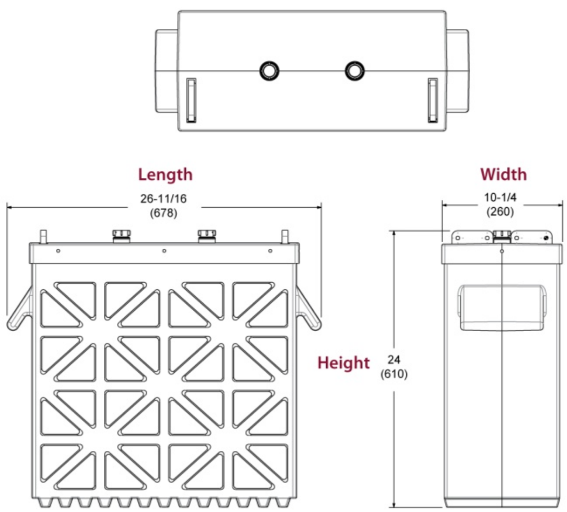
CYCLE LIFE



CAPACITY VS. TEMPERATURE



BATTERY DIMENSIONS



TERMINAL CONFIGURATIONS

14	IND	Ind Terminal
		*Terminal Height Inches (mm)* 1-3/4 (44) *Torque Values LB-IN (Nm)* 100 – 120 (11 – 14) *Through-hole Diameter Inches (mm)* 3/8 (9.5)

VENT CAP OPTIONS

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