The Design of a 2kW Off-Grid Photovoltaic System

Table of Contents

Abstract

This paper describes an ongoing team-based capstone senior design project. The project involves designing critical components for a 2kW photovoltaic system which features maximum power point tracking (MPPT), a $LiFePO_4$ battery storage system, and a Supervisory Control and Data Acquisition (SCADA) system. This paper will also show how to size a solar panel array system and calculate system costs for such a system. In addition important design requirements and issues associated with the design project are presented along with an overview of the project status.

Introduction

Energy consumption in the United States has been steadily increasing for many years as shown in Figure 1. This trend has been driven by population growth and increased use of energy dependent technological devices such as cell phones, computers, and cars. Without drastic changes in the population growth and social habits, energy consumption is likely to continue to increase further in the future.

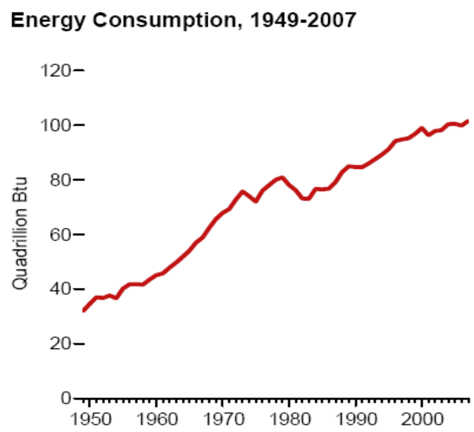

Figure 1. Energy Consumption in the US [3]

While energy consumption is increasing, the supply of non-renewable resources is decreasing. As shown in Figure 2, the US has become dangerously dependent on these diminishing non-renewable sources with petroleum, natural gas, and coal accounting for 85% or our energy consumption[5]. Non-renewable sources cannot continue to support the growing energy consumption indefinitely. Renewable sources such as geothermal, wind, and solar power must be explored quickly to replace non-renewable sources.

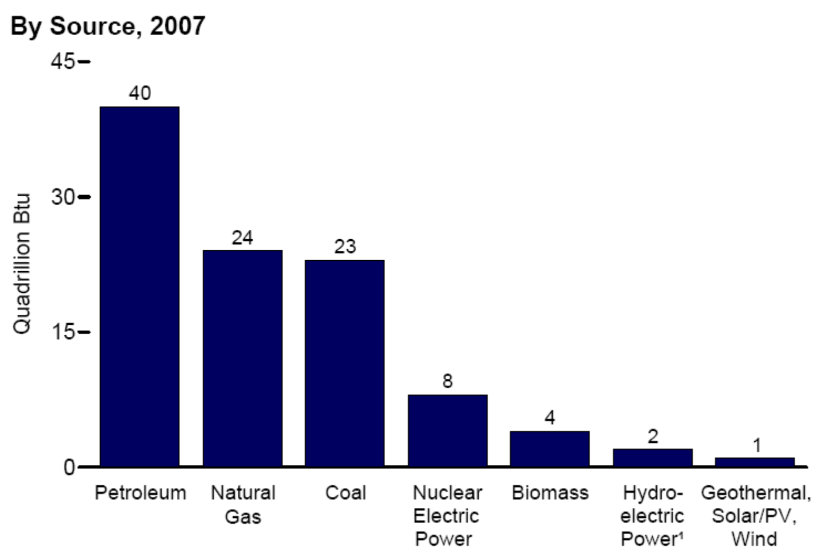

Figure 2. Energy Consumption by source in the US [5]

Of the renewable sources, solar energy is particularly interesting. It has virtually no environmental impact, is produced domestically, and has the potential to strengthen our economy while providing energy independence. While solar energy currently accounts for a very small portion of our energy generation (~ 0.5%) [5] it is growing rapidly. Figure 3 shows the annual domestic solar panel shipments in the US over the past 10 years. As seen in the table, every year more and more solar panels are being purchased.

Annual Photovoltaic Domestic Shipments, 1998 - 2007	
Year	Photovoltaic Cells and Modules[1]
1998	15,069
1999	21,201
2000	19,838
2001	36,310
2002	45,313
2003	48,664
2004	78,346
2005	134,465
2006	206,511
2007	280,475
U.S. Total	**886,193**

[1]Total shipments minus export shipments.
Notes: Totals may not equal sum of components due to independent rounding.
Total shipments include those made in or shipped to U.S. Territories.
Source: Energy Information Administration, Form EIA-63B, "Annual Photovoltaic Module/Cell Manufacturers Survey."

Figure 3 - Annual Photovoltaic Domestic Shipments [6]

The goals of this paper are three-fold. First, the method to size a solar panel array system for a typical household in Pennsylvania will be described. Next, an engineering economics analysis of a household solar panel system will be analyzed in order to determine if solar energy is a viable option in our geographic region. Finally, an overview of an ongoing team-based capstone senior project involving the design of a 2kW solar system will be presented.

Photovoltaic Sizing and Economics

Solar panels (or photovoltaic arrays) transform the energy coming from the sun into electrical power. Photovoltaic (PV) cells are basically semiconductors in which photons from sunlight hit the space charge region of a semiconductor diode. This produces an electron-hole pair that moves through the semiconductor due to an electric field and creates an electrical current. PV cells can be made from a variety of materials including cadmium telluride, copper-indium selenide, gallium arsenide, and polycrystalline silicon. In today's solar panel market, most solar panels are made from polycrystalline silicon cells that have efficiencies in the range of 6-12%.

In addition to the fundamental efficiency of the PV cell, there are additional efficiency losses that are a function of the orientation and angle of the installed solar panels. Panels should face directly south and be tilted at an angle equal to the installation site latitude. However, many arrays are tilted at an angle less than the latitude because of practical mounting issues associated with wind loading and aesthetics. According to Lambert's cosine law in Equation 1, the panels will lose an efficiency approximately proportional to the angle between the latitude and the array tilt. [1]

$$I = I_0 \cos(\theta) \qquad \textbf{Eq. 1}$$

Geographic location obviously plays a critical role in the design and economics of solar panel systems. This is because the input energy from the sun, which is called the insolation, varies greatly with geographic region and season. Therefore the first step in designing a PV solar system is to understand the insolation data for the installation site.

Insolation

Insolation is the measure of solar radiation energy received on a surface over a given time and has units of W/m^2. Insolation data for a given geometric region can be obtained using software such as Virtual Test Bed (VTB) [14] or from sources like the National Solar Radiation Database (NSRD) [11]. Figure 4, shows a how the insolation varies throughout the day in our region of Pennsylvania on the first of March, July, September, and December. As shown in the figure, in the summer months the sun energy is present more hours of the day and it is also more intense. The daily insolation curves were integrated for 365 days to find an average of 3.86kWh/m^2/day our region. This data will be important to size a solar panel system.

In sizing a system, it is also important to account for cloudy days. For this analysis it will be assumed that on cloudy days the solar panel system is shut down and the house is powered by the grid. An estimate for the average monthly insolation can be determined by derating the insolation based on the average number of cloudy days per month which can be obtained from the National Oceanic and Atmospheric Administration (NOAA) [12].

Month	Average Monthly Insolation (kWh/m^2/day)	Non-Cloudy days form NOAA [12]	Total Insolation in a Month (kWh/m^2)
Jan	1.89	15	28.35
Feb	2.7	15	40.5
Mar	3.69	16	59.04
Apr	4.71	16	75.36
May	5.44	17	92.48
Jun	5.96	19	113.24
July	5.87	20	117.4
Aug	5.33	20	106.6
Sept	4.19	18	75.42
Oct	3.06	19	58.14
Nov	1.95	15	29.25
Dec	1.57	14	21.98
Annual Ave	3.86	Total: 204 days	Total: 817.76 kWh/m^2
(817.76 kWh/m^2) / 204 days = 4 kWh/m^2/day			

Table 1. Insolation adjustments for cloudy days.

In table 1, the total insolation for non-cloudy days is found in kWh/m^2 and then is divided by the number of non-cloudy days. This gives the average insolation in 4kWh/m^2/day for our region given it is a non-cloudy day.

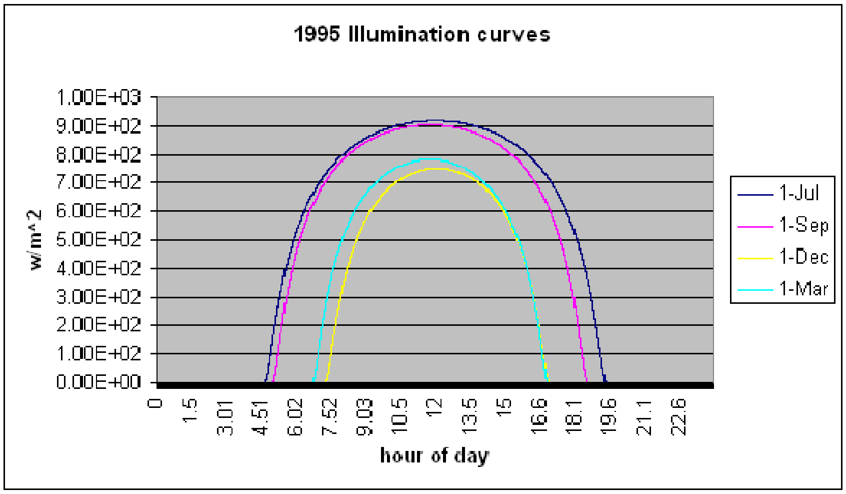

Figure 4. Daily insolation curves given by VTB at "the university"

System Sizing

A solar panel system appropriate for a given location can be sized given the average household energy consumption, insolation data, and the solar panel efficiency. The Department of Energy (DOE) reports that the typical household in our region uses an average of 28.7kWh/day. The particular General Electric panels chosen for this project are 7.3% efficient. A system which would provide an average of 28.7kWh/day can be sized using equation 2. Note that the average insolation given it is non-cloudy is used in the equation since that is the condition in which the system will be on.

$$size = \frac{AveEnergyConsummed}{AveInsolation * PVefficiency} = \frac{28.73kWh/day}{4kWh/m^2/day * .073} = 98.4m^2 \quad \textbf{Eq.2}$$

In addition to the physical size, the maximum capacity of such a system can be calculated. When referring to the capacity of a solar panel system, the maximum capacity is usually given. The maximum capacity, in the unit Watts-peak (Wp), can be calculated according to equation 3. The maximum insolation is 1000W/m^2, which can occur on a clear sunny day when the sunlight is perpendicular to the arrays [13].

$$\begin{aligned} capacity &= \max Insolation * area * PVefficiency \\ &= 1000W / m^2 * 98.4m^2 * .073 = 7150Wp \end{aligned} \qquad \textbf{Eq.3}$$

These findings are consistent with the normal household solar array systems installed in this area. Trinity Solar, who installed the panels for this project, reports they install 5-10KWp systems for houses.

Economic Analysis of Solar Energy

Economic viability is a large concern when dealing with solar energy. The main expenses when dealing with solar energy include initial system cost, time value of money, and replacement of critical items. Below is an economic analysis over the course of a solar panel system's 20 year lifespan to determine if solar energy is viable in our geographical region. The analysis is based on a 7kW system determined above with a panel area of 98.4 m^2.

Solar panels have an estimated cost of 4.5$/Wp and the inverter has an estimated cost of $0.85/Wp [10]. The panels and inverter will cost approximately $32,850 and $6,200 respectively. The panels will last 20 years, but the inverter must be replaced after 10 years. A modest battery system lasting for 2.5 days with an average energy use of 28.7 kWh/day and a battery cost of $150/kwh will cost $10,800. The batteries for this system will need to be replaced every 7 years, but it is estimated the battery cost will go down by 15% every 7 years due to technological advances [10]. These costs are given in table2.

Initial costs = $57,830				Replacements		
Solar Panel Cost ($)	Installation ($)	Inverter Cost ($)	Battery Cost ($)	Batteries at year 7 ($)	Inverter at year 10	Batteries at year 14 ($)
32850	8000	6205	10775.34	9159.041	6205	7785.185

Table2. Photovoltaic system estimated costs.

On the 161 cloudy days in the year, an average of 28.7 kWh/day at $0.1095/kWh [4] will be bought from the grid. This means $475/year of electricity will be bought from the utility. Equation 3 shows the present day cost of the system assuming 5% interest per year over a 20 year system lifetime is $74,200. The photovoltaic energy will cost 59.7 cents/kWh, which is 5.45 times the region's average. The cash flow diagram for the project is shown figure 5. Clearly at this time it is not economical to run a household off a solar panel system.

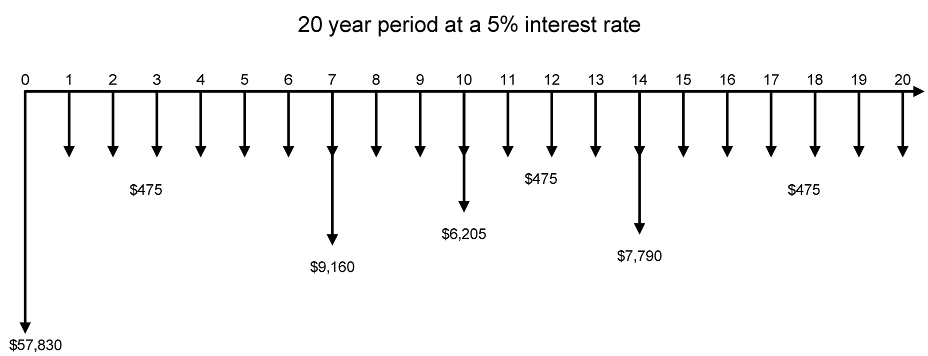

Figure 5. Cash flow diagram for a household solar panels system in this region

PresentWorth= InitialCost+PresentWorth(AnnualUtilityCost for 20yrs @ 5%)+PresentWorth(BatteryReplacement in 7yrs@ 5%) + PresentWorth(InverterReplacement in 10yrs@ 5%+PresentWorth(BatteryReplacement in 14yrs@ 5%)

$$\begin{aligned} P &= \$57,830 + \$475(P/A, 5\%, 20) + \$9,160(P/F, 5\%, 7) \\ &+ \$6205(P/F, 5\%, 10) + \$7,790(P/F, 5\%, 14) = \$74,200 \end{aligned}$$ **Eq. 3**

Although solar panels today are not economically viable, they will play an important part in the future of energy. Solar panel technology has not reached its full potential and there is ongoing work to improve photovoltaic cell efficiencies and to use low cost materials such as polycrystalline solar cells. New power algorithms are being explored to maximize the energy that can be obtained from photovoltaic arrays. One of the limiting factors on the lifespan of a solar panel system is the electrolytic capacitors used in the inverter. Research is ongoing to find alternatives to using these capacitors. One of the goals of this project was to gain experience with power electronics and the subsystems involved in this upcoming technology. The next section will provide an overview of an ongoing design of a 2 kW solar panel system.

A 2 kW Photovoltaic System Design

The 2kW photovoltaic system is being designed by 22 students as a one-semester capstone senior design project. One project requirement is that the system must be able to power a grill to cook hamburgers for approximately two hours for an end of semester party. The design is also subject to a number of other more technical requirements that are outlined in a 55 page requirements document provided in a statement of work (SOW) at the beginning of the project. For example, the system is subject to National Electric Code 690 safety requirement for PV systems. The system must also be able to automatically shut down if any fault should occur, such as a safety issue. All components in the design must only draw power from the PV system. A monitoring system is required which will be powered by the system, to make sure all of the currents, voltages, and temperatures are at a safe level.

This PV system has been divided into four major sub-systems as shown in Figure 6. The sub-systems are the Raw Power Interface (RPI) which is responsible for safely connecting the PV array to the system, the Energy Storage System (ESS) which stores energy in an array of batteries, the Energy Delivery System (EDS) which provides proper array impedance and converts DC to AC, and the Supervisory Control And Data Acquisition (SCADA) which monitors the system to watch for any safety hazards as well as controls the system states. Each major system component will be briefly described below.

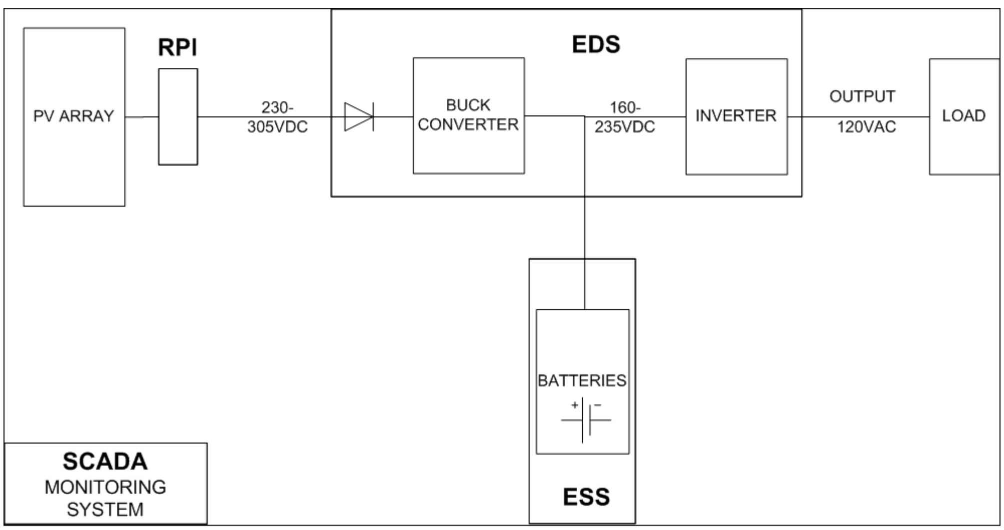

Figure 6 – Overall System Block Diagram

PV Array Subsystem - The PV array was provided to the design team and consists of 10 GEPVp-200-MS modules solar panels connected in series configuration using cinder blocks for weight to avoid penetrating the roofing material. They are placed at a 5 degree tilt because of wind loading. Figure 7A shows a picture of the panels mounted on the roof of the engineering building. The current and voltage coming out of the photovoltaic array vary depending on the temperature and insolation conditions as the photovoltaic specifications show in figure 7B.

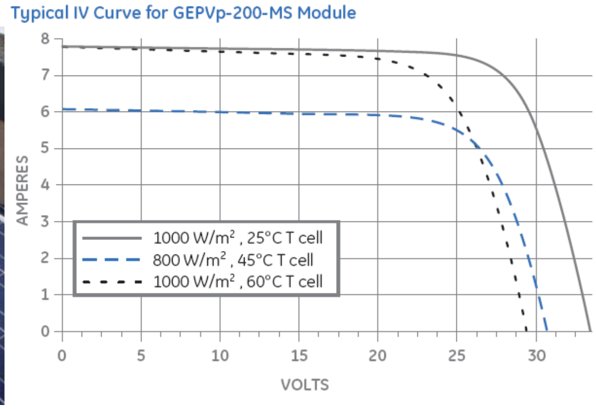

Figure 7A (Left) – Picture of the Photovoltaic Array used in this project. Figure 7B (Right) - Current and voltage curves provided by general electric for these arrays [6].

RPI Subsystem - Energy from the sun is collected by the photovoltaic array and fed into RPI, which connects the system to the photovoltaic arrays consistent with National Engineering Code Article 690 for PV systems. RPI's main function is ground fault protection. This will shut the system down if the current leaving the RPI is different from the current coming back, which would happen when the current is traveling through an external body to ground.

EDS Subsystem - The Energy Delivery System consists of a buck converter and an inverter mounted on a single printed circuit board. The buck converter shown in figure 8 controls the ratio of the input voltage to the output voltage by changing the duty cycle driving the switch. This functionality allows it to perform maximum power point tracking (MPPT) which collects the most energy possible out of the photovoltaic panels. The MPPT algorithm will make the photovoltaic arrays operate at the knee of the IV curve in figure 7B, where the power (current times voltage) is the highest. This is not always the same point as seen in the figure because temperature and insolation affect the location of the IV curve. The buck converter also converts the high voltage (230 – 305V) coming out of the photovoltaic array to a lower voltage (160 – 235V) that can be used to charge the batteries. A picture of the prototype for the buck converter is shown in figure 9B.

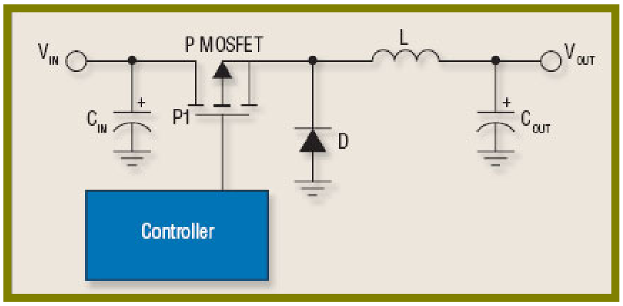

Figure 8 – Buck converter topology

The inverter converts the DC power coming from the buck converter to an AC supply for the load. It consists of 4 insulated gate bipolar transistors (IGBTs) in an h-bridge configuration. The signals to drive the IGBTs will be created by a microcontroller. These four transistors are turned off and on in a scheme such that the output of the IGBTs is easy to filter out to a 60 Hz signal. If there is excess DC power, it is passed to ESS to charge the batteries.

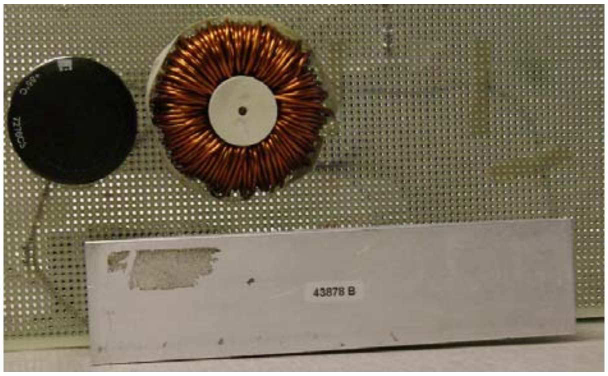

Figure 9A (left) – Photo of the batteries used in the project. Figure 9B (right) – Photo of a prototype of the buck converter.

ESS Subsystem – The ESS subsystem contains the batteries that will store energy for the system. One of the batteries used is shown in figure 9A. The battery technology chosen for this design is Lithium Iron Phosphate. This battery technology is just beginning to emerge on the market. This technology shares some of the same advantages with other lithium ion based battery technologies such as high current output, long cycle life, and good energy density.

ESS also contains a printed circuit board which has the circuitry for VIT (voltage, current, and temperature) sensors, a module to communicate with SCADA, and a DC/DC converter. The PCB layout is shown in figure 10. This converter draws from the batteries to create 5 volts to be used by the low voltage components in the system.

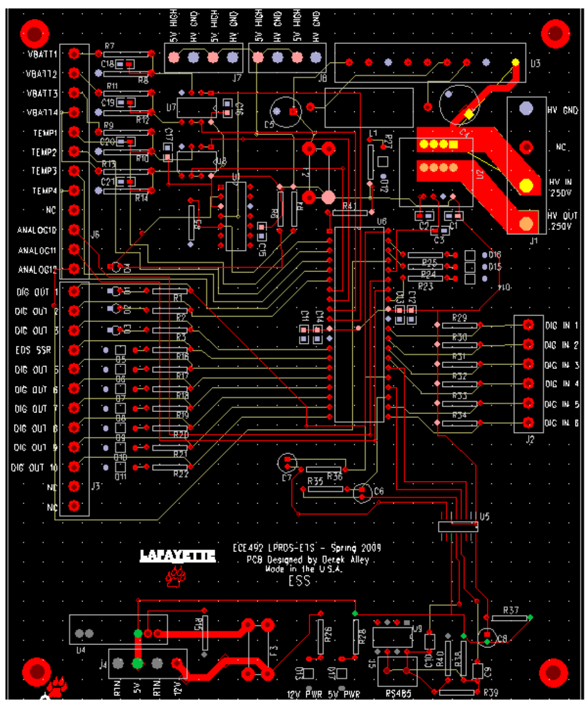

Figure 10 – ESS PCB Layout

SCADA Subsystem-

The system also implements a SCADA system that controls the system states, monitors key voltages, currents, and temperatures, and displays this and other system status information on a LCD screen in the project room. SCADA also serves a webpage to allow system information to be observed on a remote computer. If any fault should occur, such as the voltage, temperature, or current being too high, SCADA will disconnect the system from the load and will log what fault occurred. This is useful for troubleshooting the system.

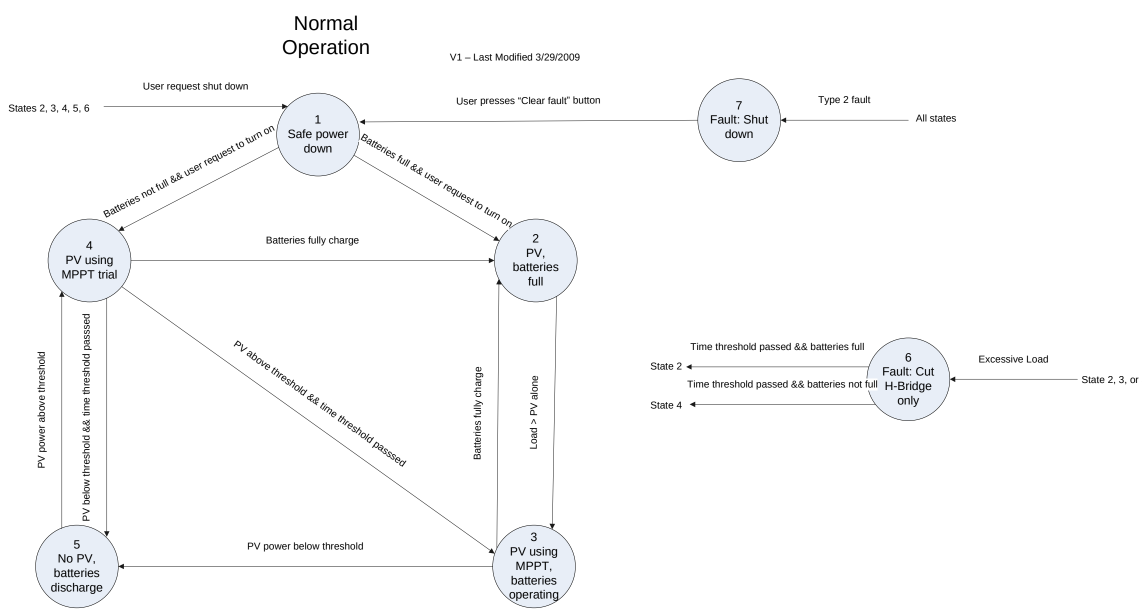

Figure 11 – System states of the 2 kW photovoltaic system.

The states of the system that are controlled by the SCADA subsystem are shown in figure 11. The system will need to operate in a number of states that are dependent on the AC load requirements, the battery charge state, and the insolation level. In the system the load is the highest priority. If there is more power coming in from the photovoltaic array than is needed by the load, the batteries will be charged. If the system cannot meet the AC load requirement then it will disconnect the load.

Conclusion

Currently, solar is not an economically viable alternative source of energy in our region. The initial cost and replacement costs of the critical components are too high to make positive returns. Although solar panels systems are not currently economical, they still hold great promise for the future. Scientific American reports that “There are approximately 30 billion square feet (2.8 billion square meters) of expansive, flat roofs in the U.S., an area large enough to collect the sunlight needed to power 16 million American homes, or replace 38 conventional coal-fired power plants [2].” In addition, there is significant work being done to improve the critical components in solar panels systems. The great potential for solar energy will encourage research and interest in future decades. A high level overview of an ongoing PV system design was presented. Additional technical details will be provided in the presentation.

References

1) Absolute Astronomy. Lambert's Cosine Law. 01 Apr. 2009 <http://www.absoluteastronomy.com/topics/Lambert's_cosine_law>

2) Biello, David."Cylindrical Solar Cells Give a Whole New Meaning to Sunroof." Scientific American. Oct. 7 2008. 27 Mar 2009. <http://www.sciam.com/article.cfm?id=cylindrical-solar-cells-give-new-meaning-to-sunroof>

3) Energy Information Administration. Energy Information Administration - EIA – Energy Consumption and Expenditure Indicators. 01 Apr. 2009 <http://www.eia.doe.gov/emeu/aer/pdf/pages/sec1_12.pdf>

4) Energy Information Administration. Energy Information Administration - EIA – Frequently Asked Questions - Electricity. 01 Apr. 2009 <http://tonto.eia.doe.gov/ask/electricity_faqs.asp#electricity_use_home>

5) Energy Information Administration. Energy Information Administration - EIA - Official Energy Statistics from the U.S. Government. 01 Apr. 2009 <http://www.eia.doe.gov/emeu/aer/pdf/pages/sec1_8.pdf>.

6) Energy Information Administration. Energy Information Administration - EIA – Solar Photovoltaic Cell/ Module Manufacturing Activities. 01 Apr. 2009 <http://www.eia.doe.gov/cneaf/solar.renewables/page/solarphotv/solarpv.html>

7) GE Energy. GEPVp-200-MS 200 Watt Photovoltaic Module for 600 Volt Applications Datasheet. <ge-energy.com/solar>

8) Guler, Roger, Juliano De Pellegrin Pacheco, Helio L. Hey, and Johninson Imhoff. "A Maximum Power Point Tracking System With Parrallel Connection for PV Stand-Alone Applications." IEEE Explore Vol. 55 No. 7 July 2008: 2674-683.

9) Landau, Charles R. "Optimum Orientation of Solar Panels." MACS Lab, Inc. 01 Apr. 2009 <http://www.macslab.com/optsolar.html>

10) Matthews, H. S., Gyorgyi Cicas, and Jose L. Aguirre. "Economic and Environmental Evaluation of Residential Fixed Solar Photovoltaic Systems in the United States." Journal of Infrastructure Systems Vol. 10 No. 3 Sept. 2004: 105-10.

11) National Solar Radiation Database. National Solar Radiation Database - NSRD. 27 Mar. 2009 < http://rredc.nrel.gov/solar/old_data/nsrdb/>

12) NCDC. "Cloudiness - Mean Number of Days." NCDC: * National Climatic Data Center (NCDC) *. 23 Mar. 2009 <http://lwf.ncdc.noaa.gov/oa/climate/online/ccd/cldy.html>

13) Stickler, Greg. "Solar Radiation and the Earth System." Welcome to GESSEP. 26 Mar. 2009 <http://edmall.gsfc.nasa.gov/inv99Project.Site/Pages/science-briefs/ed-stickler/ed-irradiance.html>.

14) University of South Carolina. Virtual Test Bed. 26 Mar. 2009 <http://vtb.engr.sc.edu/>.

15) US Department Of Energy. Department of Energy - DOE – Average Monthly Bill by Sector, Census. 28 Mar. 2009 <http://www.eia.doe.gov/cneaf/electricity/esr/table5.xls>