Simulation of Cal Poly SuPER System SimuLink Model using Insolation Variation

by

Jacob Kory

Senior Project

ELECTRICAL ENGINEERING DEPARTMENT

California Polytechnic State University

San Luis Obispo

2010

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to acknowledge the following people for their support and guidance through this project:

To Professor James Harris
for his outreach and for encouraging me to become involved with SuPER.

To Professor Ali Shaban
for his guidance, supervision, and resource in developing this project.

To Matthew McFarland
for his insight on the current SuPER model, as well as an advanced version of the model for use in my project.

To Chris Ardnt of WeatherElement.com and SLO Water Reclamation Facility
for gathering local insolation data.

Abstract

This senior project focuses on simulation of the Cal Poly SuPER system using an insolation model. First, local and historical weather data is examined to determine the range of limits that the model will utilize. Then, the insolation model is constructed to fit into the existing SuPER model. The overall system is tested under a variety of insolation values to determine system performance of motor and static loads. Based on these simulations, several factors of the current model are discovered that limit the power consumption profile under off-peak load conditions. Finally, recommendations on improvements to the model are discussed

I. Introduction

The purpose of the Cal Poly Sustainable Power for Electrical Resources (SuPER) project is to develop a low-cost, sustainable source of power with a 20-year life cycle suitable to power a family unit with renewable energy (1). The SuPER project will be provided to people in underdeveloped nations as an alternative to government aid programs. The system uses a photovoltaic cell and stores solar energy in a battery. The project is based on current existing technology and extrapolates capabilities according to Moore's Law model allowing SuPER to be economical. The SuPER system incorporates a photovoltaic cell for energy capture, a 12VDC battery, and a control system to regulate the flow of current from the panel to the battery and loads. SuPER powers various DC loads such as LED lighting, DC motors, and computer devices.

A working prototype for SuPER has been in place for several years, with many students' contributions in improving the efficiency, design, power load, and to extend the system's operational lifetime. This senior project will investigate the ability of the system to sustain various DC loads over duration of a simulated week as a function of incident solar radiation ("in-sol-ation") on the SuPER photovoltaic (PV) module. In order to reliably simulate the system, an insolation model will be developed to use as input for the SimuLink model developed by Tyler Sheffield (2) and then updated by Matthew McFarland. The model will be developed with worst-case conditions to test the system at minimum power inputs. The simulation will be able to determine minimum criteria for stable operation of the SuPER system of PV modules and loads. Additionally, the simulation will determine the maximum duration of motor operation that the system can operate under normal conditions.

II. Background

The current SuPER system model appears in Figure 1, which shows the top level block diagram for the system. The model contains many function blocks that perform calculations on the voltage and current generated by the block labeled "*PV, DC-DC Conv, Control Module.*" This module takes input insolation and temperature data and converts it to current and voltage using a model developed for the PV panel by Tyler Sheffield. The current and voltage values are then fed into a system bus which connects to the battery model and simulated loads. From here, the battery model records the charge mode, the state of charge, and the battery's terminal voltage and current. The model assumes 25°C for all temperatures. Lastly, loads are simulated with simple switches and timing schedules (see Appendix F) to determine the current drain on the battery. All of this data send to output as parameters of battery conditions: "**vbatt.mat**", "**batt_curr.mat**", and "**soc_7days.mat**".

The current SuPER model currently uses a fixed insolation data set that was recorded in San Luis Obispo, CA on a relatively clear day for use in model testing and shown in Figure 2. This data is empirically accurate, but contains noise that makes a wide scale evaluation of the model difficult. Additionally, the data is fixed to roughly 1100 W/m^2 peak insolation, and as such makes testing the model using lower and higher insolation inputs difficult. As this input method to the SimuLink model is inflexible, a new input model will be developed that will allow flexible control of the following factors: length of sunlight hours and peak insolation; both of which contribute to how much energy the PV panels will collect over the course of a day.

Local weather data from http://wx.sloweather.com and historical data from http://www.gaisma.com/en/location/san-luis-obispo-california.html were queried to gain an understanding of weather conditions that would be appropriate for a model.

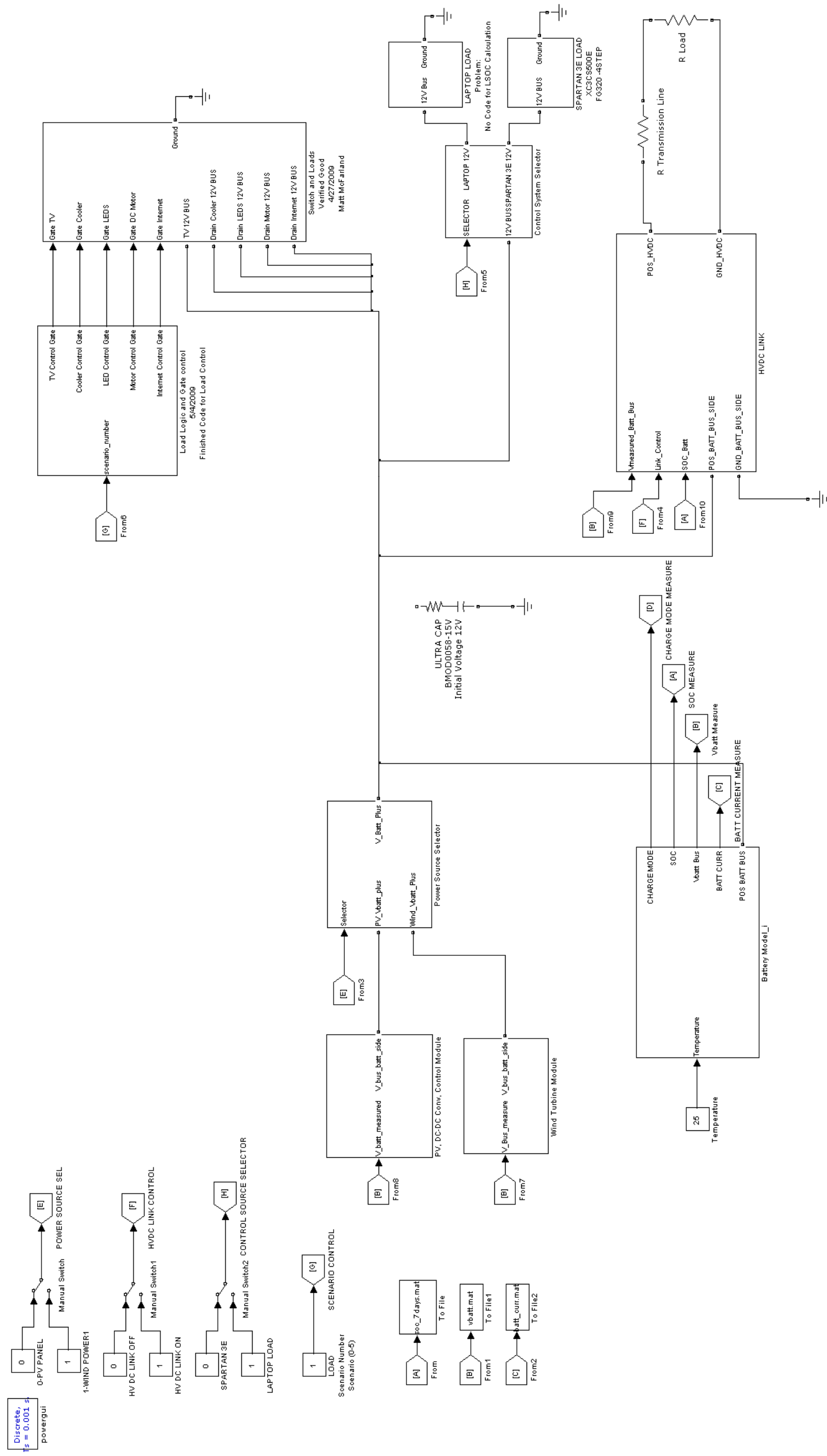


Figure 1 - SuPER SimuLink Model

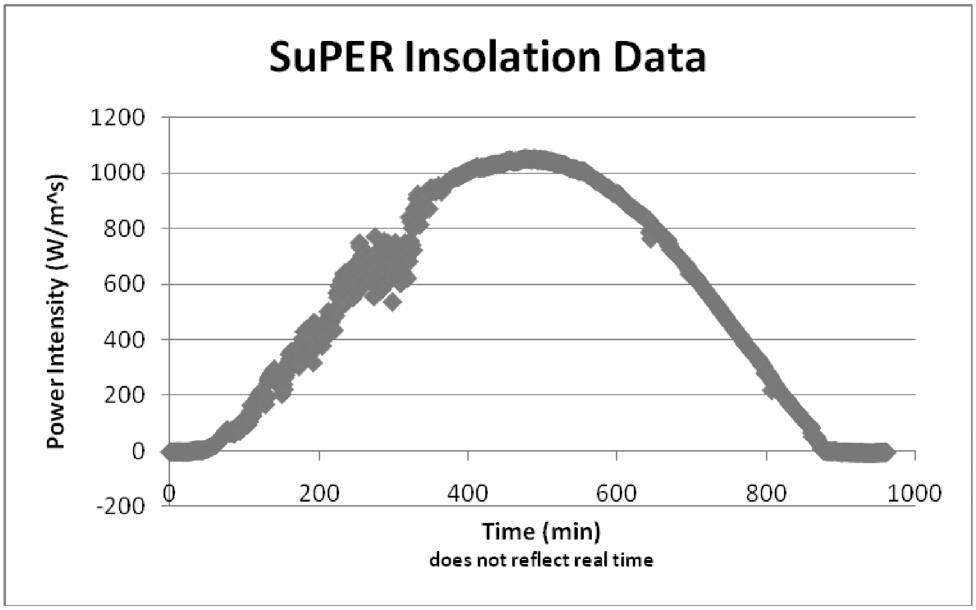


Figure 2 - SuPER Insolation Data used in T. Sheffield and M. McFarland models

There is also a matter of the angle at which the PV panel points to the incident solar rays that arrive onto the surface of the planet. Adjusting the tilt of the panel with relation to the movement of the sun allows more energy to be captured due to the time of day incident rays normal to the panel peak. However, modeling a simple fixed tilt panel will suffice for this simulation. Figure 3 shows an example of local insolation data for the date of May 30, 2010. It is apparent that this curve can be modeled as a sinusoid due to the rotating nature of the planetary bodies.

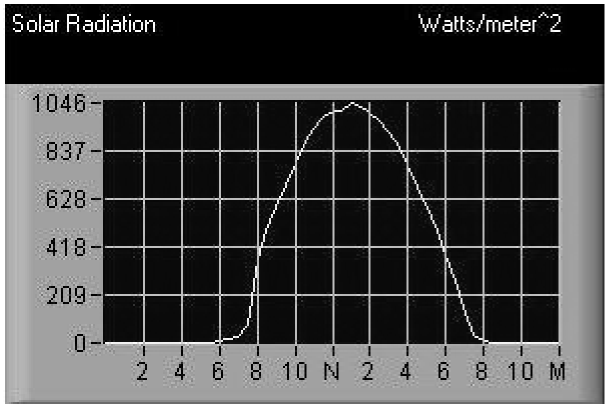
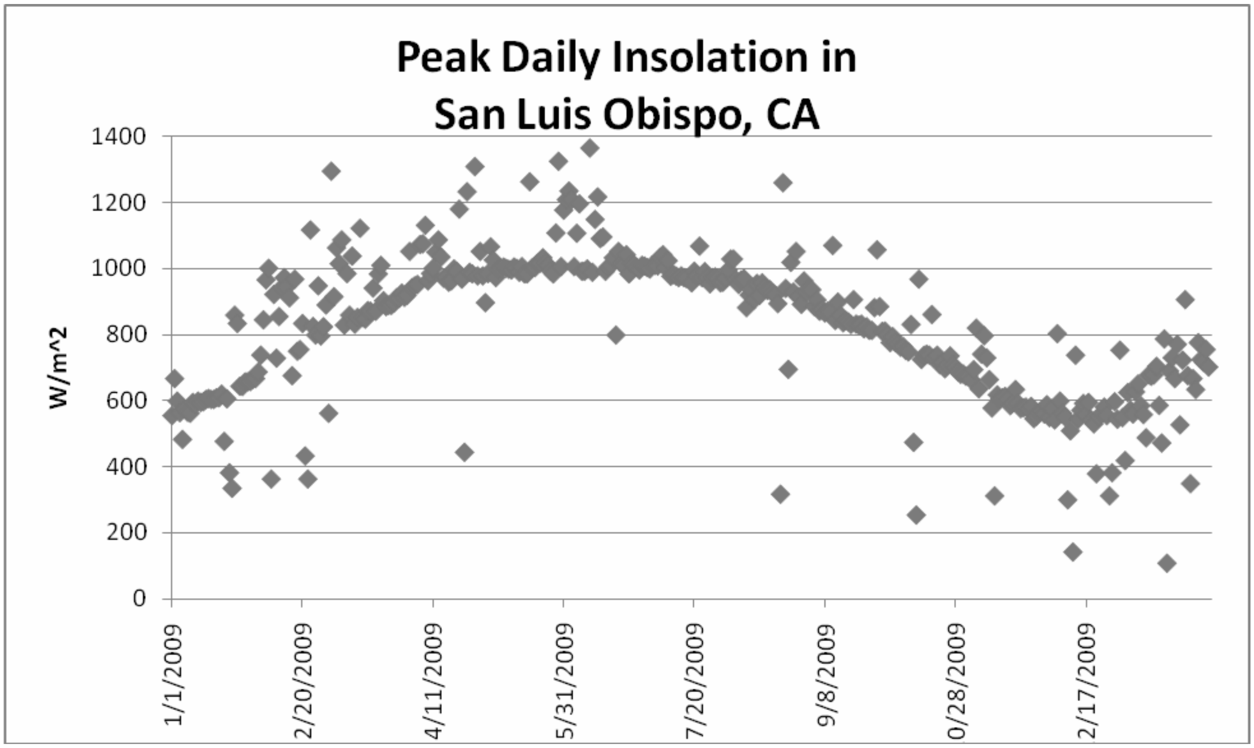


Figure 3 - Sample insolation data for May 30, 2010 in San Luis Obispo, CA
Courtesy of http://wx.sloweather.com/graphs.htm

III. Insolation Model

To effectively run the simulation on the SimuLink model, a consistent set of input parameters must first be constructed. For example, Figure 4 shows the daily peak insolation recorded over a year's period between Jan. 1st, 2009 and Feb. 1st, 2010 in San Luis Obispo, CA (see Appendix A). This graph does not indicate cloud cover; only the maximum achieved for that day is recorded. Of particular interest for this project, the trend shown in the graph reveals that the minimum insolation at the winter solstice (shortest day of the year) is near 500 W/m^2. Similarly, the trend for maximum insolation occurs near the summer solstice (longest day of the year) at just above 1000 W/m^2. The ideal insolation data does not take into account factors such as cloud cover and shading that may occur during the course of the day since the data from NASA Langley Research Center Atmospheric Science Data Center (3) already takes into account those factors in the calculation of the average surface radiation. These values represent the minimum and maximum insolation required to be tested on the SuPER system.

However, there are other factors in building the insolation model. The length of the day is of interest since more sunlight hours will allow more energy (Watt-hours) to be collected by the PV panels. Again, focusing on the extremes of the seasons, winter solstice and summer solstice will be the limits of the simulation in regards to the length of the day. Specifically, the worst-case scenario will be considered for the simulation, and the data will be modeled for a winter solstice setting – short length of day and minimum peak insolation.



Finally, the local data gathered can be modeled as a half-sine wave allowing the input data to be iterated through differing strengths of insolation.

Figure 4 - Peak daily insolation in San Luis Obispo, CA from Jan 1st, 2009 to Feb 2010.
Courtesy of Chris Arndt and WeatherElement.com. See Appendix A.

Calculating the length of the day

The first step in the simulation model is to determine the length of the day for any given year. A MATLAB program is written to calculate the length of the day based on specific latitude (see Appendix B). An algorithm for calculating the length of a day was utilized (4), and implemented in MATLAB. Since we are interested only in the shortest day of the year, we take the first iteration of the program's outputs (Day 1 = December 21, typically winter solstice). The program generates an animation plot of the year's daily insolation curves for a specified latitude and peak insolation. This model is useful for a year-long simulation; however, the length of such a simulation would require a

long processing time or a super-computer to get effective results. Thus, the simulation will only focus on seven day's worth of data to shorten the time period required for the computer system to simulation in MATLAB/SimuLink.

A MATLAB/SimuLink model is also generated that would take as inputs the latitude of region under simulation (San Luis Obispo, CA = 35.28N) and the peak insolation curve desired. Using the algorithm described earlier, seven days worth of insolation data is constructed for use as input to the SuPER model. Figure 5 shows the block diagram of the SimuLink model, and its code is available in Appendix C. There is an assumption made in this model that only the minimum, or worst-case conditions, will be tested. Thus, *InsolationWeekly* block will generate seven identical "winter solstice" days to test. More criteria and methods used in this simulation are described in the following section of this document.

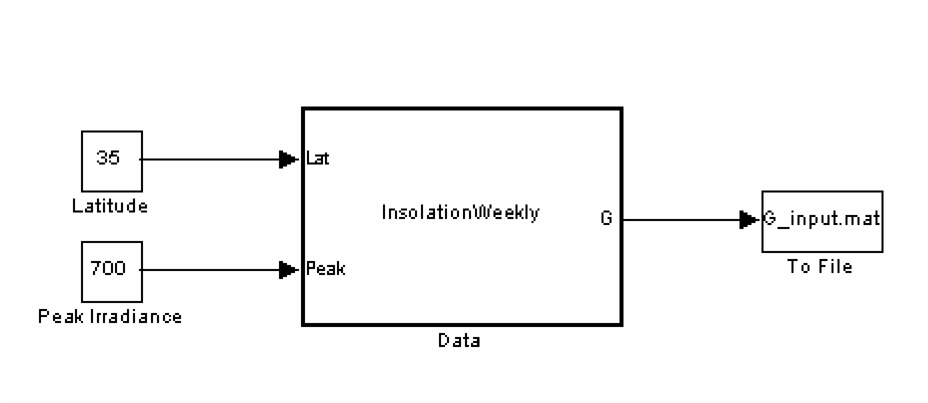


Figure 5 - Insolation Seven Day SimuLink Model

IV. Methods of Simulation and Testing

The goal of this project is to test the SuPER system model with multiple input parameters and find the minimum insolation required to operate the system for uninterrupted durations. To achieve this simulation requirement, the insolation model described in the previous section will be used. Next, the simulation will vary the DC loading on the system and determine stability points for various load demands. The criterion that will be used in this simulation is to maintain the battery's state of charge (SOC) at 80% of capacity. This is chosen to enable the system to maintain a long lifetime of operation. Thus, 80% SOC will be the exit criterion for each simulation.

The SuPER system should be operated at the proper tilt angle to capture the maximum amount of radiated energy from the sun. Under this assumption, it is possible to model insolation due to historical data in specific regions on Earth (4). Data was also collected from local weather stations and used as the baseline for generating ideal insolation data. As described in the section regarding the insolation model, the range of insolation used in the simulation will vary between 300-1000 W/m^2.

On each SuPER module, there is a PV cell, battery, ¼ HP motor, and various static loads such as refrigerator, television set, portable computer, and LED lighting. Additionally, the battery must also maintain at least 80% state-of-charge (SOC) in order to maximize its lifetime and usefulness as part of the SuPER concept. This restriction and the desire to have the system be maintained completely stand-alone require careful scheduling of loads in order to maximize the energy captured. Modeling the solar power intensity to charge on the battery is important due to the reliance on the battery for motor operation on a daily basis. Furthermore, the PV panel used for SuPER is rated

at 150W maximum. This rating of the PV panel means that the battery will need to supplement loads greater than 150W total. When power from the PV panel exceeds the battery charging requirement (SOC = 100%), the auxiliary power generated by the PV panel is used to power loads directly. The excess power can run these loads that would normally require battery power, further extending the life and stored energy of the battery.

The simulation of the SuPER system is performed in two phases. The first phase is to test the motor operation solely using a variety of insolation levels. This testing will begin with the motor operating for one hour, and will find the minimum peak insolation required to maintain the system at 80% SOC. Due to the motor's large operating current (≈20 Amperes max) and power rating (237W max), the ideal time of operation is at the solar noon of each day. This means that the PV panel is collecting the maximum amount of solar radiation which will supplement the battery in providing the high current load. Once the minimum insolation value for one hour operation is determined, increased duration of the motor will be tested to find other values that maintain the system stability at the battery's charge threshold.

The second phase of the simulation will be performed on static loads, such as LED lighting, television set, radio equipment, and the cooler. These devices are also rated at a much lower power rating than the motor. Similar methodology will be used in testing the static loads, beginning with 100W-hr/day. Furthermore, since these loads are not required to operate during solar noon (specifically with the case of LED lighting which would be redundant) a timing schedule is created to manage off-peak load demand. Two scenarios are tested (see Appendix F) with similar energy demand (100

W-hr/day) but at different times of the day. These scenarios will test the system's capability to deal with current draw during off-peak hours. Similar to the motor simulation, the insolation levels will be increased until the SOC on the battery reaches 80% threshold.

Table II lists the power ratings of each of the loads tested in this project. These loads are modeled as ohmic devices that draw a steady state power. They are switched on and off from SuPER's logic controller using MOSFET transistors. Additionally, the load scheduling used in simulation is listed in Appendix F.

Table I - SuPER model loads under test

Load	Rating (W)
Motor	237
LED	4.5
TV	8
Cooler	60
Internet	24

A set of insolation data graphs were prepared to have consistent and repeatable input data to use for all simulations in this project. For each insolation step of 100 W/m^2, data points were generated using the *InsolationWeekly* SimuLink model and stored as .MAT files. Beginning with 300 W/m^2, each simulation was run and the resulting SOC output found in "**soc_7days.mat**" was examined. If the particular trial did not achieve 80% SOC, the next step of insolation graph was used until the threshold was achieved. Figure 6 below shows a sample of the input data used for this simulation.

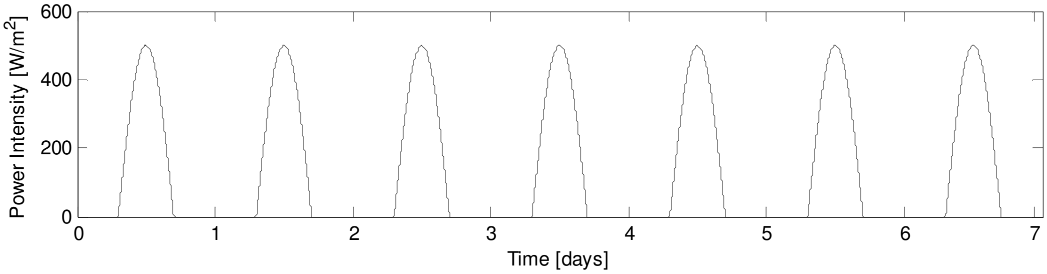


Figure 6 - Sample input data for the SuPER SimuLink simulation

V. Results of Simulation

The results of the individual simulations are available in Appendix D for motor loads, and Appendix E for static loads. The results are tabulated below in Table II and Table III respectively.

Table II - Results from simulation of motor loads

		Peak Insolation (W/m²)					Comments
		300	400	500	600	700	
Duration (hrs)	1	fail	fail	pass	-	-	Stable at 90% SOC
	2	fail	fail	pass	-	-	Stable at >85% SOC
	3	fail	fail	fail	pass	-	500 W/m² reveals daily loss, but >80% after 7 days 600 W/m² stable at >80% SOC
	4	fail	fail	fail	fail	pass	Stable at >80% SOC

Table III - Results from simulation of static loads

		Peak Insolation (W/m²)							
		300	400	500	600	700	800	900	1000
Load Scenario	1	fail	fail	fail	fail	fail	pass	-	-
	2	fail	fail	fail	fail	fail	fail	fail	fail

The first observation concerned the motor load at varying levels of insolation. Simulation was started with 1 hour loading of the motor (237W) at the solar noon with 300 W/m² peak insolation. Unfortunately, 300 W/m² peak curve is insufficient to maintain the battery charge above 80% after only two days of operation. Increasing

the peak insolation to 400 W/m^2 also does not solve this problem, but 500 W/m^2 achieves stable balance between load and charge. The latter operation is able to maintain the charge at least to 90% on a daily basis. This method is repeated for a motor duration of two hours, and again 500 W/m^2 is sufficient to maintain SOC. Running the motor for three hours requires 600 W/m^2 peak insolation to maintain the SOC. Running the motor for four hour requires between 600-700 W/m^2 to maintain the charge; however, the system is more stable for day-to-day operation under 700 W/m^2 insolation, while 600 W/m^2 still shows some loss of charge on a daily basis.

While the simulation of the motor duration only simulated one load at solar noon, the static loads were switched on at varying times of the day. See Appendix F for a full scheduling of loads used in both scenarios. It was predicted that these simulations would behave similarly to the motor for similar sized loads. Since the motor is rated at 237W, it was predicted that operating 230W load around the same time would result in similar SOC curves. However, the simulations revealed that this is not the case.

Starting with scenario # 1 with 100.5 W-hr/day load and 96W of load running near the solar noon, a simulation was run at 300 W/m^2 peak insolation. The last 4.5W of load is LED running at time 20:00. The off-peak loading put a tremendous amount of strain on the battery's SOC. Almost immediately on the first day, the charge on the battery dropped to 70%. Increasing the peak insolation by steps of 100W revealed how much the effect of off-peak loading had on the system, for to maintain the static load of 100.5 W-hr/day with 4.5W off-peak required 800 W/m^2 insolation to maintain a SOC of 80%. Furthermore, the resulting SOC for this scenario appears to be marginally stable as evident by the decline in charge starting at Day 4 of the simulation (see Figure 24).

Simulation scenario #2 ran with 117W-hr/day load, this time with two hours of LED at off-peak. Similar to the previous simulation, the system required a much larger insolation value than the motor. Even at 1000 W/m^2 peak insolation data to the PV module, the system could not maintain the SOC to the threshold required.

VI. Recommendations

Currently, the battery model runs on a 50% threshold which determines the charging algorithm. For power flow into the battery above this threshold, there are logarithmic gains to the SOC in the battery. When the SOC is below the threshold, there are exponential gains to the SOC in the battery. Thus, at certain conditions, the stability point between daily insolation and load schedule would settle below this threshold due to the increased charging rate. A more accurate model of the battery would model the chemical properties and careful attention to charge mechanisms for the specific battery used on SuPER.

Additionally, there are always-on devices on the SuPER cart that draw energy from the battery. This includes the Spartan 3E control module that regulates the load and power flow switching to and from the battery. While the device itself draws a low current, this steadily drops the SOC on the battery by roughly 5-7% on a daily basis. With no load, this system can maintain battery state nearly indefinitely with very minimal insolation levels. However, at low to moderate loading, this constant current draw presents some difficulties for the battery to recharge properly to the 80% SOC threshold under heavy stress loads such as the motor operation. Incidentally, it was found that moderate loads running for as long as four hours also presented similar stresses on the battery to maintain the 80% threshold.

VII. Conclusion

This project takes an existing model for the SuPER system and builds on-top of the work of Tyler Sheffield and Matt McFarland. A new insolation model was created to simulate and test the SuPER SimuLink model and examine the system's capability to operate in a variety of insolation. The insolation calculator was constructed in a manner to allow the SuPER model to be tested in regions other than San Luis Obispo, CA. The simulations provide a good tool to gauge the efficiency of the system for operating loads such as motors and LED lighting.

The two simulations also reveal how much an effect off-peak loading has on the SuPER system running on only PV modules. The power rating of the PV module, 150W max, is most likely the reason the system cannot convert more solar energy to keep up with large DC loads; while the battery's model is the most likely source of error in the simulation. However, defining a realistic battery model is difficult to define as most are based on chemical properties of the materials rather than electrical. These two factors are likely places for improving the SuPER model.

This project was successful in meeting its goals of determining minimum insolation required to operate the motor for several operation durations. Through the simulation, it was found that the off-peak loading has a detrimental effect on the battery's charge. Prolonged use of the SuPER system during non-daylight hours will affect the longevity and reliability of the battery. In this respect, finding high efficiency devices such as LED lighting and radio equipment would benefit the SuPER system. Fortunately, the simulation of the motor proved to have good results compared to the static loads. The ability of the SuPER system to operate the motor on a regular basis for at least one hour

daily is beneficial to the purpose of the SuPER project in helping underdeveloped countries to obtain useful electrical power.

VIII. Works Cited

(1) Harris, JG. "White Paper for Sustainable Power for Electrical Resources – SuPER." 2005. <http://courseware.ee.calpoly.edu/~jharris/research /super_project/white_paper_susper.pdf> (Accessed 2010 March 20).

(2) Sheffield, T. "Cal Poly SuPER System Simulink Model and Status and Control System." 2007. <http://courseware.ee.calpoly.edu/~jharris/research /super_project/ts_thesis.pdf> (Accessed 2010 January 17).

(3) "San Luis Obispo, California - Sunrise, sunset, dawn and dusk times for the whole year - Gaisma," 2002. (Online). < http://www.gaisma.com/en/location/san-luis-obispo-california.html> (Accessed 2010 January 18).

(4) Glarner, T. "Length of Day and Twilight," July 2009. (Online) <http://www.gandraxa.com/length_of_day.aspx> (Accessed 2010 January 17).

IX. Appendix

A. Peak Daily Insolation as recorded by Chris Arndt of SLO Water Reclamation Facility and WeatherElement.com

Date	W/m^2	Time
1/1/2009	554	12:09:20
1/2/2009	666	12:45:28
1/3/2009	598	12:46:27
1/4/2009	563	12:15:00
1/5/2009	482	11:58:57
1/6/2009	573	11:47:58
1/7/2009	564	12:15:41
1/8/2009	561	12:12:09
1/9/2009	594	12:25:49
1/10/2009	589	12:08:14
1/11/2009	598	12:25:22
1/12/2009	594	12:10:51
1/13/2009	596	12:07:45
1/14/2009	603	12:11:49
1/15/2009	606	12:14:46
1/16/2009	603	12:20:46
1/17/2009	603	12:09:39
1/18/2009	608	12:14:08
1/19/2009	608	12:14:41
1/20/2009	619	12:22:14
1/21/2009	476	10:53:40
1/22/2009	605	12:19:51
1/23/2009	381	11:01:43
1/24/2009	334	15:51:51
1/25/2009	858	11:10:26
1/26/2009	833	13:12:19
1/27/2009	643	12:35:18
1/28/2009	642	12:11:58
1/29/2009	656	12:15:54
1/30/2009	657	12:28:06
1/31/2009	657	12:18:21
2/1/2009	664	12:23:05
2/2/2009	666	12:14:31
2/3/2009	686	12:28:06
2/4/2009	737	11:14:54
2/5/2009	844	14:05:45
2/6/2009	965	13:23:38
2/7/2009	1000	12:11:37
2/8/2009	362	11:21:29
2/9/2009	921	13:06:04
2/10/2009	728	12:07:55
2/11/2009	854	12:29:35
2/12/2009	942	13:15:47
Date	**W/m^2**	**Time**
2/13/2009	972	12:07:41
2/14/2009	944	11:13:39
2/15/2009	911	12:00:09
2/16/2009	675	11:39:34
2/17/2009	967	11:29:32
2/18/2009	749	11:28:40
2/19/2009	754	12:20:13
2/20/2009	833	13:02:30
2/21/2009	432	12:30:59
2/22/2009	362	12:48:54
2/23/2009	1116	12:30:55
2/24/2009	824	12:48:52
2/25/2009	798	12:16:48
2/26/2009	947	12:27:22
2/27/2009	795	13:11:55
2/28/2009	823	12:09:14
3/1/2009	889	13:59:39
3/2/2009	561	13:54:06
3/3/2009	1294	12:22:27
3/4/2009	914	13:40:21
3/5/2009	1062	11:44:43
3/6/2009	1014	11:37:10
3/7/2009	1086	11:55:42
3/8/2009	828	13:08:42
3/9/2009	984	12:19:18
3/10/2009	858	13:09:53
3/11/2009	1037	14:05:01
3/12/2009	831	13:09:22
3/13/2009	851	13:09:19
3/14/2009	1121	12:34:47
3/15/2009	851	13:25:52
3/16/2009	846	13:17:47
3/17/2009	872	13:20:14
3/18/2009	870	13:12:44
3/19/2009	940	13:21:19
3/20/2009	870	13:32:45
3/21/2009	983	12:14:09
3/22/2009	1009	14:59:21
3/23/2009	902	13:15:40
3/24/2009	884	13:16:18
3/25/2009	888	13:07:48
3/26/2009	888	13:18:52
3/27/2009	895	13:04:15
Date	**W/m^2**	**Time**
3/28/2009	911	13:52:21
3/29/2009	909	13:07:14
3/30/2009	925	13:15:14
3/31/2009	912	13:16:49
4/1/2009	918	13:06:14
4/2/2009	1051	13:18:14
4/3/2009	942	13:13:16
4/4/2009	947	13:20:46
4/5/2009	951	12:54:20
4/6/2009	1072	14:06:27
4/7/2009	1074	14:30:35
4/8/2009	1130	12:25:53
4/9/2009	962	13:18:08
4/10/2009	984	12:50:05
4/11/2009	1000	13:30:28
4/12/2009	1049	12:10:48
4/13/2009	1086	14:06:18
4/14/2009	1034	15:04:54
4/15/2009	970	13:03:39
4/16/2009	972	13:06:08
4/17/2009	958	13:03:35
4/18/2009	962	13:09:02
4/19/2009	998	13:00:02
4/20/2009	991	13:21:59
4/21/2009	1179	14:43:41
4/22/2009	967	12:54:29
4/23/2009	443	14:01:01
4/24/2009	1232	12:13:21
4/25/2009	988	13:55:01
4/26/2009	983	13:12:25
4/27/2009	1308	13:14:33
4/28/2009	977	12:52:38
4/29/2009	1051	14:00:48
4/30/2009	977	12:57:05
5/1/2009	896	11:34:30
5/2/2009	984	12:04:07
5/3/2009	1065	13:37:15
5/4/2009	1025	12:32:41
5/5/2009	972	13:05:15
5/6/2009	997	12:51:50

5/7/2009	1000	12:52:55	6/25/2009	983	13:20:30	8/13/2009	954	13:15:28
5/8/2009	1004	12:53:52	6/26/2009	1014	13:20:39	8/14/2009	918	13:40:55
5/9/2009	1000	12:53:52	6/27/2009	1011	13:20:49	8/15/2009	956	13:22:26
5/10/2009	997	12:51:37	6/28/2009	1002	13:21:21	8/16/2009	940	13:07:21
5/11/2009	995	12:53:13	6/29/2009	995	13:21:02	8/17/2009	933	13:08:22
5/12/2009	1004	13:23:54	6/30/2009	1009	13:21:42	8/18/2009	935	14:01:29
5/13/2009	1000	12:51:06	7/1/2009	1007	13:21:46	8/19/2009	925	13:33:07
5/14/2009	988	14:18:07	7/2/2009	1002	13:20:24	8/20/2009	919	13:07:33
5/15/2009	1005	14:18:28	7/3/2009	998	13:22:28	8/21/2009	893	13:19:02
5/16/2009	983	12:44:38	7/4/2009	1011	13:24:05	8/22/2009	316	12:14:27
5/17/2009	983	12:44:00	7/5/2009	1009	13:22:42	8/23/2009	1259	14:11:35
5/18/2009	1262	13:16:29	7/6/2009	1007	13:23:15	8/24/2009	939	13:17:28
5/19/2009	1002	12:49:01	7/7/2009	1034	14:32:04	8/25/2009	694	16:04:44
5/20/2009	1002	12:48:18	7/8/2009	1041	13:44:07	8/26/2009	1018	13:39:53
5/21/2009	1016	13:11:35	7/9/2009	1002	13:29:46	8/27/2009	928	13:11:07
5/22/2009	1016	12:41:53	7/10/2009	1023	13:48:28	8/28/2009	1051	12:54:32
5/23/2009	1032	10:23:45	7/11/2009	976	13:03:29	8/29/2009	914	13:00:31
5/24/2009	1016	12:58:22	7/12/2009	981	13:26:36	8/30/2009	891	13:13:28
5/25/2009	1009	13:19:46	7/13/2009	977	13:03:46	8/31/2009	962	11:50:20
5/26/2009	991	12:53:37	7/14/2009	972	13:13:58	9/1/2009	928	13:23:59
5/27/2009	983	12:53:34	7/15/2009	977	12:52:01	9/2/2009	939	13:51:01
5/28/2009	1107	14:27:54	7/16/2009	972	13:06:01	9/3/2009	935	13:31:58
5/29/2009	1324	12:28:50	7/17/2009	969	13:33:08	9/4/2009	884	13:47:59
5/30/2009	1005	10:32:10	7/18/2009	1403	12:41:37	9/5/2009	904	13:15:53
5/31/2009	1176	12:31:00	7/19/2009	956	12:57:50	9/6/2009	870	13:06:20
6/1/2009	1208	12:29:45	7/20/2009	991	13:34:26	9/7/2009	875	13:06:52
6/2/2009	1234	12:33:12	7/21/2009	977	13:36:26	9/8/2009	865	13:12:52
6/3/2009	1208	12:51:01	7/22/2009	1067	14:04:34	9/9/2009	870	13:14:46
6/4/2009	1005	13:17:26	7/23/2009	972	12:58:05	9/10/2009	868	13:00:11
6/5/2009	1106	11:29:06	7/24/2009	990	12:57:32	9/11/2009	1069	13:39:25
6/6/2009	1195	10:46:01	7/25/2009	972	12:59:24	9/12/2009	842	13:11:21
6/7/2009	991	13:16:22	7/26/2009	953	12:55:25	9/13/2009	898	13:53:22
6/8/2009	991	13:18:58	7/27/2009	972	13:38:00	9/14/2009	858	12:56:14
6/9/2009	998	13:16:35	7/28/2009	974	13:15:52	9/15/2009	835	12:50:46
6/10/2009	1364	12:41:40	7/29/2009	969	10:33:34	9/16/2009	842	13:06:42
6/11/2009	988	11:07:02	7/30/2009	956	12:58:05	9/17/2009	838	13:13:44
6/12/2009	1148	12:04:18	7/31/2009	958	12:58:18	9/18/2009	830	12:55:15
6/13/2009	1216	13:17:02	8/1/2009	970	12:54:21	9/19/2009	905	12:54:44
6/14/2009	1090	14:29:45	8/2/2009	995	14:21:25	9/20/2009	831	13:06:44
6/15/2009	1095	11:13:26	8/3/2009	1028	13:01:14	9/21/2009	828	12:53:15
6/16/2009	991	13:17:46	8/4/2009	1028	12:40:09	9/22/2009	831	13:01:47
6/17/2009	1004	13:17:45	8/5/2009	965	13:03:13	9/23/2009	817	13:03:39
6/18/2009	1009	13:18:52	8/6/2009	951	13:06:07	9/24/2009	823	13:10:39
6/19/2009	1032	14:34:59	8/7/2009	965	13:01:08	9/25/2009	812	12:44:08
6/20/2009	798	12:38:54	8/8/2009	969	14:13:43	9/26/2009	812	12:58:41
6/21/2009	1051	14:31:40	8/9/2009	881	12:19:28	9/27/2009	881	12:35:09
6/22/2009	1014	13:19:07	8/10/2009	919	13:30:33	9/28/2009	1056	13:22:46
6/23/2009	1009	13:19:12	8/11/2009	933	12:59:00	9/29/2009	884	12:14:36
6/24/2009	1041	12:40:47	8/12/2009	905	12:57:28	9/30/2009	809	13:00:09

10/1/2009	810	13:02:14
10/2/2009	798	12:59:44
10/3/2009	775	13:03:11
10/4/2009	793	12:41:06
10/5/2009	775	12:47:08
10/6/2009	770	13:01:41
10/7/2009	761	12:53:31
10/8/2009	763	12:51:58
10/9/2009	751	12:44:25
10/10/2009	747	12:56:26
10/11/2009	830	14:04:00
10/12/2009	473	12:45:30
10/13/2009	253	11:17:22
10/14/2009	967	14:54:53
10/15/2009	724	12:53:51
10/16/2009	737	12:56:14
10/17/2009	740	14:26:42
10/18/2009	737	11:48:21
10/19/2009	860	12:19:58
10/20/2009	729	12:58:32
10/21/2009	737	13:09:48
10/22/2009	708	13:01:15
10/23/2009	714	13:18:16
10/24/2009	696	12:46:42
10/25/2009	708	12:52:10
10/26/2009	735	13:01:39
10/27/2009	707	12:50:42
10/28/2009	700	12:44:12
10/29/2009	686	12:46:47
10/30/2009	679	12:46:40
10/31/2009	680	12:50:14
11/1/2009	673	11:44:37
11/2/2009	673	11:49:40
11/3/2009	663	11:40:38
11/4/2009	693	12:59:53
11/5/2009	819	10:54:41
11/6/2009	635	11:54:30
11/7/2009	740	12:54:32
11/8/2009	796	12:12:01
11/9/2009	729	12:23:01
11/10/2009	663	12:06:59
11/11/2009	577	0:00:11
11/12/2009	311	9:01:58
11/13/2009	617	11:59:48
11/14/2009	605	11:44:46
11/15/2009	608	11:59:18
11/16/2009	612	11:58:42
11/17/2009	603	11:43:49
11/18/2009	584	11:56:18
11/19/2009	592	11:50:21
11/20/2009	633	10:51:17
11/21/2009	591	11:47:26
11/22/2009	575	11:45:26
11/23/2009	578	11:44:04
11/24/2009	580	11:57:49
11/25/2009	573	12:01:22
11/26/2009	582	11:46:53
11/27/2009	545	14:11:33
11/28/2009	552	11:52:20
11/29/2009	564	11:55:20
11/30/2009	568	11:55:48
12/1/2009	559	12:08:18
12/2/2009	587	11:14:15
12/3/2009	548	12:09:15
12/4/2009	575	12:02:44
12/5/2009	541	10:05:34
12/6/2009	802	11:39:39
12/7/2009	598	13:55:50
12/8/2009	561	11:49:38
12/9/2009	550	12:03:53
12/10/2009	299	10:42:15
12/11/2009	508	13:43:35
12/12/2009	141	11:02:14
12/13/2009	737	13:19:59
12/14/2009	543	12:58:41
12/15/2009	570	13:07:15
12/16/2009	591	11:08:26
12/17/2009	557	11:54:00
12/18/2009	594	11:32:00
12/19/2009	540	13:13:05
12/20/2009	529	12:56:36
12/21/2009	378	12:45:34
12/22/2009	550	12:15:27
12/23/2009	561	12:02:27
12/24/2009	580	12:47:01
12/25/2009	554	12:14:57
12/26/2009	311	9:41:04
12/27/2009	381	13:48:58
12/28/2009	596	10:50:42
12/29/2009	543	12:18:47
12/30/2009	752	12:57:04
12/31/2009	548	12:02:54
1/1/2010	418	11:49:55
1/2/2010	624	11:39:53
1/3/2010	571	12:14:54
1/4/2010	559	12:17:54
1/5/2010	626	11:24:49
1/6/2010	650	11:49:54
1/7/2010	584	13:04:28
1/8/2010	557	11:59:21
1/9/2010	487	10:58:12
1/10/2010	677	12:59:20
1/11/2010	673	13:08:53
1/12/2010	677	10:21:08
1/13/2010	703	12:52:20
1/14/2010	585	12:23:42
1/15/2010	471	10:21:07
1/16/2010	786	13:45:32
1/17/2010	107	8:46:33
1/18/2010	689	12:40:01
1/19/2010	729	13:13:19
1/20/2010	666	14:06:34
1/21/2010	770	13:55:52
1/22/2010	526	11:35:05
1/23/2010	722	12:45:21
1/24/2010	905	12:14:36
1/25/2010	675	11:17:54
1/26/2010	348	15:00:18
1/27/2010	666	12:39:26
1/28/2010	633	12:15:41
1/29/2010	775	12:56:19
1/30/2010	724	12:23:38
1/31/2010	715	13:15:55
2/1/2010	754	11:01:01
2/2/2010	701	10:58:18

B. *LengthOfDay.m – MATLAB code for calculating length of sun-hours*

```
% Algorithm adopted from http://herbert.gandraxa.com/length_of_day.aspx
%
% This program generates an animation plot of a simplified insolation curve
% from Winter Solstice for a whole year based on user defined latitude and
% peak insolation.  Sampling the variable 'i' at a specific day (0-364) and
% examining variable 'p' will reveal the insolation graph over time for that
% day.

% Vector holding the days of the year, starting with the Winter Solstice
Day = linspace(0,364,365);

% Earth's axial tilt to the solar plane [Degrees]
Axis = 23.439;

% Define daily peak Solar Insolation (W/m^2) and generate vector
Peak = input('Enter the peak insolation for this simulation in
       W/m^2 [0-1100]: ');
G_peak = Peak*ones(1,365);

% Define latitude for location
Lat = input('Enter the latitude at which the simulation will occur
      [0-90]: ');

% Load user defined data for Insolation data [Optional]
% temp = xlsread('E:\Sr Project\Insolation_Data_SLO.xls',2);
% Lat = temp(1);
% G_avg = rot90(temp(2:366));

% Calculate the length of the day
% Angle between observer and sun's zenith [Degrees]
z = 90 - Lat - cos(pi * Day / 182.625)*Axis;

% Angle between solar plane and sun's zenith [Degrees]
a = z + Lat;

% Distance between observer to sun's zenith
d = 1./sind(a);

% Distance from observer to the center of the sun's circle
t = d.*cosd(a);

% Exposed radius part between sun's zenith and sun's circle
m = 1 + tand(-Lat).*t;

% Fix m dataset to make sure it falls between 0 and 2
for i=1:1:365
    if m(i) > 2
        m(i) = 2;
    end
    if m(i) < 0
        m(i) = 0;
    end
```

```
end

% Angle between center of sun's disc and sunrise or sunset point on the
% solar circle (not the planet's disc), resp.
f = acosd(1-m);

% Exposed fraction of the sun's circle (0=never...1 = whole day)
b = f/180;

% Length of Day in hours
Length = b*24;

% Transform the average insolation (W/m^2) into peak instantaneous
% solar radiation (W/m^2) to generate insolation as function of time of
% day. [Optional]
% if (~isempty(G_avg))
%    G_peak = 2*G_avg./b;
% end

% Time of day in minutes
t = linspace(1,1440,1441);
% determine peak value from avg value + length of day

for i=1:1:365
    p = zeros(1,1440);
    for j=1:1:1440
        % G_peak gives max value of sin wave, period modulated to reflect
        % the length of the day as a function of the time of year.
        sunrise = floor(720 - Length(i)*30);
        if j < sunrise
            p(j) = 0;
        else
            p(j) = G_peak(i)*sin(pi/(Length(i)*60)*t(j-sunrise+1));
        end
        if p(j) < 0
            p(j) = 0;
            break;
        end
    end

    avg(i) = sum(p)./(2*Length(i)*60);

    plot(p,'DisplayName','p','YDataSource','p');
    set(gca,'XTick',0:60:1440)
    set(gca,'XTickLabel',{0:24})
    xlabel('Time (hrs)')
    ylabel('Power Intensity (W/m^2)')
    axis ([0 1440 0 1100]);
    title(['\fontsize{16}Day ',num2str(i)]);
    figure(gcf)
end
```

C. *InsolationWeekly.m – MATLAB code for generating seven days of insolation data*

```
% Function Insolation returns a year's worth of data for given Latitude
% and a Peak insolation, reported in minutes. Contains 24*60*365 = 525600
% data points.
function G  = InsolationWeekly(Lat,Peak)

% Vector holding the days of the year, starting with the Winter Solstice
Day = linspace(0,364,365);

% Earth's axial tilt to the solar plane [Degrees]
Axis = 23.439;

% Define daily peak Solar Insolation (W/m^2) and generate vector
G_peak = Peak*ones(1,365);

% Load user defined data for Insolation data [Optional]
% temp = xlsread('E:\Sr Project\Insolation_Data_SLO.xls',2);
% Lat = temp(1);
% G_avg = rot90(temp(2:366));

% Calculate the length of the day
% Angle between observer and sun's zenith [Degrees]
z = 90 - Lat - cos(pi * Day / 182.625)*Axis;

% Angle between solar plane and sun's zenith [Degrees]
a = z + Lat;

% Distance between observer to sun's zenith
d = 1./sind(a);

% Distance from observer to the center of the sun's circle
t = d.*cosd(a);

% Exposed radius part between sun's zenith and sun's circle
m = 1 + tand(-Lat).*t;

% Fix m dataset to make sure it falls between 0 and 2
for i=1:1:365
    if m(i) > 2
        m(i) = 2;
    end
    if m(i) < 0
        m(i) = 0;
    end
end

% Angle between center of sun's disc and sunrise or sunset point on the
% solar circle (not the planet's disc), resp.
f = acosd(1-m);


% Exposed fraction of the sun's circle (0=never...1 = whole day)
b = f/180;
```

```
% Length of Day in hours
Length = b*24;

% Transform the average insolation (W/m^2) into peak instantaneous
% solar radiation (W/m^2) to generate insolation as function of time of
% day. [Optional]
% if (~isempty(G_avg))
%    G_peak = 2*G_avg./b;
% end

% Time of day in minutes
minute = linspace(1,1440,1441);

% Builds the data set for the points, and stores in a .MAT file. Assume
% minute N*1440 is the first solar minute of each day.
G = zeros(1,10080);
for i=1:1:7
    for j=1:1:1440
        % G_peak gives max value of sin wave, period modulated to reflect
        % the length of the day as a function of the time of year.
        sunrise = floor(720 - Length(i)*30);
        k = (i-1)*1440+j;
        if j < sunrise
            G(k) = 0;
        else
            G(k) = G_peak(i)*sin(pi/(Length(i)*60)*minute(j-sunrise+1));
        end
        if G(k) < 0
            G(k) = 0;
            break;
        end
    end

    if i == 7
        break;
    end

    % avg(i) = sum(p)./(2*Length(i)*60);

    % plot(p,'DisplayName','p','YDataSource','p');
    % set(gca,'XTick',0:60:1440)
    % set(gca,'XTickLabel',{0:24})
    % xlabel('Time (hrs)')
    % ylabel('Power Intensity (W/m^2)')
    % axis ([0 1440 0 1400]);
    % figure(gcf)
end
end
```

D. State of Charge plots for Motor Loads

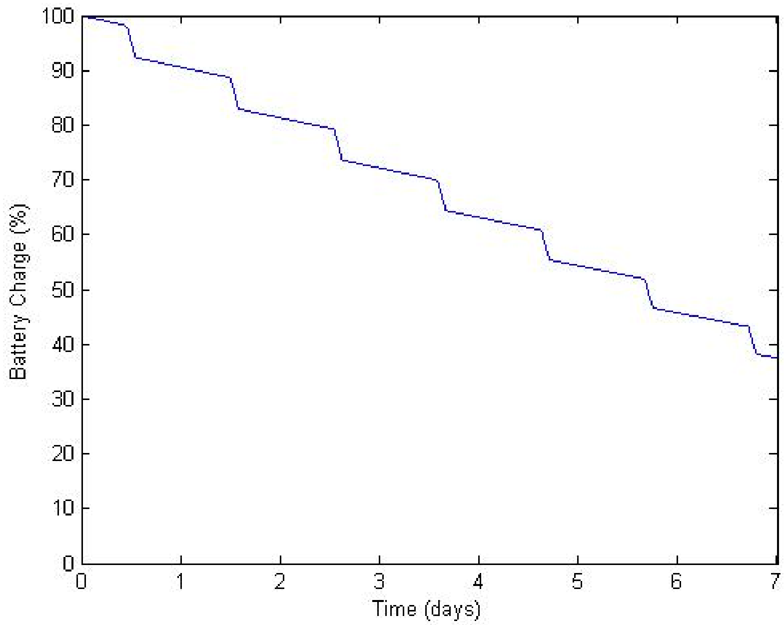


Figure 7 - Motor Duration: 1 hr, Peak Insolation: 300 W

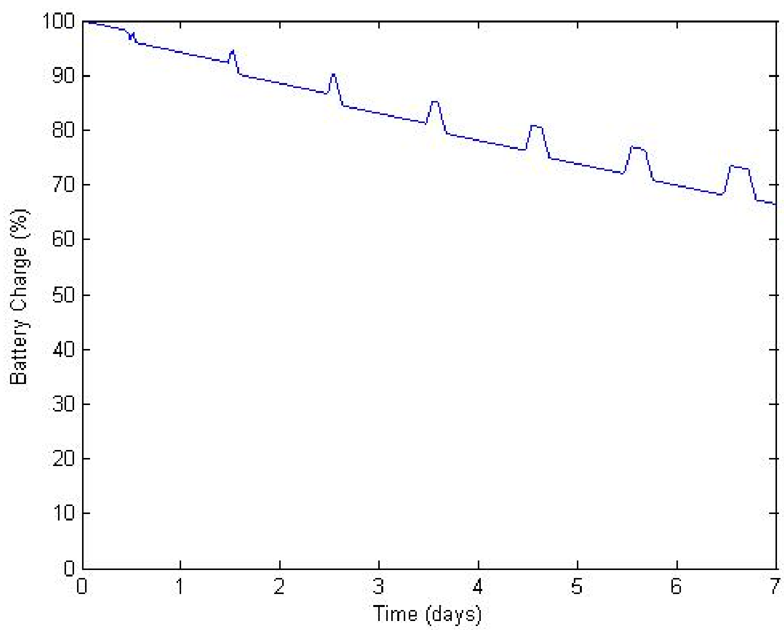


Figure 8 - Motor Duration: 1 hr, Peak Insolation: 400 W

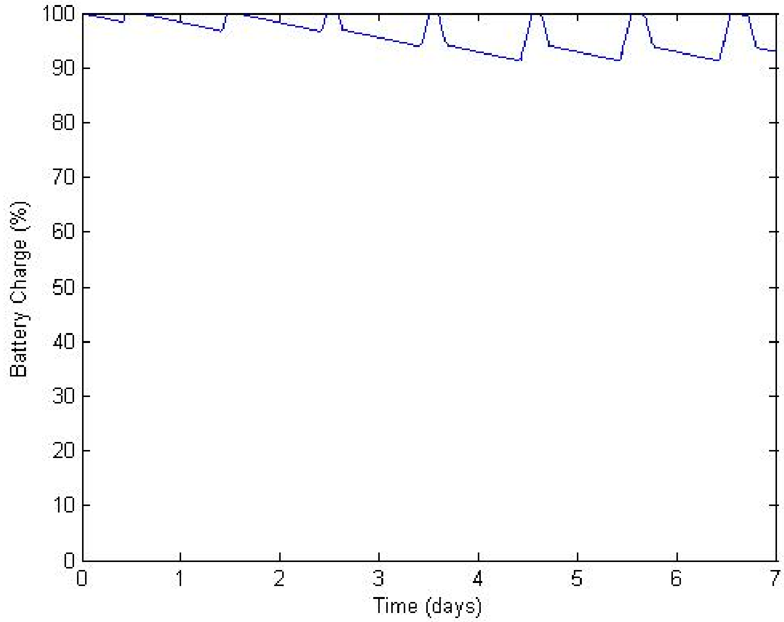


Figure 9 - Motor Duration: 1 hr, Peak Insolation: 500 W

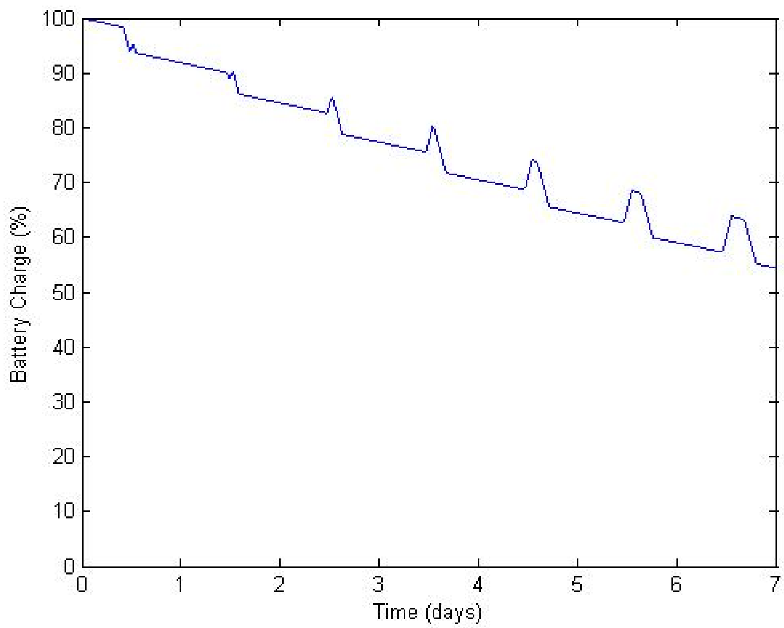


Figure 10 - Motor Duration: 2 hr, Peak Insolation: 400 W

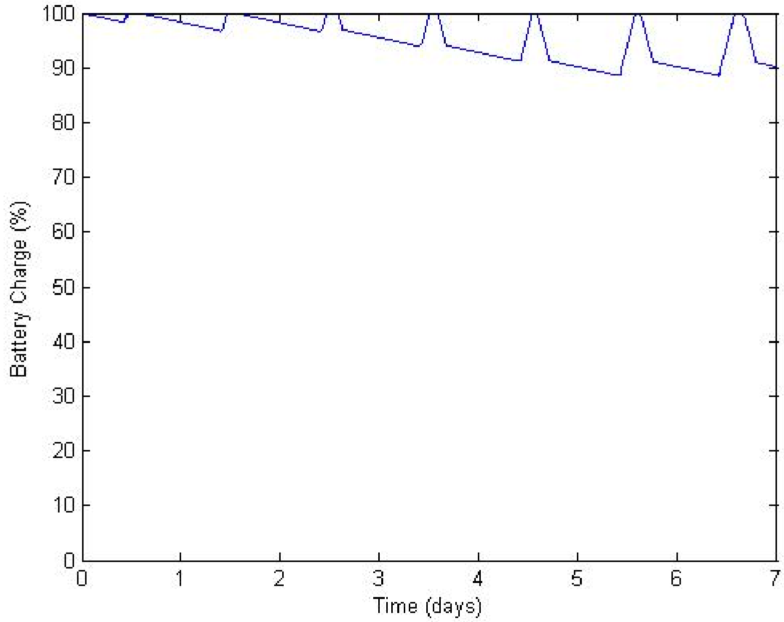


Figure 11 - Motor Duration: 2 hr, Peak Insolation: 500 W

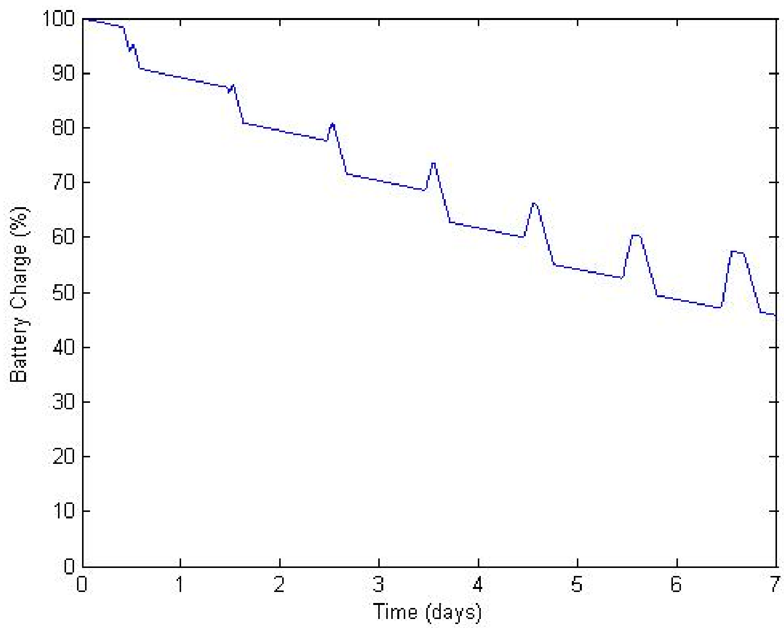


Figure 12 - Motor Duration: 3 hr, Peak Insolation: 400 W

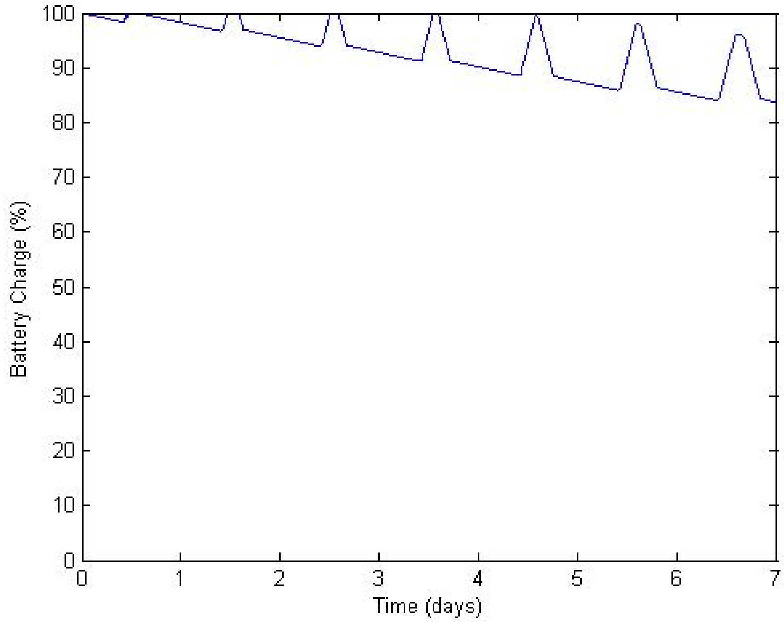


Figure 13 - Motor Duration: 3 hr, Peak Insolation: 500 W

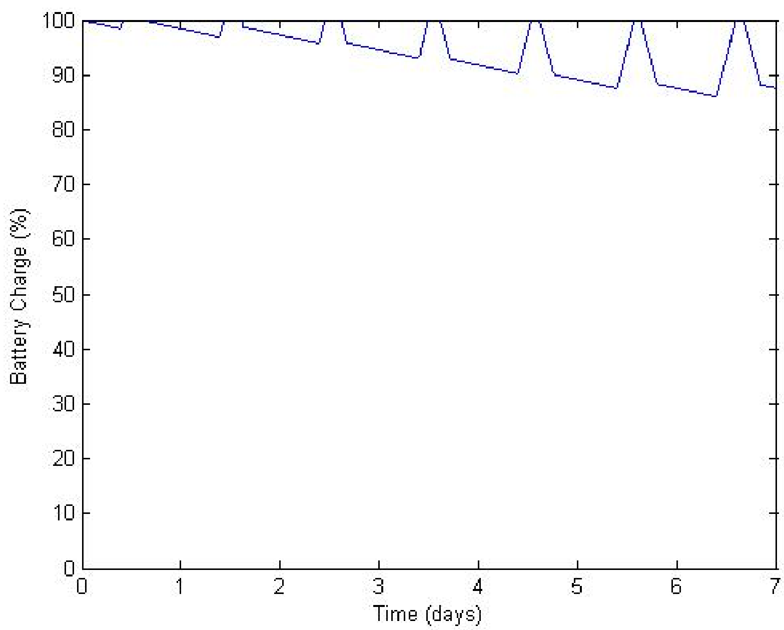


Figure 14 - Motor Duration: 3 hr, Peak Insolation: 600 W

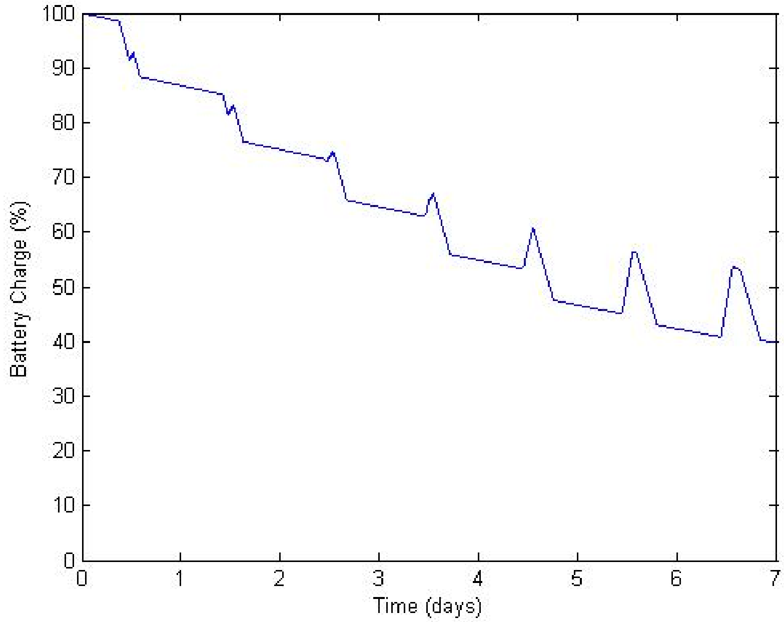


Figure 15 - Motor Duration: 4 hr, Peak Insolation: 400 W

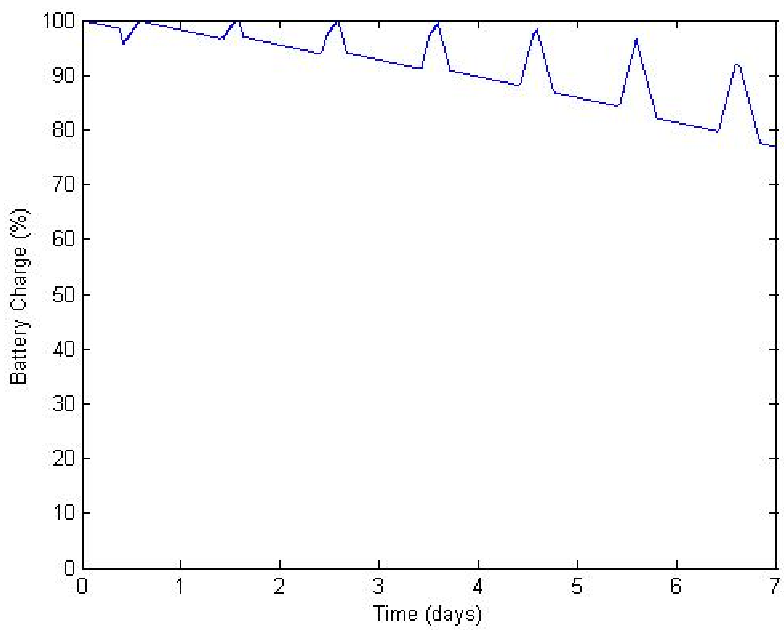


Figure 16 - Motor Duration: 4 hr, Peak Insolation: 500 W

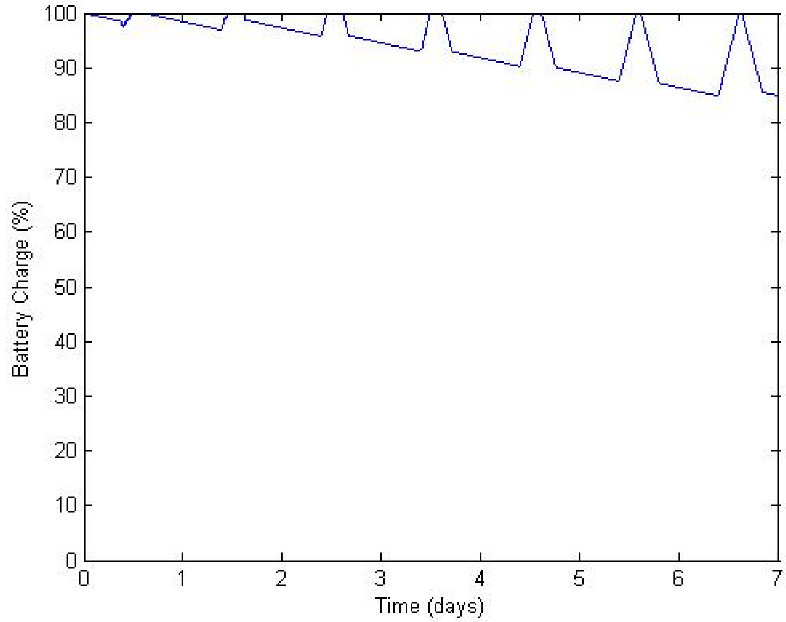


Figure 17 - Motor Duration: 4 hr, Peak Insolation: 600 W

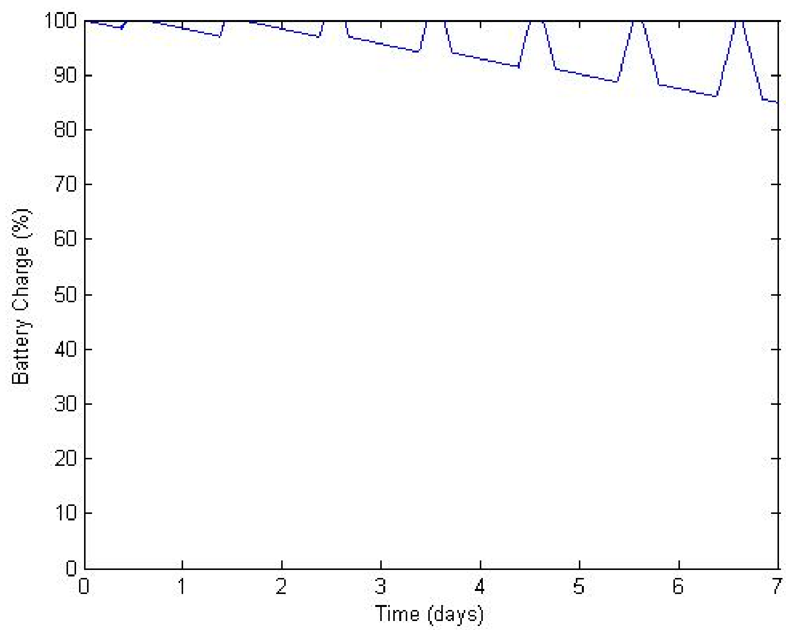


Figure 18 - Motor Duration: 4 hr, Peak Insolation: 700 W

E. State of Charge plots for Static Loads

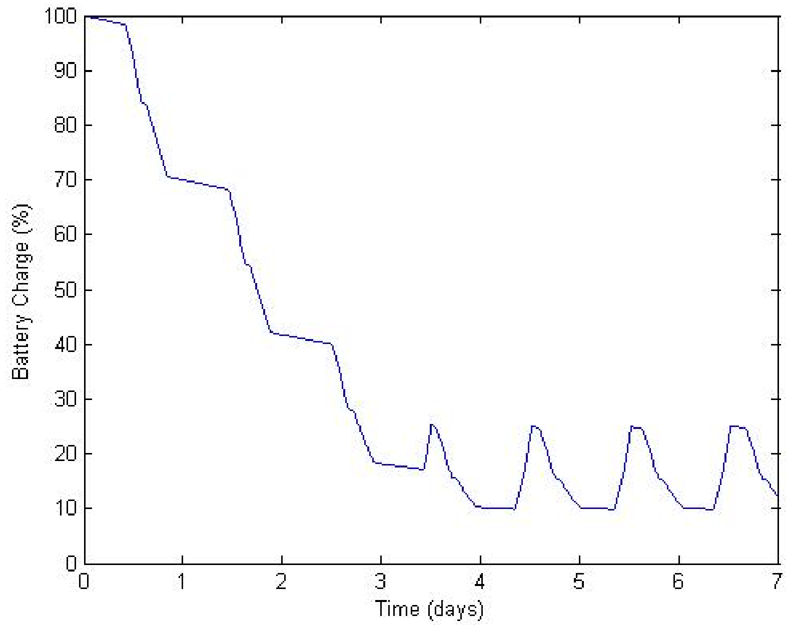


Figure 19 - Static Load Scenario 1. Peak Insolation: 300W

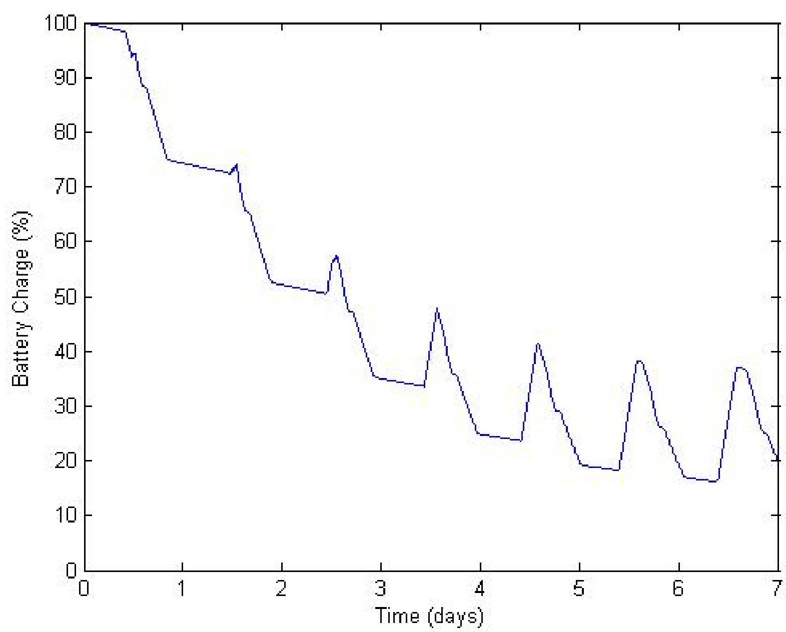


Figure 20 - Static Load Scenario 1. Peak Insolation: 400W

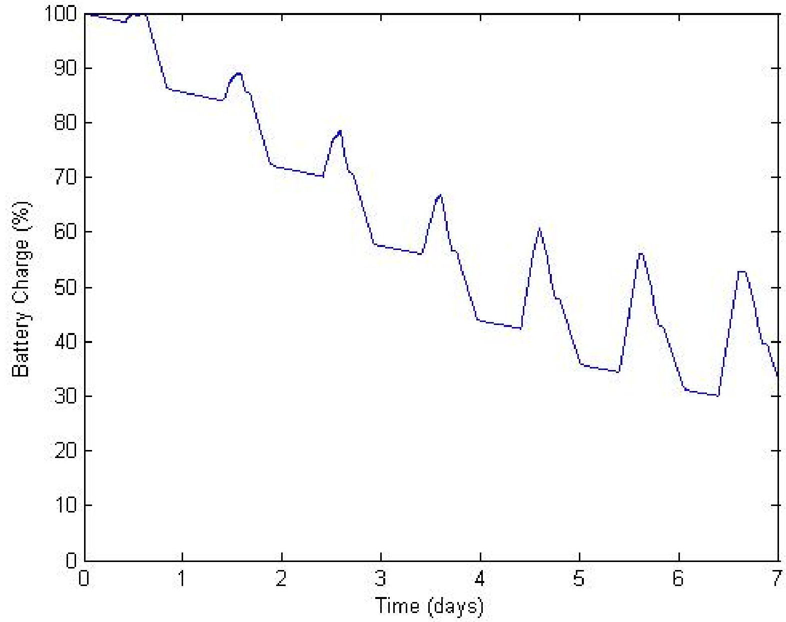


Figure 21 - Static Load Scenario 1. Peak Insolation: 500W

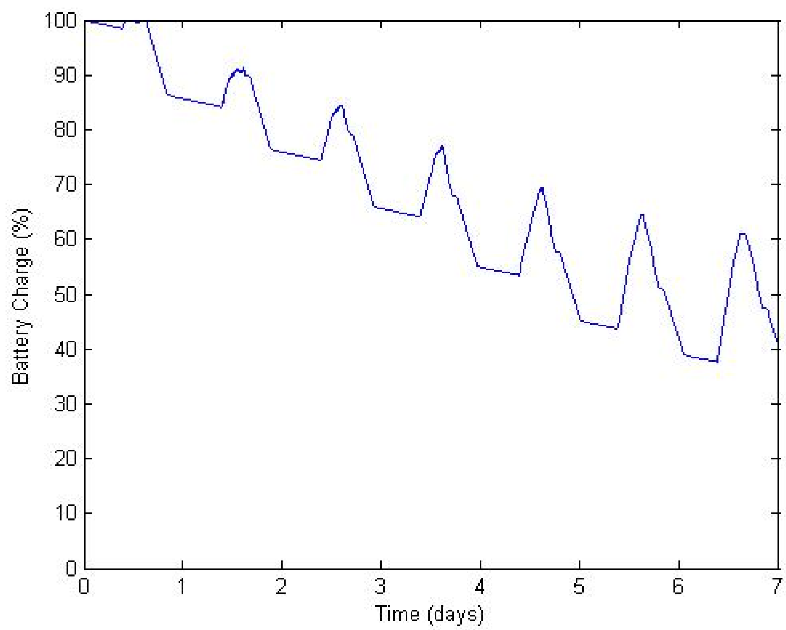


Figure 22 - Static Load Scenario 1. Peak Insolation: 600W

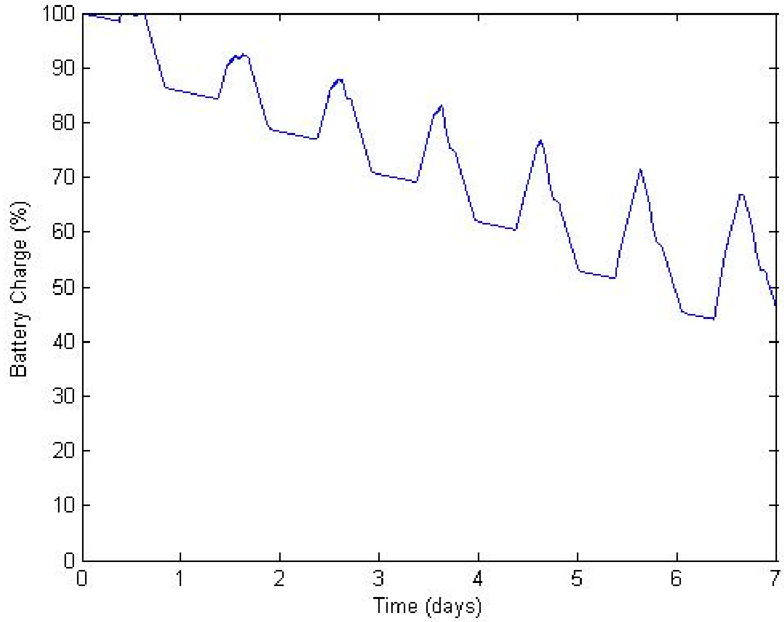


Figure 23 - Static Load Scenario 1. Peak Insolation: 700W

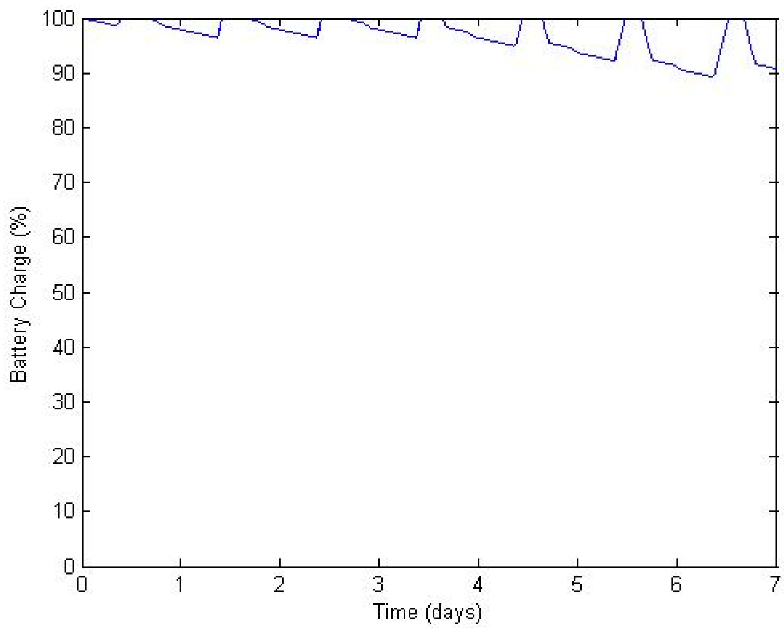


Figure 24 - Static Load Scenario 1. Peak Insolation: 800W

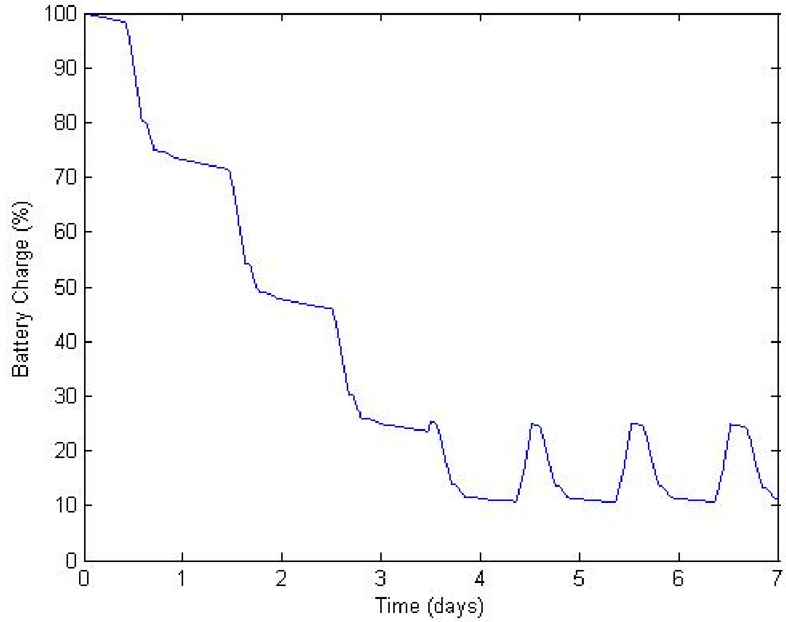


Figure 25 - Static Load Scenario 2. Peak Insolation: 300W

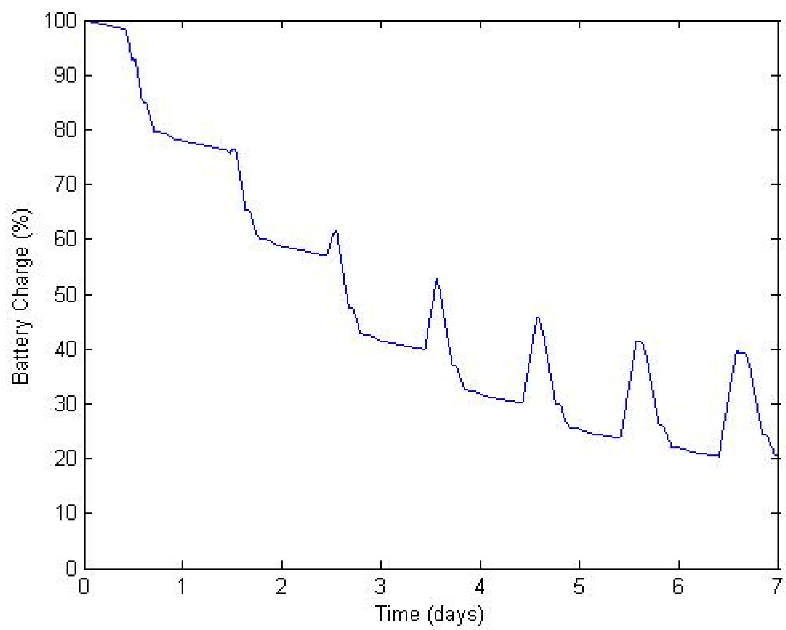


Figure 26 - Static Load Scenario 2. Peak Insolation: 400W

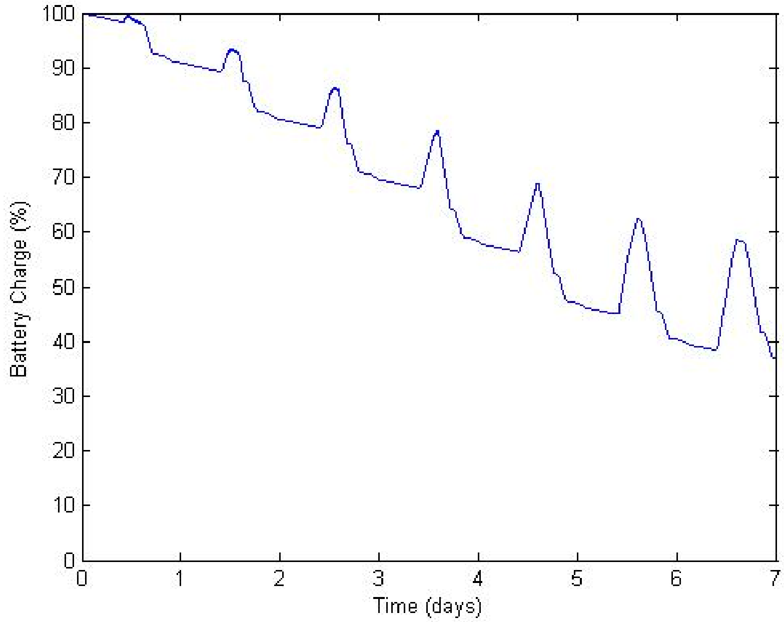


Figure 27 - Static Load Scenario 2. Peak Insolation: 500W

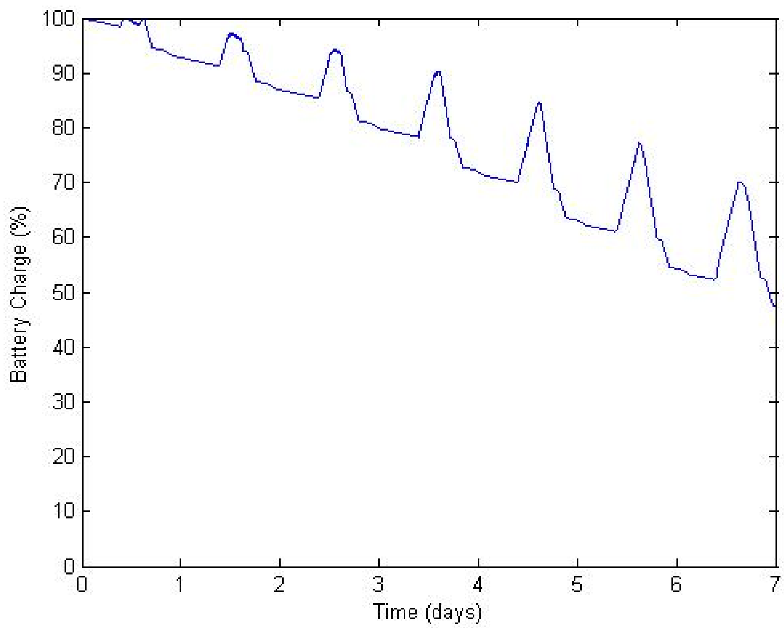


Figure 28 - Static Load Scenario 2. Peak Insolation: 600W

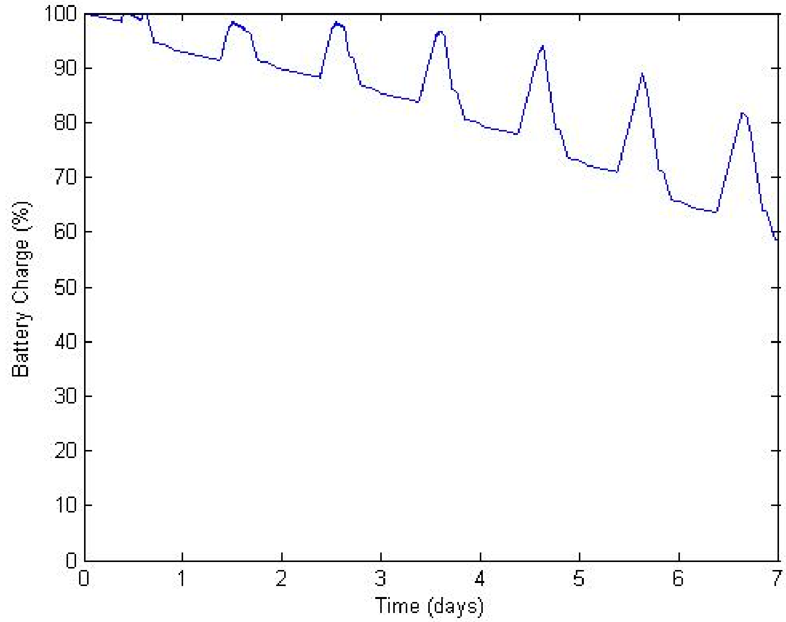


Figure 29 - Static Load Scenario 2. Peak Insolation: 700W

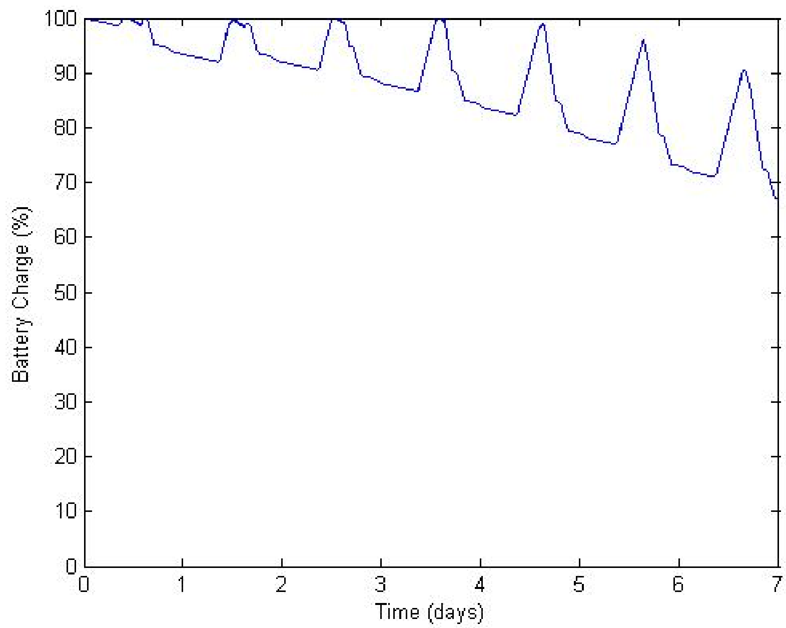


Figure 30 - Static Load Scenario 2. Peak Insolation: 800W

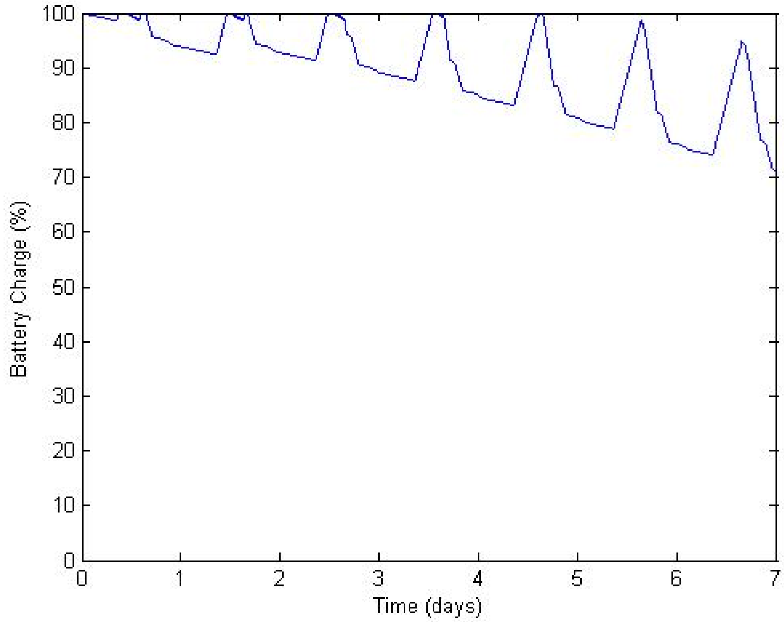


Figure 31 - Static Load Scenario 2. Peak Insolation: 900W

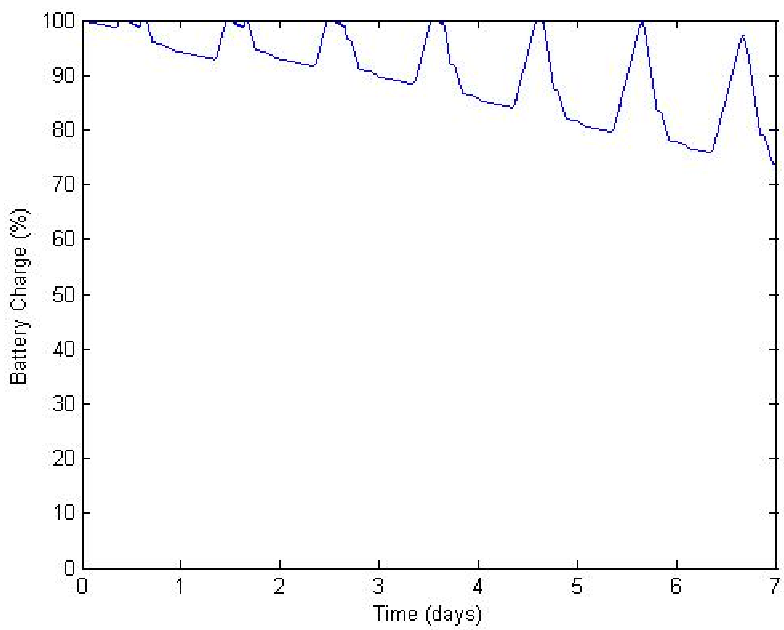


Figure 32 - Static Load Scenario 2. Peak Insolation: 1000W

F. Static Load Scenario Schedules

Table IV – Static Load Scenario 1

	Scenario 1		Total W-hr/day	100.5
Time (hr)	LED (4.5W)	TV (8W)	Cooler (60W)	Internet (24W)
0	-	-	-	-
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	-	-	-	-
6	-	-	-	-
7	-	-	-	-
8	-	-	-	-
9	-	-	-	-
10	-	-	-	X
11	-	-	-	X
12	-	-	-	X
13	-	-	-	X
14	-	-	-	-
15	-	-	-	-
16	-	-	-	-
17	-	-	-	-
18	-	-	-	-
19	-	-	-	-
20	X	-	-	-
21	-	-	-	-
22	-	-	-	-
23	-	-	-	-

Table V – Static Load Scenario 2

	Scenario 2		**Total W-hr/day**	**117**
Time (hr)	LED (4.5W)	TV (8W)	Cooler (60W)	Internet (24W)
0	-	-	-	-
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	-	-	-	-
6	-	-	-	-
7	-	-	-	-
8	-	-	-	-
9	-	-	-	-
10	-	-	-	X
11	-	-	-	X
12	-	-	X	-
13	-	-	-	-
14	-	-	-	-
15	-	-	-	-
16	-	-	-	-
17	-	-	-	-
18	X	-	-	-
19	X	-	-	-
20	-	-	-	-
21	-	-	-	-
22	-	-	-	-
23	-	-	-	-

G. Analysis of Senior Project Design

Summary of Functional Requirement

This project extends the model of the SuPER system by using more flexible test parameters. It examines weather phenomenon and builds an insolation model suitable for testing the SuPER system for a variety of conditions from the power input stage. From this insolation model, the maximum duration of motor operation was determined. Finally, the script written can be used in other solar related projects.

Primary Constraints

This project presented a few constraints. Since the majority of the project was based in SimuLink, it was necessary to learn the software to implement the project. The largest constraint was computing time necessary to run simulations, as the software took upwards to 15 minutes for a simple simulation of a single day's data. An attempt was made to run a simulation of a networked grid of SuPER modules, and it was found that simulation time ran extremely long. Additionally, manipulating data samples as a discrete time process was challenging with the amount of sequential data points.

Economic

This project did not have a direct cost as it was achieved on readily available software in the EE labs. The SuPER project itself is aimed at achieving its primary goal of small-scale power system un $500 or less.

Environmental and Sustainability

The SuPER project strives to supply power to underdeveloped countries that do not already have a central power infrastructure. The system is self-contained and captures solar energy for use in closed power systems. The system is also comprised of readily available components in the market and would not incur new manufacturing. Upgrading the SuPER system is only limited by the ingenuity of future designers and power rating of equipment such as the PV panel.

Ethical

There are no ethical implications relating to the design, manufacture, use, or misuse of this project.

Health and Safety

There is no health concerns associated with the design, manufacture, or use of this project. There is a possible safety concern with the power distribution lines on the SuPER module due to high current loading from the battery. Proper protection measures would mitigate these safety factors.

Development

Through the course of this project design, I became familiarized with several new techniques in system testing. First, I became familiar with block diagram modeling when I learned how to use SimuLink. Secondly, I learned how to write out a test plan for

performing system testing on a complex system. Finally, I became proficient with MATLAB system to build data sets necessary for building models.