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Load Leveling Battery Energy Storage System in Areas with Photovoltaic Generation

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Abstract

The electricity demand of both residential and commercial customers is a constantly changing characteristic of large scale power systems. This is a challenge that utility companies all over the world are faced with every day. One of the methods that is currently being used to help with the challenges created by fluctuating load during peak demand is called load leveling. The basic premise behind load leveling is that energy during off-peak times is stored using some form of an energy storage system. During peak demand times, this energy that was stored previously during off-peak times is discharged to the load. There are many benefits to approaching energy management in this fashion from both the utility and customer point of view.

The objective of this project is to provide successful load leveling capabilities to a simulated commercial customer using a battery energy storage system (BESS). This particular battery storage system incorporates the functions of photovoltaic (PV) generation in order to maximize load leveling capabilities and enhance voltage regulation of the battery units. Both lithium ion and lead acid batteries are considered with the PV generation. The addition of the PV generation creates a reduction in load that can be used in conjunction with the load leveling capabilities of the storage system.

Through successful implementation of a load leveling algorithm incorporating both the batteries and PV generation, quantifiable results will be presented detailing the positive impact seen by the commercial customer utilizing demand side management.

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Problem Description

Constantly having to account for large fluctuations in system loading continues to be a challenge for utility companies in today's world. There are a few different approaches that can be taken in order to help alleviate this problem. Shown below is a demonstration of how a commercial customer's load profile changes drastically over the course of a single day, as well as the seasonal impact.

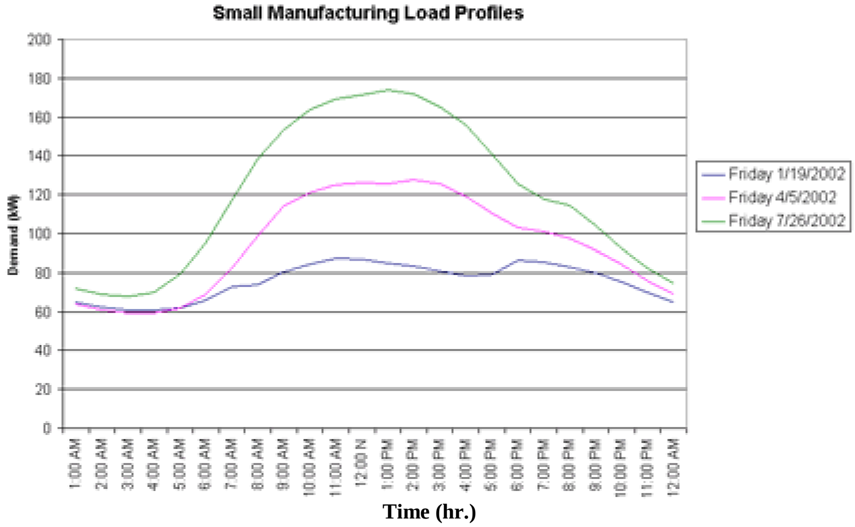


Figure 1. Example Load Profile for a Small Manufacturing Plant [10]

The first type of management that can occur is called supply side management. Supply side management is any action that is taken by the utility to ensure that generation, transmission, and distribution of energy are conducted efficiently [1]. Some of the methods that utility companies utilize in order to manage electric demand are spinning reserves and fossil fuel generation plants that can be operational in minutes. When interested in managing electric demand on a smaller scale (customer level) there is a different type of management that can be utilized.

The type of management that is explored by this project is more commonly referred to as demand side management. As opposed to leaving the job of reacting to peak demands solely on the utility company, demand side management implements tactics that are operated by the customers to help reduce the overall peaks of electricity demand over the course of a day. Large, commercial customers who are able to maintain a flat load profile throughout the course of the day help the utility company greatly because they are able to more efficiently determine their economic dispatch. This concept is known as load leveling. One method of demand side management that can be a very useful tool for a commercial customer is a Battery Energy Storage System (BESS) that incorporates photovoltaic generation within its load leveling capabilities.

In order to reduce the necessity of running generation plants at levels that can greatly reduce efficiency, load leveling systems such as the BESS provide a known demand that does not fluctuate as much. The batteries used, whether they are lithium ion or lead acid batteries, are able to store energy during times when the peak demand is low. This stored energy can then be discharged to the commercial customer's load during times of peak demand. Benefits to the utility company are that the peak loads demanded by large customers that implement these systems are lower and more predictable. From the customer's perspective, they are saving money by buying more energy at a lower rate and avoiding the higher tariffs that occur when demand is at its maximum during the day. Environmental benefits are seen by both the utility company and the commercial customer as well.

Introducing photovoltaic generation into the scheme of a BESS is a very interesting concept; one that has the potential to improve efficiency of load leveling practices even further. Photovoltaic generation creates electric power from the conversion of solar radiation into direct current. Since the capability of such a system relies heavily on the current conditions of the sun, it is not a viable source of energy throughout the whole day. However, the peak loads often occur during the warmest times of the day. This is also when photovoltaic generation is most viable. Incorporating PV generation into the algorithm used for load leveling can allow for a second type of load leveling relief provided to the load. This PV generation may also be able to charge the BESS if for some reason there was a shortage of cheaper energy in off peak times necessary to charge the BESS fully for its next load leveling operation. The single line diagram of the system used during this project is shown in Figure 2 below.

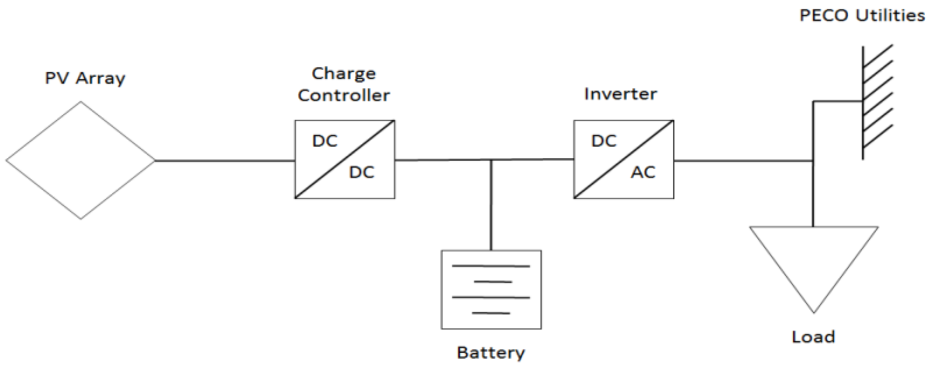


Figure 2. System Single Line Diagram

Deliverables

- Matlab code to run software simulations of the load leveling system with lithium ion batteries
- Results of hardware test of load leveling system with lithium ion batteries to verify accuracy of simulations
- Results of tests on lead acid batteries to see if PV generation can provide sufficient relief to maintain lead acid battery voltage
- Economic analysis of proposed system to determine viability
- Lab guide that could be used in classroom setting, such as ECEP-354 or ECEP-451

There are two different types of battery sets that are available for testing in the Drexel Power Lab. One set is a 24V lead acid battery set (see Appendix H), while the other is a 24V lithium ion battery set. Prior senior design groups working with this equipment only utilized the lithium ion for load leveling [6]. Physical testing of this system with the addition of the PV generation was run and compared against prior groups. Appendix I shows a block diagram of the current lab set up that was used.

For the analysis of the effectiveness of this system, load factor is considered as a parameter. Load factor is defined as the average load divided by the maximum load in a given time frame (in this case, 24 hours). An ideally leveled load would have a load factor of 100%. While this level of success is unfeasible, it is expected that there will be significant improvement after the system is connected to the load. Also, success can be evaluated by analyzing the money saved through the load leveling system. With the knowledge of peak and off-peak energy costs, the amount the commercial customer would spend before and after load leveling can be determined and compared to decide if an adequate difference has been made.

In order to load level with the lead acid battery set, the prior issue of battery voltage needed to be addressed. Prior groups have been unable to maintain the terminal voltage of the lead acid battery above its refloat voltage to allow for effective load leveling. The refloat voltage is essentially a “shut off” point and when it is reached, the lead acid battery set will no longer be able to discharge. This voltage limit is reached long before the minimum state of charge (SOC) limit is attained due to the nature of battery discharge. Simulations were run on the lead acid battery in the Power Lab in order to determine the SOC characteristics versus the battery voltage to determine what acceptable discharge duration would be.

The original proposed deliverables that had been established at the beginning of the project will be altered due to unforeseen circumstances. The deliverables that have to be removed from the project include the extension of PV availability to the Reconfigurable Distribution Automation and Control (RDAC) lab to allow for greater use by all students and researchers. This also included the creation of a portable inverter on a cart to make the inverter accessible anywhere. The reason for removing these aspects is because of the intense inclement weather during winter term, which prevented hardware testing due to a lack of solar irradiance. The additional time that will be available will be used to focus on the hardware testing and analysis of the results.

Progress

Part 1 – Software Testing

The primary focus of Winter Term was on creating accurate simulations of the proposed load leveling system in Matlab, taking into account both the battery energy storage system and the photovoltaic generation. It was decided that the viability of this system should be analyzed both seasonally and geographically, to account for varying loads and solar availability. To represent this, two locations were be modeled: Philadelphia, PA, where hardware testing was be performed, and Phoenix, AZ, which served to represent an ideal solar setting. Each of these locations was modeled in both summer and winter.

In order to include the PV power, accurate solar models were needed. Using the NREL provided System Advisor Model (SAM) [2], the 1.6kW PV system located on Drexel's Main Building was modeled for both cities. The yearly output of these models can be seen in Appendix B. Using this data, average daily values were calculated for each location during both summer and winter, which are shown in Appendix C. Finally, a standard commercial load was found on OpenEI [3]. A standard summer and winter day were found and these loads were used as a constant in both locations (see Appendix D).

The Matlab code used for the simulation is based off the previous year's design [6]. The Matlab code and flowchart were altered in order to incorporate the addition of PV into the system. The alterations that we performed on their flowchart are contained in the first section, which is run at the beginning of every 24-hour period. This version receives both the forecasted load and the forecasted PV output. The PV output is then subtracted from the load profile and the remaining load average is calculated. Based on this data, the charge and discharge rates at each hour are calculated. At each hour, the current load is compared to the average to determine if it should charge or discharge. It then checks that the battery SOC can handle the charge/discharge, and does so if able. The current flowchart being used can be viewed in Appendix E.

With the Matlab simulation code set up, and the relevant data inputs gathered, four simulations were run. In the case of these simulations, a 4.5kWh battery (the same size available in the Drexel CEPE) was used. The results of these simulations are based on their improvement to the load factor, defined as:

$$Load\ Factor = \frac{Average\ Load}{Maximum\ Load}$$

The results are summed up in Table 1 below, which compares the original and improved load factor of the commercial load. Based on this initial analysis, the system shows an improvement over the previous system in all four cases. As expected, Arizona in the summer showed the greatest improvement with the implementation of this system. However, the differences in improvement were minimal, suggesting that this system could function year round in a variety of geographical locations.

Table 1. Results of initial Matlab simulations.

Simulation	Original Load Factor	New Load Factor	Improvement
PA – Summer	62.38%	71.34%	8.96%
PA – Winter	54.34%	63.68%	9.34%
AZ – Summer	62.38%	73.37%	10.99%
AZ - Winter	54.34%	61.09%	6.75%

The second major topic that was investigated throughout the course of Winter Term was the voltage regulation of the lead acid battery set. As previously stated, prior groups were unable to maintain the voltage of the lead acid battery above the “sell voltage”. Maintaining the battery voltage above the sell voltage ensures that the battery is able to discharge to the load for load leveling purposes. If this cannot be maintained, then all load leveling capabilities are lost for the lead acid battery. The lithium ion battery set does not run into this problem because it comes with a battery management system.

The SimPowerSystems feature of Mathworks Simulink was used in order to model the 24V lead acid battery set. This battery model is used to implement the common dynamic models that are representative of the most popular types of rechargeable batteries. The main differentiation between any of the available types of rechargeable batteries is the discharge model and the charge model. The given models implemented by this SimPowerSystems model are shown in Appendix G.

It can be seen that both the charging and discharging models are a function of the extracted capacity, the low frequency current dynamics, the battery current, and the exponential zone dynamics. The extracted capacity can be how much of the lead acid battery’s charge has already been used prior to the current cycle. The low frequency current dynamics play a role in time period that is defined as the exponential voltage drop which will be defined shortly. The battery current is the amount of current that is either being used to charge the battery or being discharged from the battery depending on the cycle it is currently in. The final variable is the exponential zone dynamics. The charging and discharging characteristics of any battery are not linear characteristics. The “exponential zone” denotes the initial exponential voltage drop when the battery is being discharged. This can be seen graphically by the sample model given by MathWorks below in Figure 3:

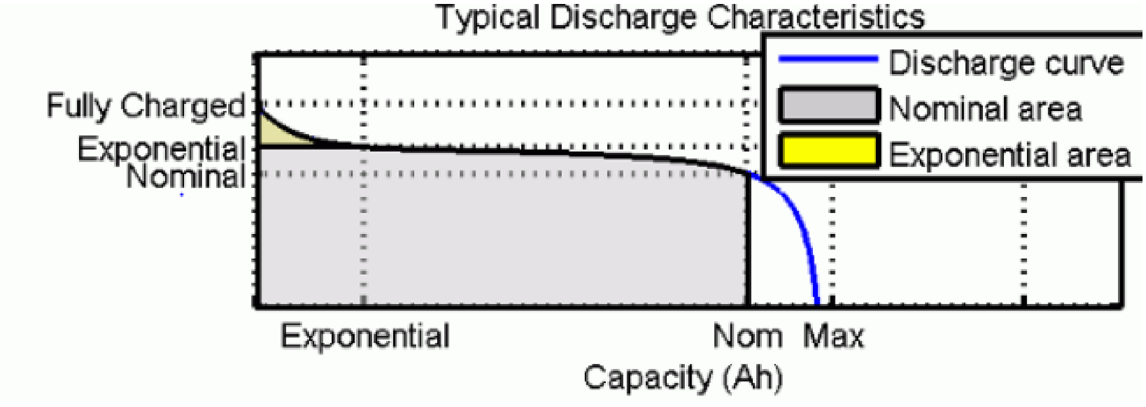


Figure 3. Typical Battery Discharge Characteristics [13]

For any battery discharge there are typically three different sections that can be analyzed. The exponential section show in yellow in the figure above shows the exponential voltage drop at the beginning of the discharge. The light colored area shows the nominal area. The nominal area is the area where the battery can continue to successfully discharge because the battery has not yet reached a voltage below its “float voltage”.

After this model was investigated and the parameters were defined, simulations were run in order to demonstrate the theoretical voltage characteristics of the lead acid battery in the lab against the theoretical state of charge. Four main rates were used to simulate the lead acid battery and the theoretical time that it would be above the “float voltage”. Once again, the battery voltage needs to be maintained above the float voltage in order for the battery to successfully discharge to the load for the purposes of load leveling. If this battery voltage cannot be maintained, the inverter will then have to prepare the battery to be charged by the utility. All sense of load leveling is lost in this case. The results of this are shown in Table 2, below. The scope outputs are shown in Appendix G.

Table 2. Summary of Lead Acid Battery Testing Results.

Discharge Rate	**Capacity (Ah)**	**Discharge Current (A)**	**Battery Voltage Maintained after 1 hour of discharge? (Y/N)**
100 hour rate	532	5.32	Y
50 hour rate	476	9.52	Y
10 hour rate	340	34	Y
1 hour rate	140	144	N

These simulated results can all be seen on the same plot when the discharge characteristics are plotted together in Figure 4. There, the y-axis shows the lead acid battery voltage against the x-axis which shows the time that the battery is being discharged.

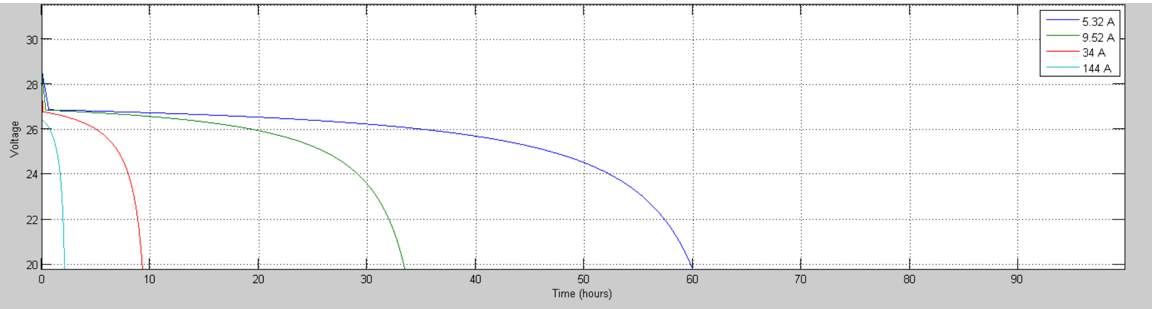


Figure 4. Plot of Lead Acid Battery Voltage Characteristics Based on Discharge Rates

It can be seen from Figure 3 above that for a lesser discharge current, the battery voltage is maintained for a longer duration. The deepest discharge possible, per the manufacturer specifications, is shown as 144A. Since this is considered the “1 hour rate” it makes perfect sense that the voltage drop-off point where the battery can no longer discharge occurs at approximately the 1 hour mark in the plot above. It can also be seen that the lowest amount of discharge current, per the manufacturer specifications, is 5.32 A. When the lead acid battery is discharging at this rate there is a significant period of time when the battery is able to hold its voltage above the specified float voltage. The only downside to this approach of lead acid battery operation is that there will not be significant load factor improvements to be seen from such a small amount of current being discharged from the battery to the load. The utility will still need to supply the large majority of the load for the simulated commercial customer.

Part 2 – Battery Diagnostic Testing

Before actually testing the load leveling concept, diagnostic tests were performed on the lead acid and lithium ion batteries in the Drexel Center for Electric Power Engineering to confirm that they were operating at the same level as last year, when they were previously used. Two tests were performed on each set of batteries: a constant load test and variable load test, with the battery voltage, current and state of charge (SOC) measured over time for each.

Constant load tests for both the lead acid and lithium ion batteries were performed first, with the testing plan shown in Appendix J. During a planned two hour test for the lead acid batteries, a breaker tripped after 45 minutes, ending the test. Upon reviewing the manuals in lab, it was found that the system has a safety feature to shut down when voltage drops below 21V. The test was repeated, and the results were almost identical with the system shutting off after 45 minutes due to the battery voltage passing below 21V. When the same test was performed on the lithium ion batteries, the same results were seen, as the batteries passed below 21V and the system shut down. All of these results are shown in Appendix K, where they are compared with the previous tests performed on the battery a year prior. Despite this limitation, the data gathered up to the 45 minute mark showed the batteries to be in similar condition to the tests that were performed by last year’s team. The battery voltage appears to be slightly lower this year, which caused the batteries to pass below the 21V mark much earlier than last year’s team. The rate at which state of charge decreased was very similar to last year.

Based on the shut off time, it was decided that the variable load test would be run using intervals of 1 minute for the lead acid battery and 2 minutes for the lithium ion battery, to make sure the system remains active during the test. The testing plan for this is also included in Appendix J, while the results are shown in Appendix L. The voltage, current and SOC again behaved as expected, with two exceptions. The battery voltage again lowered faster than expected, cutting the lithium ion test short by 6 minutes, but still yielding viable data. Also, the SOC for the lithium ion remained at 100% for more than half of the test, indicating that the calculation of SOC was incorrect, and the battery was not fully charged at the start of the test. If it had more charge, it likely would have been able finish the test.

Analyzing the results of these tests, it was decided that while the batteries were operating at a slightly lower voltage than the last time they were tested, they would still function for the load leveling tests. However, many of the assumed voltage set points would not be able to be used, as the battery was now operating below their level. It was also decided that 2 minute intervals would be used for the final load leveling test, as the batteries would be able to maintain their voltage for this time.

Part 3 - Renewable Resource Center and MPPT Testing

Before a final load leveling test could be completed, the renewable load center (RLC) was tested piece by piece. The first testing that was done has already been explained within the battery diagnostic section. The second testing that was completed involved the PV array. Specifically, the maximum power point tracking (MPPT) and later, manual manipulations to the array's operating point were experimented with. The "operating point" of the PV array dictates the amount of power that it is able to produce at any given point. All PV arrays operate along a "knee curve" that shows the relationship between an open circuit voltage and its corresponding current output. These knee curves, as shown in Appendix Q, are dependent on cell temperature and solar irradiance levels.

The charge controller included within the RLC is able to determine the operating point for the PV array. In MPPT mode, the system automatically tracks the knee curve as it changes, based on the open circuit voltage, and determines what the max power output could be. The maximum power point is found at the very edge of the knee curve, just before the current drops off as voltage increases. The U-Pick mode allows users to operate the PV array at a specified percentage of the array's open circuit voltage. Manipulating this feature can produce an experimental knee curve, similar to those given with the array's specification sheets. One important difference is that the specifications give I-V curves per cell, whereas the figure in Appendix Q shows the I-V curve for the entire PV array.

After the MPPT and U-Pick modes of the charge controller/PV array were investigated, the RLC was connected to the utility grid to demonstrate its capability to supply a load while "selling" the excess energy generated back into the utility grid. In this situation a controllable load was used in order to program a specific load profile. Since the load profile demand was lower than the overall generating capabilities of the RLC, there was an excess. With a grid-tie connection put into place, this excess energy is able to be fed back into the utility grid. This system is illustrated in Figure 2.

In order to perform such a grid-tie experiment, a few different setting needed to be changed within the inverter and charge controller by the MATE controller first. These are detailed in Appendix P. Within grid-tie mode, the battery storage system in conjunction with the PV arrays is able to sell power through the inverter as long as the battery voltage is maintained above a specified sell voltage programmed into the inverter. "Selling" in this case means that the flow of power is going from the DC side of the inverter to the AC side. If the sell voltage is not maintained, the utility will then have to charge the battery and supply the load. Measurements were taken at the output terminals of the battery, the output of the inverter on the AC side, and the input coming from PECO, shown in Figure 43 of Appendix Q.

Adding the sold power and the load demand will equal the inverter output in the figure above, due to the conservation of energy throughout the system. Since this load profile is lower than the overall generating capability of the RLC, this load has the potential to represent the targeted amount of load that a particular commercial customer would like to level over a specified duration of time.

Further analysis was continued by applying a load that increased from 200W-600W in increments of 100W every 10 minutes, and observing the response of the system. These results were also recorded in Appendix Q, Figures 44-46. Figure 44 shows that as the load increases, the power sold back to the load decreases. Figure 45 shows that when the PV power dips, the battery power increases to compensate. Each of these plots represents a side of the inverter, and when they are added together as in Figure 46, it can be seen that the input and output of the inverter is approximately equal, within the limits of the inverters efficiency, which was approximately 85%.

Part 4 – Load Leveling Test

With the lab components properly analyzed, the load leveling testing commenced. The lab procedure shown in Appendix R was used for this test. The load applied was the same as in the software test from winter term for a summer load, but was scaled to half size to be within the limits of the programmable load in the lab. This load was programmed into the variable load, and the battery was set to charge mode when the load was below its average, and set to discharge mode when the load was above its average. The resulting utility power, along with the load, is shown in Figure 5 below.

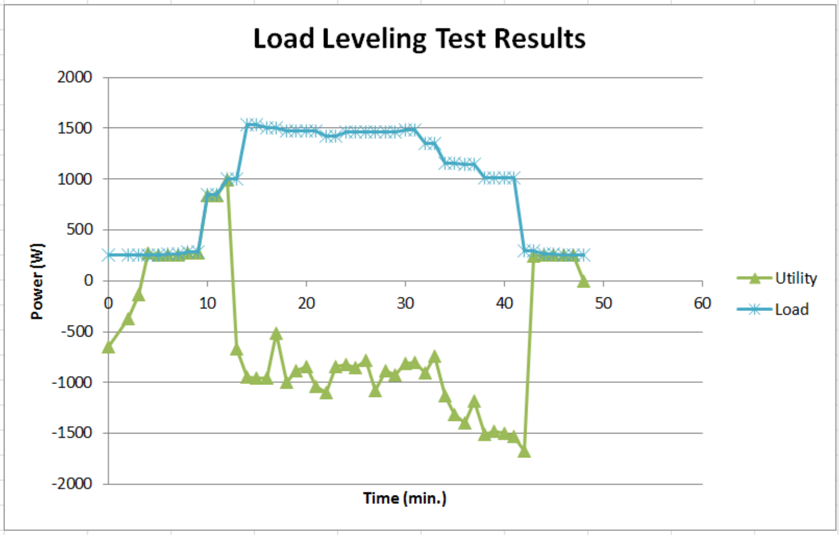


Figure 5. Load Leveling Test Results

The expectation was for the Utility plot to be a leveled version of the Load plot. Unfortunately, the team ran into an issue with the way in which the system managed the rate of discharge for the battery. The battery that Drexel purchased was oversized for the load, because it was intended to be able to work with any future expansions to the lab in terms of renewable resources (such as wind generation). As a result, the battery was large enough to fully feed the load, resulting in the Utility plot being negative during this period, as the battery was able to feed the load and still discharge back to the grid. In a real world application, the battery in a system of this nature would not be large enough to handle the entire load. The only way to handle this issue in the lab would be to limit the rate of discharge. Despite the team's efforts, no solution to this problem was found before the end of the term. Safety restrictions and current limiting capabilities of the distribution system within CEPE did not allow for a larger load to be placed in this load leveling setup. However, it can still be seen that the system was programmed in such a way that the PV and battery acted instantaneously to deliver a relatively consistent output despite the large variances in solar power generation over the course of the test. These specific results can be seen further in Appendix Q. A properly sized system will be able to provide the proper results.

The MATE3 system which controlled the inverter and charge controller had a clear set point to adjust to control the rate of charge, but no set point could be found to control the rate of discharge. This is an issue that will need to be handled by a future team if this lab set up is to be usable in future applications of this type.

Part 5 – Economic Analysis

An increasing number of utilities each year are implementing programs that are designed to benefit customers that shift their demand to "off-peak" times as opposed to "peak" times. A load leveling algorithm such as the one proposed can help to distribute this high-cost energy to low-cost times.

Please see Appendix S for the calculations of how much load will be shifted from peak to off-peak, depending on the utility company. The total cost savings per day, based on a few specific utility incentive programs, are shown below in Table 3 [15-17].

Table 3. Utility Rates.

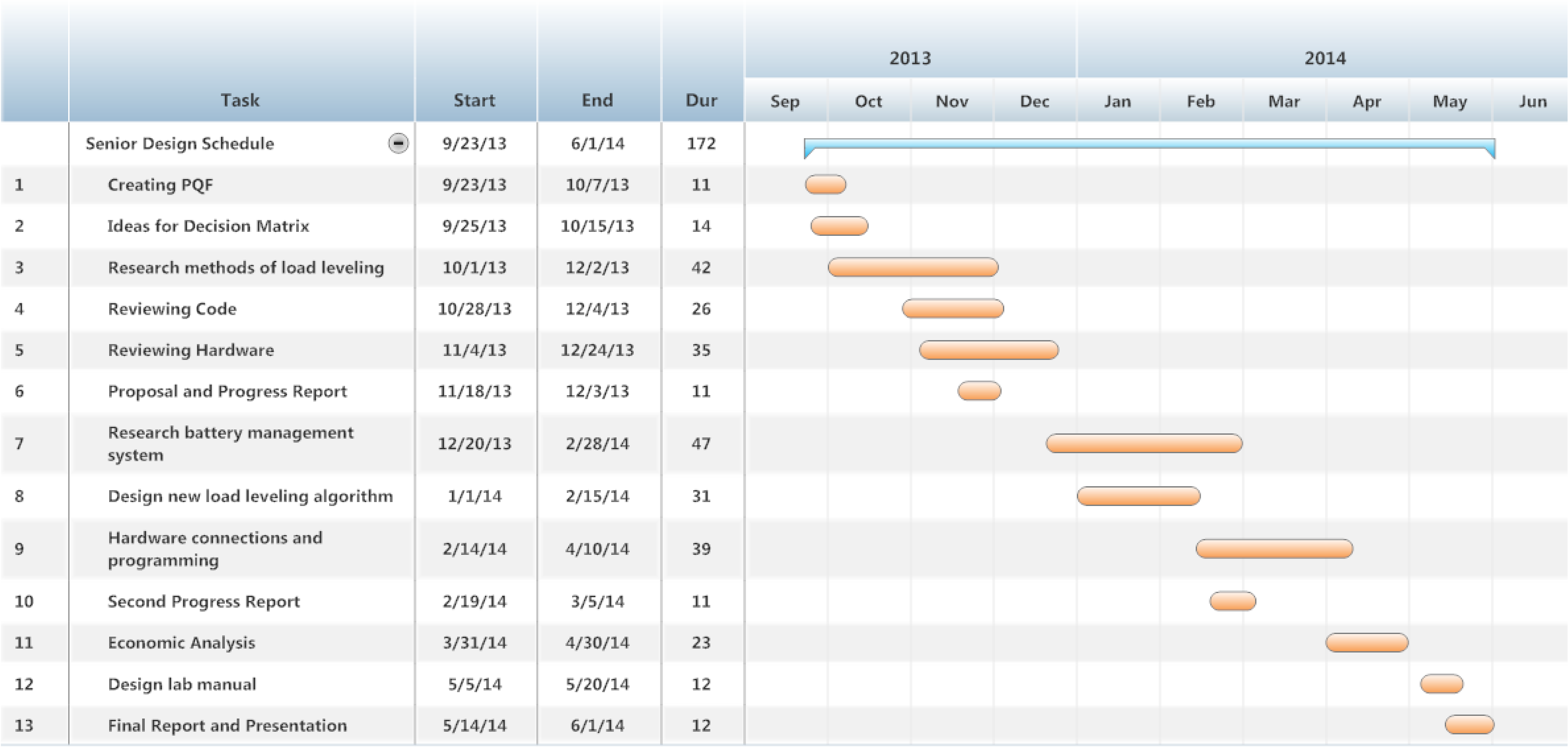
Utility Company	Program Name	"Peak" Times	Summer/Winter "Peak" Rate (cents/kWh)	"Off-Peak" Rate (Summer/Winter)	Daily Leveled Energy (kWh)	Daily Reduced Energy (kWh)
PECO (Philadelphia, PA)	Smart Time Pricing	2pm-6pm	15.95/15.95	6.85/6.85	80	210
PG&E (Northern California)	Time-Of-Use Pricing	12pm-6pm	23.60/15.9	20.2/14.1	120	330
NV Energy (Southern Nevada)	Time-Of-Use Pricing	1pm-7pm	30.03/4.887	6.144/4.887	120	315

Under proper weather conditions, a load leveling system that employs PV generation will have load that is "leveled" from peak to off-peak times as well as additional load that is essentially negated. A 60kWh PV generation was calculated in conjunction with a 20kWh usable capacity for both lithium ion and lead acid batteries. Lead acid batteries do not have as long of a life span or available depth of discharge, leading to the price difference for the same usable capacity. As can be seen below in Table 4, the yearly savings can vary largely based on the utility company and other policies. Additionally, the savings for several other system sizes were calculated and are shown in Table S.3 of Appendix S. These suggest a linear relationship between the size of the system and the savings incurred for customers of this size.

Table 4. Results of Economic Analysis

Company	Lithium Ion/PV Yearly Savings ($)	Lead Acid/PV Yearly Savings ($)
PECO	-165.545	-3565.885
PG&E	1063.92	-2336.42
NV Energy	3729.77355	329.43355

Work Schedule / Proposed Timeline



	Task	Start	End	Dur
	Senior Design Schedule	9/23/13	6/1/14	172
1	Creating PQF	9/23/13	10/7/13	11
2	Ideas for Decision Matrix	9/25/13	10/15/13	14
3	Research methods of load leveling	10/1/13	12/2/13	42
4	Reviewing Code	10/28/13	12/4/13	26
5	Reviewing Hardware	11/4/13	12/24/13	35
6	Proposal and Progress Report	11/18/13	12/3/13	11
7	Research battery management system	12/20/13	2/28/14	47
8	Design new load leveling algorithm	1/1/14	2/15/14	31
9	Hardware connections and programming	2/14/14	4/10/14	39
10	Second Progress Report	2/19/14	3/5/14	11
11	Economic Analysis	3/31/14	4/30/14	23
12	Design lab manual	5/5/14	5/20/14	12
13	Final Report and Presentation	5/14/14	6/1/14	12

Figure 6. Gantt Chart

Industrial Budget

Table 5. Breakdown of Industrial Budget.

Labor Budget			**$176,400.00**
Electrical Engineer Salaries	Weekly Hours	Payrate	Nine Month Total
Matthew Helker	40	$30/Hr.	$43,200.00
Christopher Vaile	40	$30/Hr.	$43,200.00
Matthew Yoder	40	$30/Hr.	$43,200.00
Consultant Salaries	Weekly Hours	Payrate	Nine Month Total
Dr. Chika Nwankpa	2	$250/Hr.	$18,000.00
Jesse Hill/Jon Bererdino	8	$100/Hr.	$28,800.00
Facilities and Supplies Budget			**$11,920.00**
Facilities Cost	Duration	Rate	Nine Month Total
Drexel Power Lab	5 Hrs./week	$30/Hr.	$5,400.00
Supply Cost	Quantity	Cost	Total
Mathworks MATLAB	1 License	$1,900	$1,900.00
AutoCAD	1 License	$4,200	$4,200.00
Microsoft Office 2010	3 Licenses	$140	$420.00
Net Total			**$188,320.00**
Overhead - 35%			$65,912.00
Project Grand Total			**$254,232.00**

Out-of-Pocket Budget

The out-of-pocket budget is expected to be inconsequential for this project. The Drexel Power Lab already owns all of the major equipment that is expected to be used. This includes a Kyocera photovoltaic array, Outback inverter, Flexmax charge controller, a lead acid battery (24V) and two lithium ion batteries (24V and 48V). Additionally, any cables needed to reconnect these products for the project are expected to be available from the lab. Minor expenses such as stationary and printing will be handled by the team as they arise.

Societal, Environmental or Ethical Impacts

There are many environmental, social, and ethical impacts that a BESS system that includes photovoltaic arrays can cause throughout its life cycle. This life cycle includes the construction, operation, and decommissioning of these systems. The most negative impacts occur during the construction and decommissioning stages of the life cycle. These impacts range from the mining of metals to the pollution created while producing photovoltaic modules.

Society is bound to be affected in some way by any new technologies or new strategies of using technologies. The case of the BESS system seems to bring about positive and negative impacts to people who have a BESS system as well as those who do not have a BESS system. People with a BESS system implementing photovoltaic arrays would tend to save money due to the fact that they would be acquiring energy from the grid during the nonpeak or night hours when electricity is cheaper and the energy gained from the sun is free. This small amount of savings per day may take a long time to accumulate enough to pay for the cost of the system. The amount of energy saved depends on the location and equipment of the system. Some locations have a greater photovoltaic resource supply, and equipment has different efficiencies and abilities between units. The production of such systems might actually hinder people from coming or cause them to leave a place where these modules and batteries are being made. The harmful production and decommissioning of photovoltaic modules and batteries may upset people in nearby areas. Multiple outcomes can occur from this such as protests against such actions.

The environment is largely impacted from the life cycle of the load leveling system. The photovoltaic cells are not easy to produce. Their production requires heavy metals and toxic materials. Heavy metals, including cadmium and selenium, require risky mining that entails the use of large diesel machinery, which produce emissions. The toxic materials, while only being used in small amounts, can cause harm over long periods of exposure time. Production can affect the air around the site to the point where it is unbearable to be outside. The decommissioning of photovoltaic units and batteries also can cause environmental problems. The photovoltaic units that include cadmium and selenium will pollute the area around where it is keep for disposal. Data has yet to be collected about the long-term effects of photovoltaic units due to the long life that they have and the short time that the technology has been available. The possible pollutions that the photovoltaic modules and batteries can cause brought about reason for laws to be passed in order for proper disposal of batteries. Similar laws may someday get passed that deal with the disposal of photovoltaic arrays. The load leveling system does not produce any emissions or pollutions during its potentially long use, but they can release pollutants if damaged in a fire or storm [5].

There are also some ethical issues that come about with the introduction of load leveling systems. The production affects all living things from the pollution, including humans. The total environmental footprint should be looked at for all ways of producing energy and determine if the damage to the environment is worth the use of these systems. It could also be decided how ethical the use of photovoltaic and battery use in a system compared to other sources of energy production.

Summary/Conclusions

After it was determined that the PV generation would be implemented with the previously constructed BESS system, the specifics of how the PV array would operate in conjunction with the battery sets were investigated.

It was decided that the best way to implement the PV generation into the load leveling capabilities of the lithium ion battery set was to essentially form an “adjusted” load. This adjusted load is the result of taking the normal, daily demand from the customer and subtracting the forecasted PV generation for that day. After this initialization occurs, the load will be easier to effectively level. Easier in this situation means that a smaller size of battery storage will be necessary for equivalent financial savings. There are many different places where a PV array can be installed, however not all of these locations share similar outputs in expected PV generation. For example, Phoenix, Arizona will be expected to provide a much stronger solar generation profile than Philadelphia. MATLAB simulations were run demonstrating this difference and ultimately providing a look at what type of load leveling improvements the incorporation of PV generation can provide for a commercial customer using a BESS.

Since the lithium ion battery has a built-in battery management system, maintaining the “sell voltage” of this system is not a concern. However, the same cannot be said while using the lead acid battery set for the purposes of load leveling. The lead acid battery set does not have a battery management system built in and previous load leveling testing has shown that the battery voltage is not maintained at a high enough level for a long enough time in order to produce significant load leveling improvements. One idea that was investigated was modeling the dynamics of discharge of a lead acid battery within Simulink in order to gain an understanding of the voltage vs. state of charge characteristics. It was determined that voltage was maintained sufficiently within the simulations for lower discharge rates. This knowledge leads to the idea that the PV generation could potentially be discharged directly to the load so that the requirements for discharge of the lead acid battery are slightly lowered. Lowering the demand on the lead acid battery may be able to make this a viable load leveling tool at a lower cost than the lithium ion battery set.

Implementing a system such as this will have many noticeable improvements. The load factor specific to the commercial customer will be improved by a quantifiable margin over a 24 hour period. Regarding the economic benefit of a system such as this, it can be seen that the utility company in question ultimately can determine whether a BESS with PV generation is a smart option for a commercial customer. Many utility companies have a relatively small time frame that is considered peak hours, which limits the amount of high cost energy can be transferred to low cost energy. Commercial customers, before installation, need to first calculate the role that their utility company’s programs play into their cost benefit analysis.

As PV generation becomes cheaper, which it is projected to do in the near future, a system such as this may be able to eventually be beneficial, regardless of utility policies. Continued improvements and expanded usage of load leveling systems such as this one will undoubtedly have a positive impact on the global community, reaching far beyond just the benefits seen by a simulated commercial customer.

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Appendix A: Design Constraints Summary

Team Number: ECE-23

Project Title: Load Leveling Battery Energy Storage System in Areas with Photovoltaic Generation

Summary of the Design Aspects:

This Battery Energy Storage System is designed to provide load leveling to any load profile. It is able to provide load leveling with the combined use of photovoltaic modules and batteries. The load leveling system's size will be designed to fit an industrial or commercial purpose. A previous group designed the function and placement of the photovoltaic and battery system currently in the lab. This means we will be improving upon their design and including the integration of the photovoltaic array into the load leveling process. An algorithm will also be designed to regulate the system, and will be implemented in software simulations to be compared with hardware tests. When testing is completed, a lab manual will be designed to implement the system into a future Drexel power class, such as ECEP-354 or ECEP-451.

Design Constraints:

Economic:

The Center of Electrical Power Engineering determines the economic limitations on the project. There was no exact amount that was specified, but they had to be reasonable in their standards and provide use in the future in education and/or research. Also, the equipment used for the project is very expensive, so the scale of the project has to be limited.

Manufacturability:

The manufacturability of this BESS system does not limit the project because all the components of the system are readily produced and accessible. There are no new components that need to be ordered. If a new component is needed throughout the process, there can still be tests done while the component is being manufactured and shipped.

Sustainability:

The load leveling system has the ability to have a long lifetime with care and maintenance. Photovoltaic module's average lifetime varies around 20-25 years. The batteries do not last as long as the photovoltaic modules, but they also do not cost as much as the photovoltaic modules.

Environmental:

There are environmental effects that are caused from the production and decommissioning of the photovoltaic modules and batteries. That means that they are not easily expendable, so many varieties cannot be studied. Large solar fields also take up a lot of space and can ruin habitats for animals.

Ethical, Health, and Safety:

The main limitations of health and safety are due to the harmful materials used during production and released during decommissioning. As mentioned above, habitats can be destroyed to make room for large solar fields needed to load level large loads consisting of industrial or commercial customers.

Social:

There were no impeding social limitations because the uses of load leveling systems are widely accepted among people. Photovoltaic arrays are a common integration into systems. There are ways to improve social constraints, for example use more environmentally friendly materials and procedures.

Political:

Energy production and trade is a huge political controversy in the world, especially with regard to fossil fuels. The implementation of BESS system with photovoltaic arrays may cause these controversies to weaken and strengthen the arguments for renewable resources.

Standards and Regulations:

- Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources, UL Standard 1741
- IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems, IEEE Standard 1547-2003, October 2003.
- IEEE Recommended Practice for Sizing Lead Acid Batteries for Stationary Applications, IEEE Standard 485-2010, April 15, 2011
- IEEE Recommended Practice for Personnel Qualifications for Installation and Maintenance of Stationary Batteries, IEEE Standard 1657-2009, December 18, 2009
- IEEE Guide for the Protection of Stationary Battery Systems, IEEE Standard 1375-1998, March 19, 1998.

Appendix B – Yearly Solar Data

Yearly solar data collected from SAM shows that both cities have similar peak PV resources, but that Phoenix, AZ has a much more consistent profile, making it the better choice.

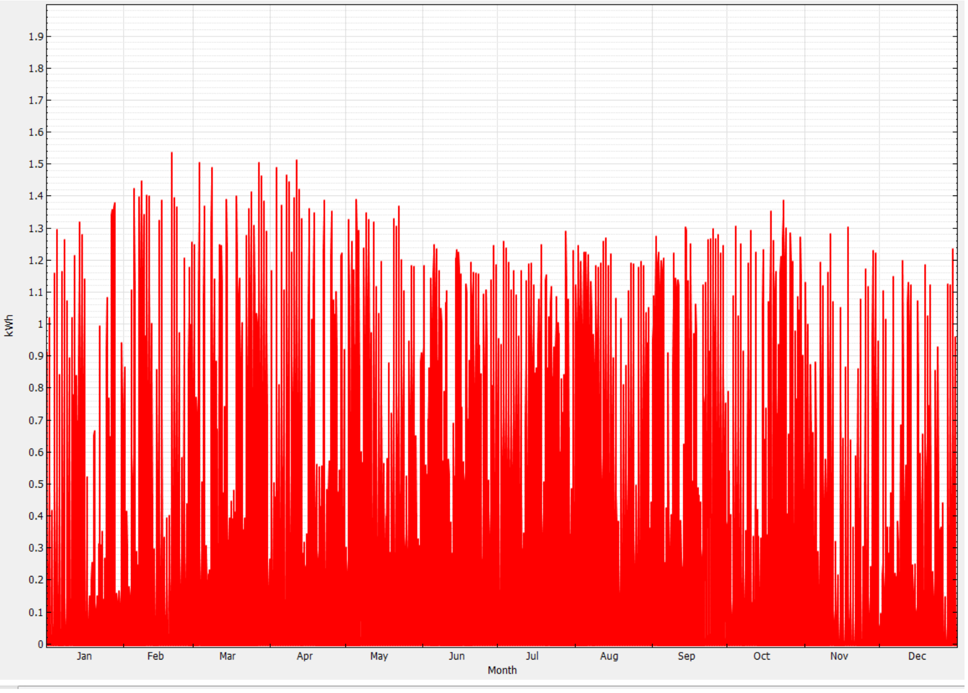


Figure 7. Yearly PV output in Philadelphia, PA

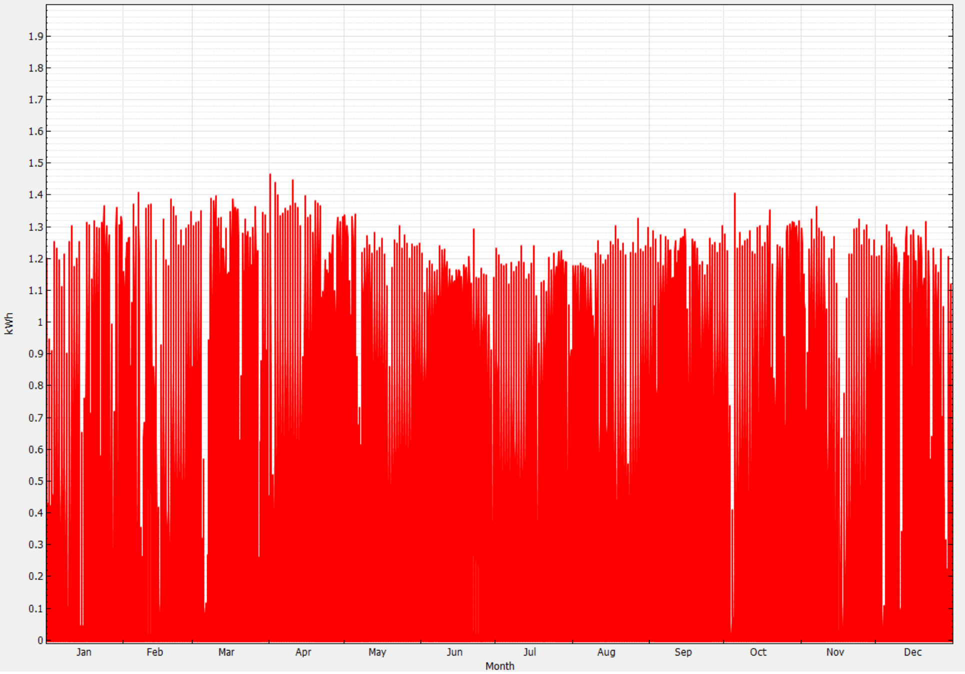


Figure 8. Yearly PV output in Phoenix, AZ.

Appendix C – Average Daily Solar Data

For each city, the PV production at each hour was averaged for the month of January to produce the standard winter curve, and for the month of July to produce the standard summer curve. Summer has a higher peak than winter, and Phoenix, AZ has higher peaks than Philadelphia, PA.

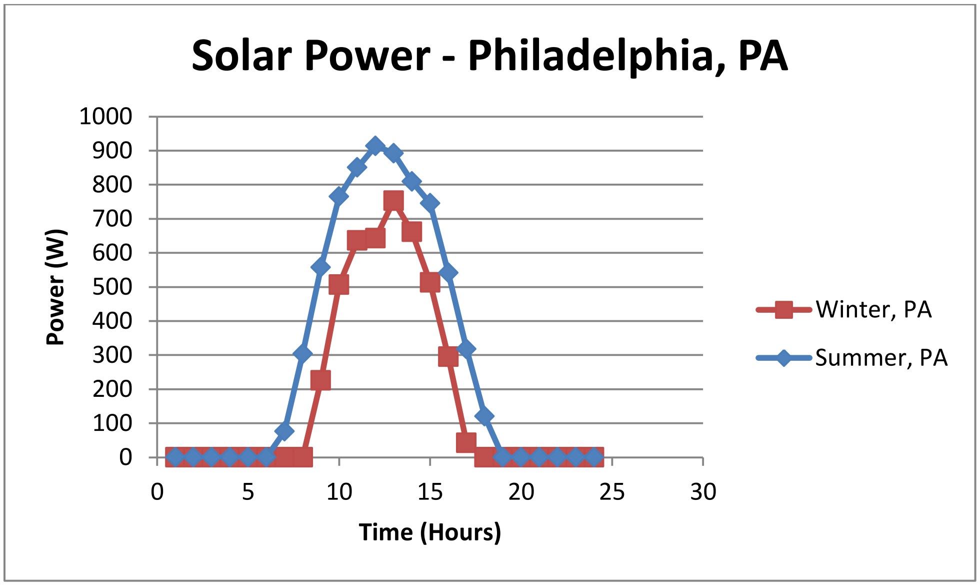


Figure 9. Average daily PV production for Philadelphia, PA.

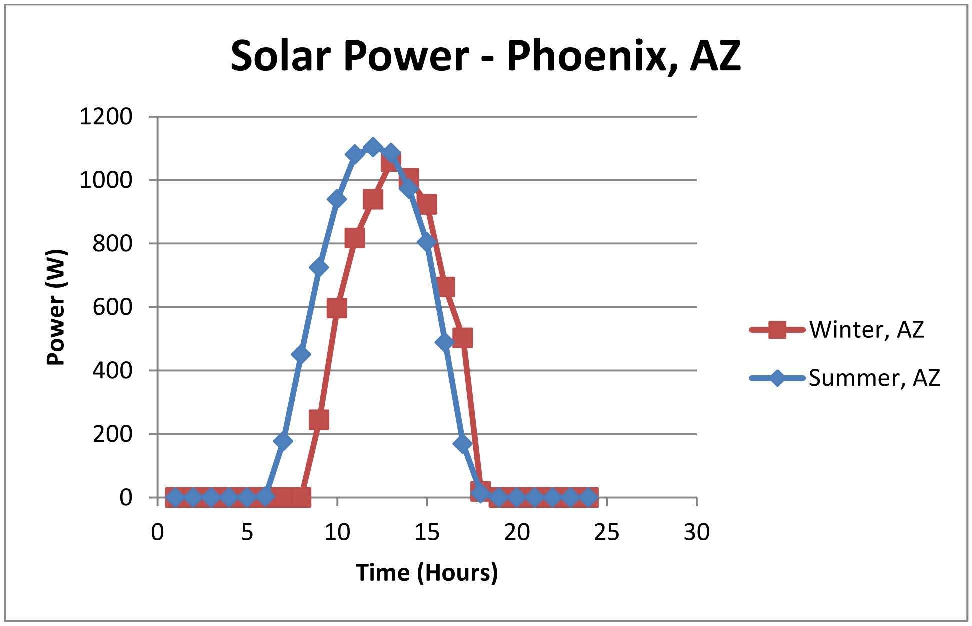


Figure 10. Average daily PV production for Phoenix, AZ.

Appendix D – Sample Commercial Load Data

Examples of standard summer and winter days were taken from the OpenEI load data for a large commercial building to create the sample loads shown. These have been scaled down by a factor of 1000 to work with the equipment available in the lab.

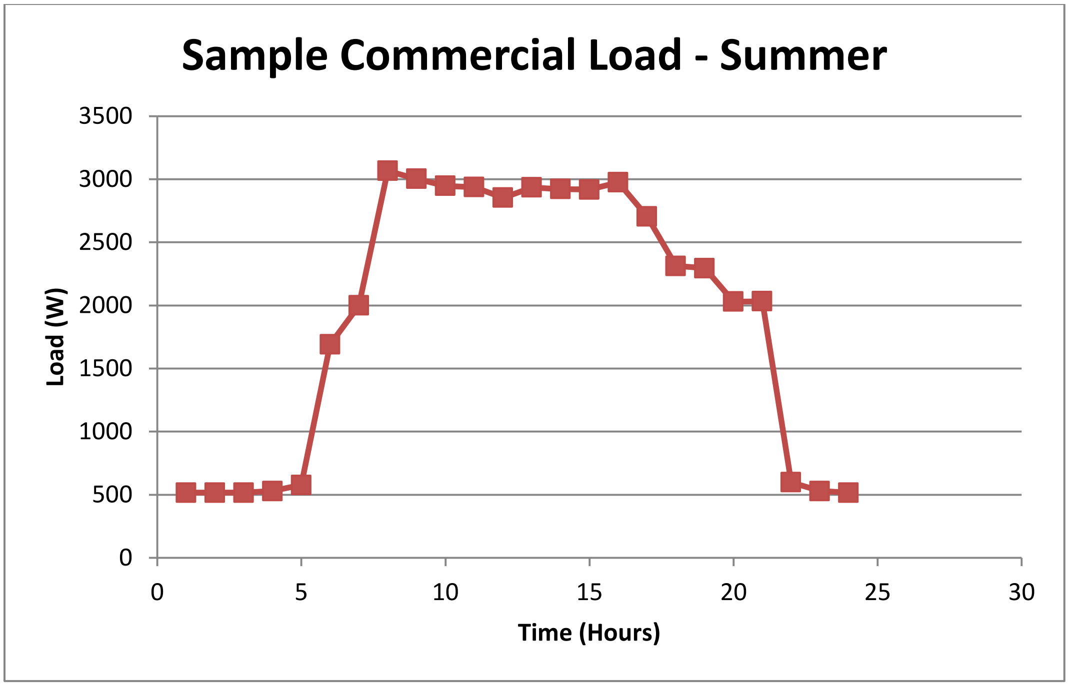


Figure 11. Sample commercial load used for summer simulations.

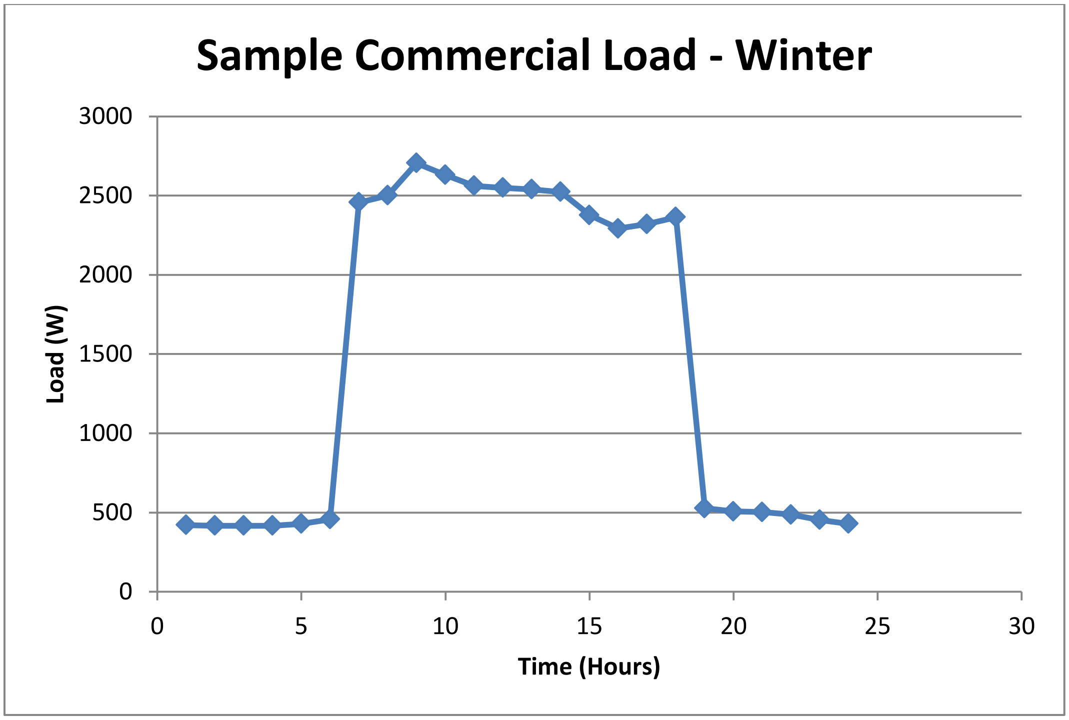


Figure 12. Sample commercial load used for winter simulations.

Appendix E: Matlab Code Flowchart

The code accepts 24 hour load forecasts and solar output forecasts. It then finds the difference between them, and then finds the average of this remaining load. At each hour, it checks if the load is greater/less than the average, and discharges/charges accordingly after making sure that the battery State of Charge (SOC) is not too low/high, respectively.

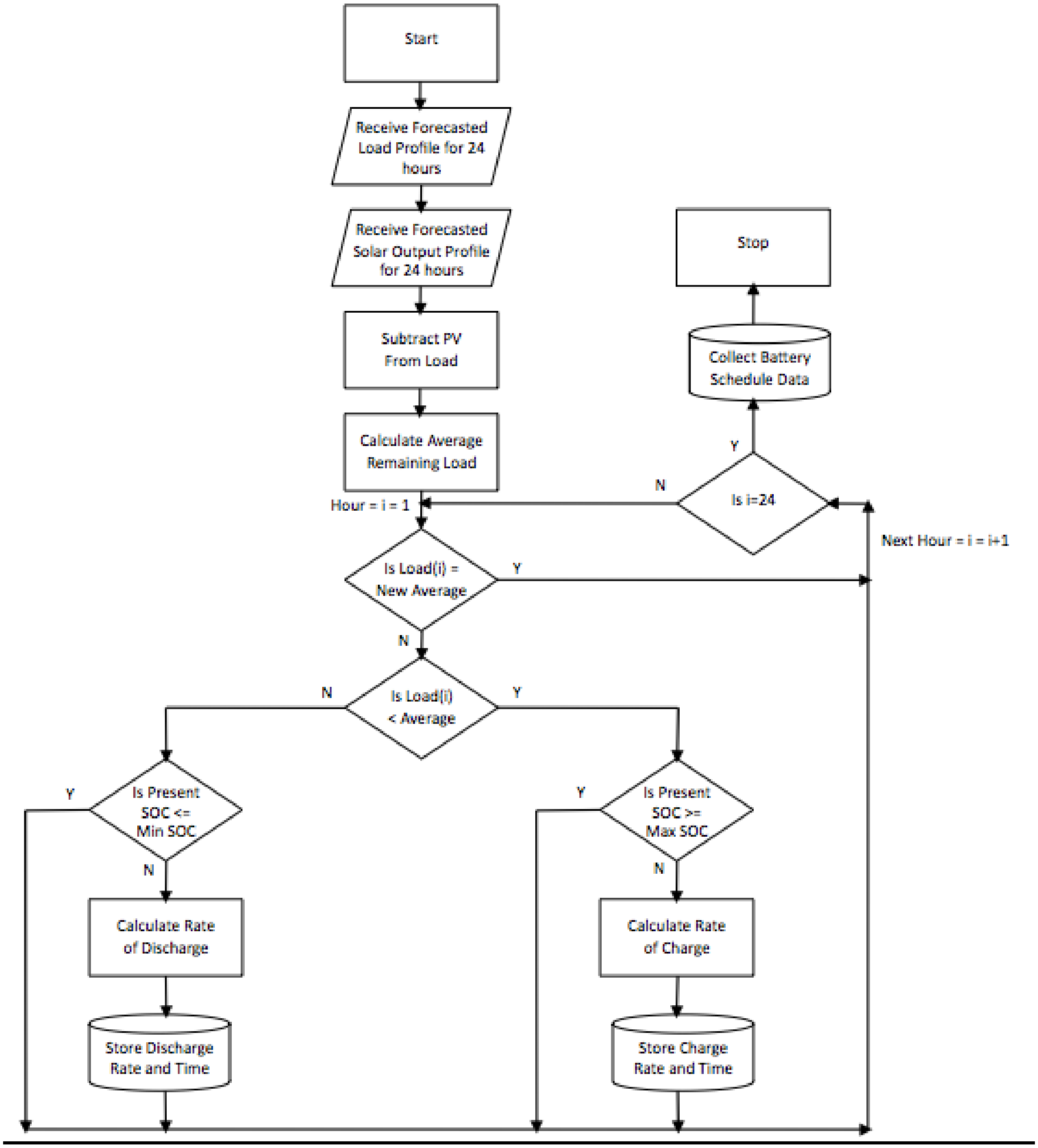


Figure 13. Simulation Flow Chart.

Appendix F – Load Leveling Simulation Results

These plots show the simulation outputs for the load leveling system with lithium ion battery and PV incorporation. Each scenario (Philadelphia and Phoenix, both in summer and winter), shows the PV power produced, original load, remaining load after subtracting PV, and final leveled load.

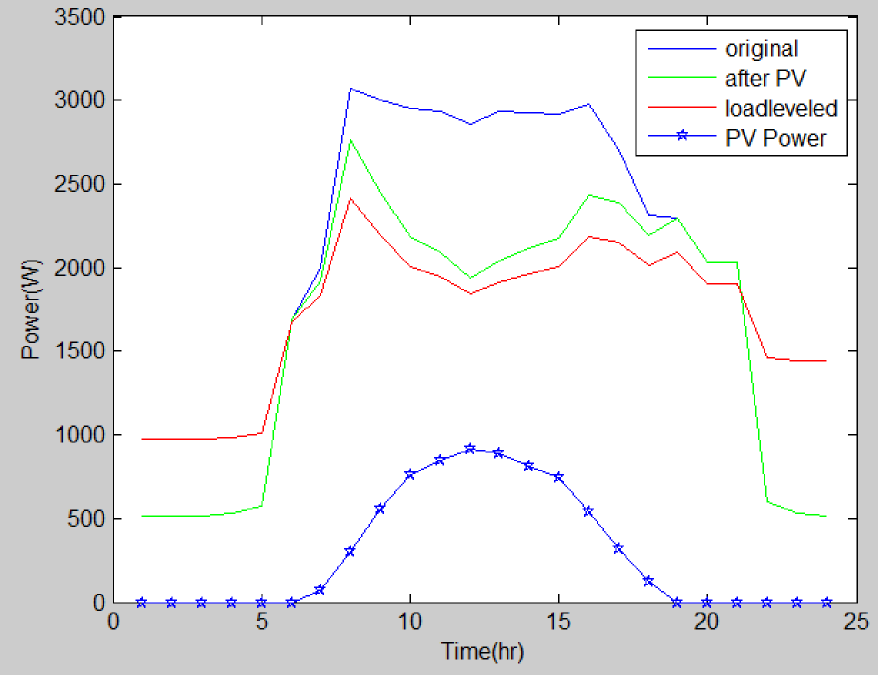


Figure 14. Simulation output for Philadelphia, PA in summer.

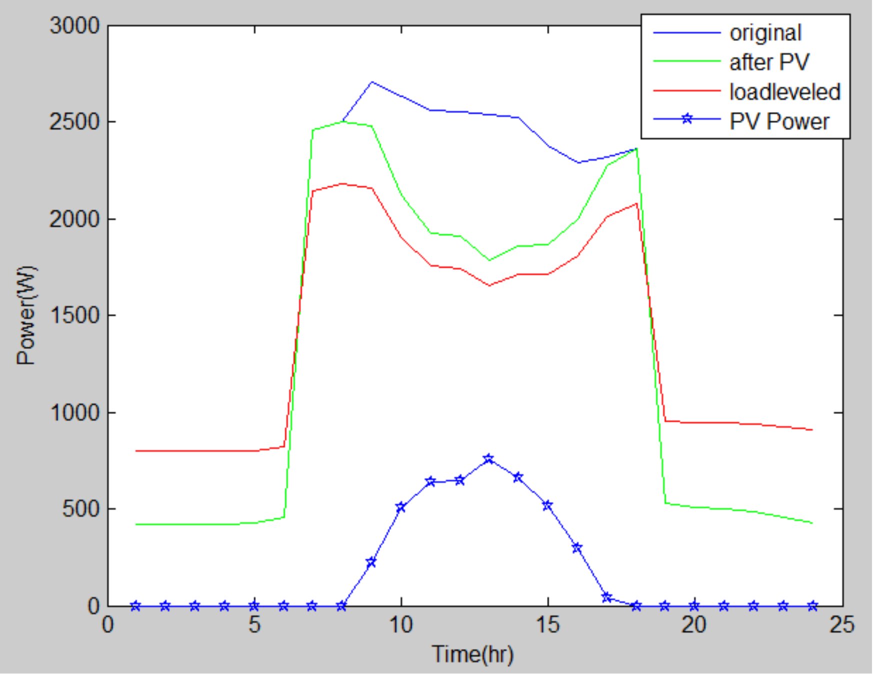


Figure 15. Simulation output for Philadelphia, PA in Winter.

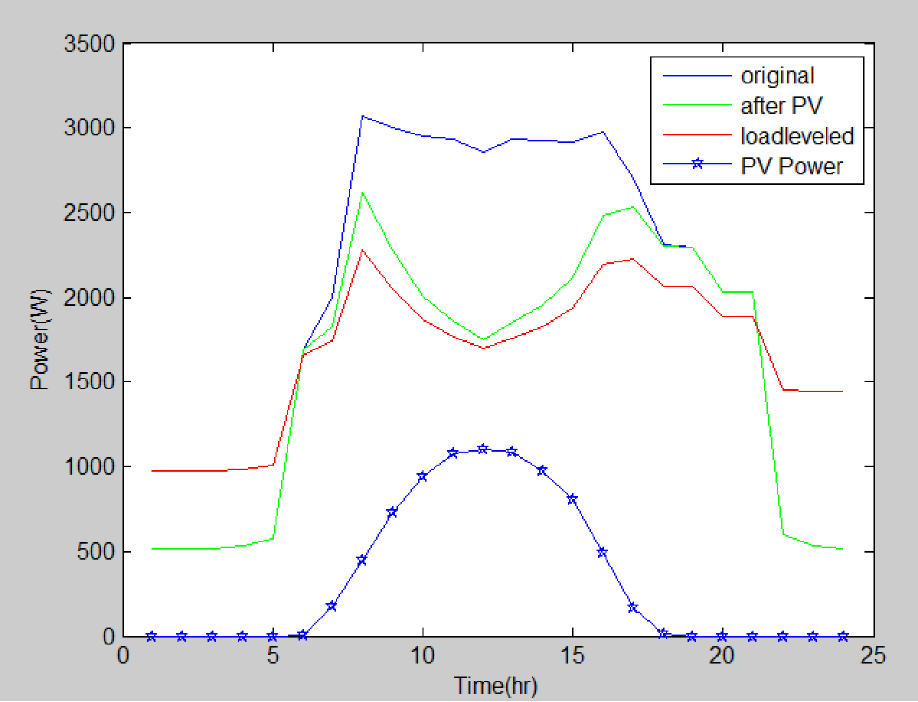


Figure 16. Simulation output for Phoenix, AZ in summer.

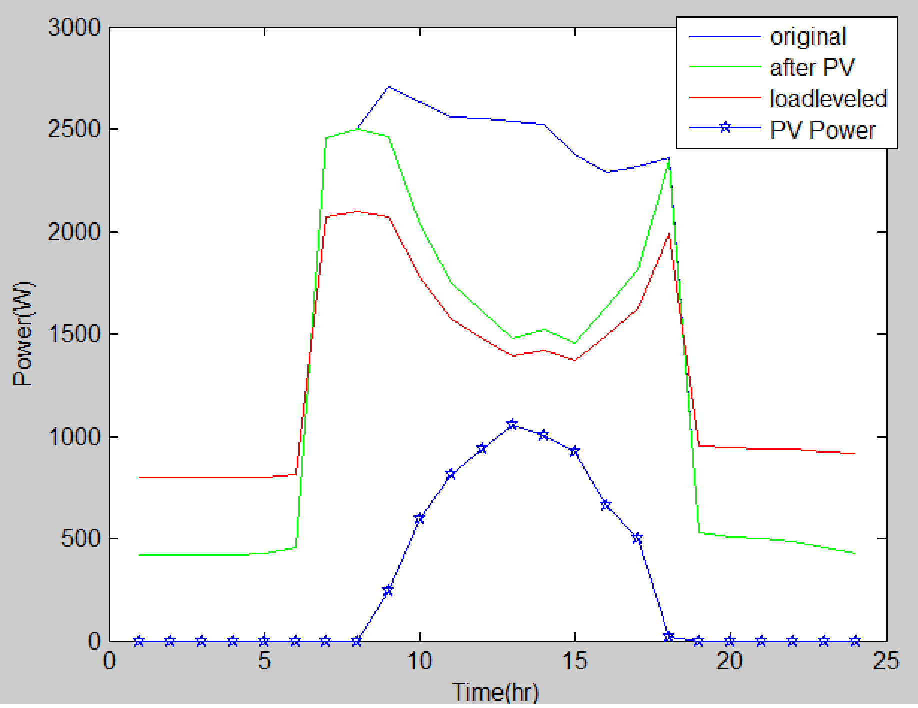


Figure 17. Simulation output for Phoenix, AZ in winter.

Appendix G: Battery "Float Voltage" Test Results

Computer simulations were run for a model lead acid battery set based on the equations below, consistent with the specifications of the battery within the Power Lab. The upper subplot is a plot of simulated battery voltage vs. time, while the lower subplot is a plot of state of charge vs. time. All plots are based off of a one hour discharge simulation.

General Lead Acid Battery Discharge Model [4]

$$f_1(it, i^*, i, Exp) = E_0 - K * \frac{Q}{Q - it} * i^* - K * \frac{Q}{Q - it} + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)}\right)$$

Where,
E_0 = Constant Voltage (V)
K = Polarization constant (Ah^{-1}) or Polarization resistance (Ohms)
Q = maximum battery capacity (Ah)
it = Extracted capacity (Ah)
i* = low frequency current dynamics (A)
Exp(s) = exponential zone dynamics (V)
Sel(s) = represents the battery mode (0 for discharge and 1 for charging)

General Lead Acid Battery Charge Model [4]

$$f_2(it, i^*, i, Exp) = E_0 - K * \frac{Q}{it + 0.1 * Q} * i^* - K * \frac{Q}{Q - it} * it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)} * \frac{1}{s}\right)$$

Where all of the variables are the same as the discharging equation above.

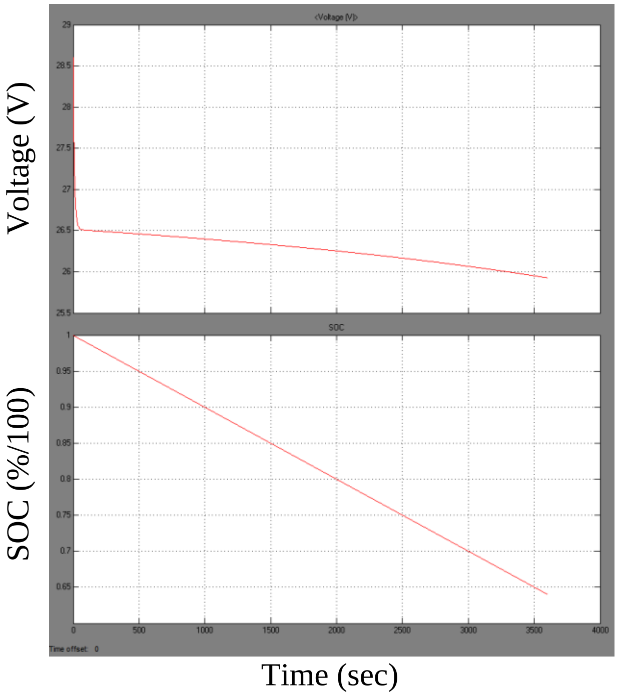


Figure 18. Lead Acid Battery Simulated Voltage and SOC at 1 hour rate

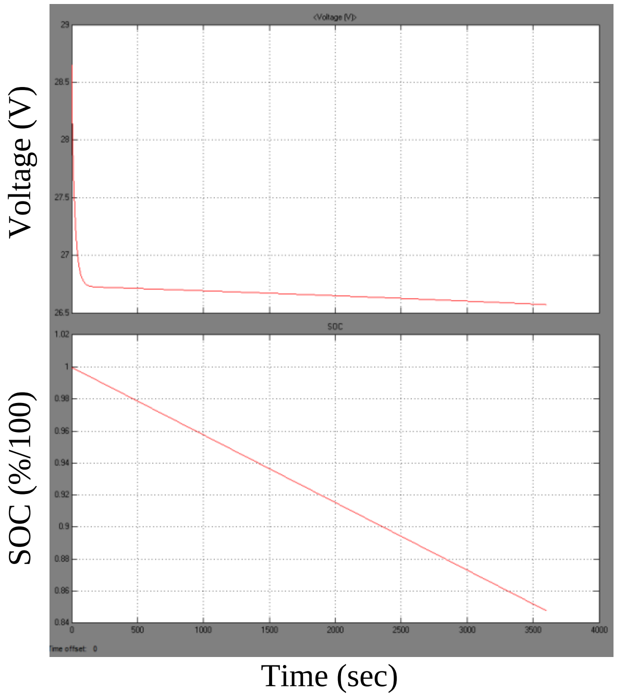


Figure 19. Lead Acid Battery Simulated Voltage and SOC at 10 hour rate

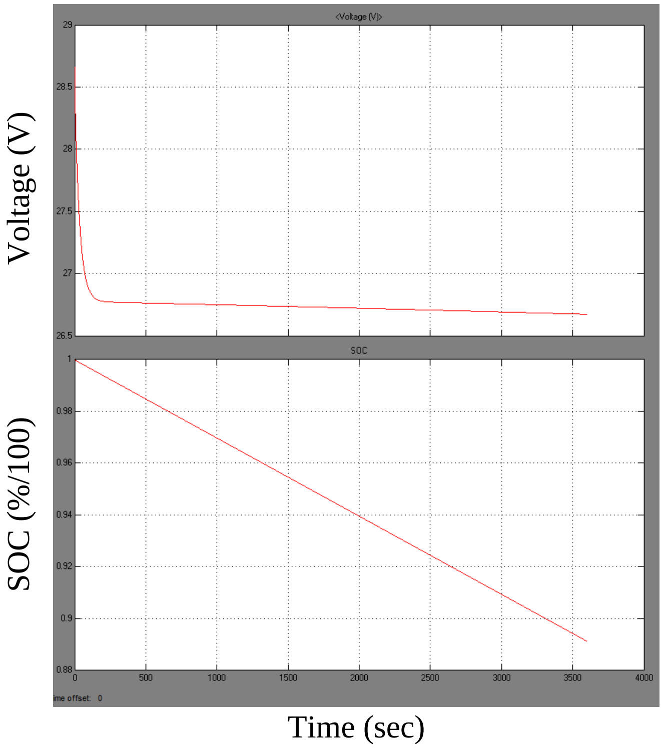


Figure 20. Lead Acid Battery Simulated Voltage and SOC at 50 hour rate

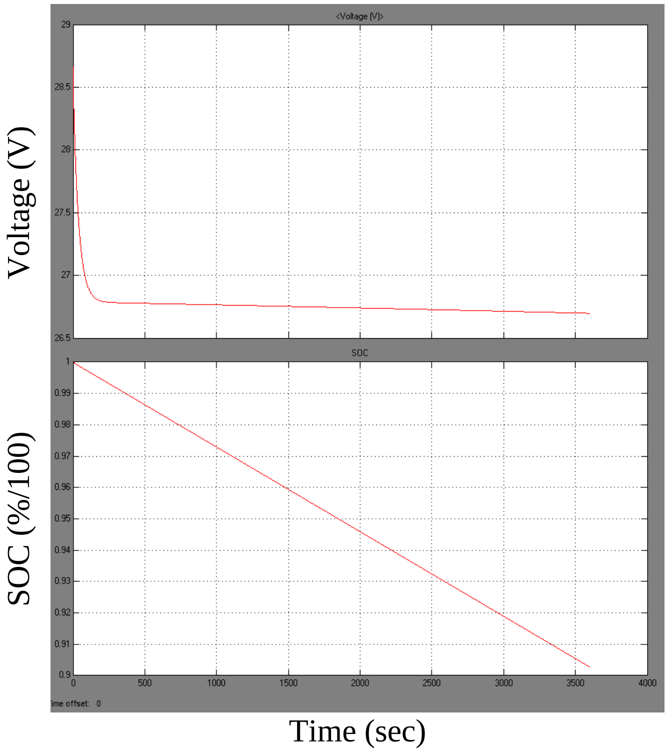
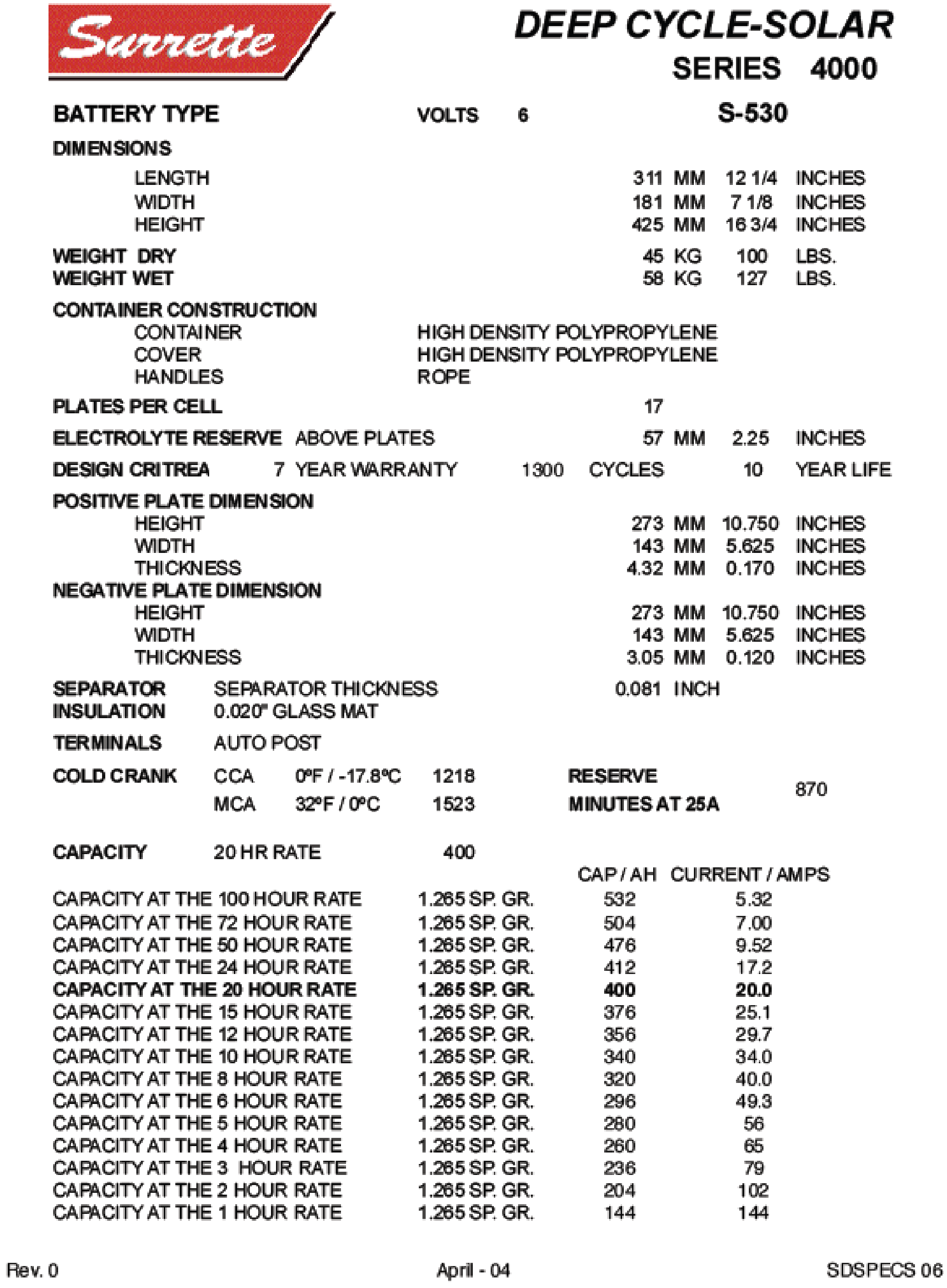


Figure 21. Lead Acid Battery Simulated Voltage and SOC at 100 hour rate

Appendix H: Specifications for Lead Acid Battery in the Power Lab

The lead acid battery set described was available in the Drexel Power Lab. The configuration is a 24VDC configuration consisting of (4) 6V cells connected in series.



Surrette

DEEP CYCLE-SOLAR

SERIES 4000

BATTERY TYPE **VOLTS** **6** **S-530**

DIMENSIONS					
LENGTH	311	MM	12 1/4	INCHES	
WIDTH	181	MM	7 1/8	INCHES	
HEIGHT	425	MM	16 3/4	INCHES	
WEIGHT DRY	45	KG	100	LBS.	
WEIGHT WET	58	KG	127	LBS.	

CONTAINER CONSTRUCTION

CONTAINER	HIGH DENSITY POLYPROPYLENE
COVER	HIGH DENSITY POLYPROPYLENE
HANDLES	ROPE

PLATES PER CELL		17			
ELECTROLYTE RESERVE	ABOVE PLATES	57	MM	2.25	INCHES
DESIGN CRITREA	7 YEAR WARRANTY	1300	CYCLES	10	YEAR LIFE

POSITIVE PLATE DIMENSION				
HEIGHT	273	MM	10.750	INCHES
WIDTH	143	MM	5.625	INCHES
THICKNESS	4.32	MM	0.170	INCHES
NEGATIVE PLATE DIMENSION				
HEIGHT	273	MM	10.750	INCHES
WIDTH	143	MM	5.625	INCHES
THICKNESS	3.05	MM	0.120	INCHES

SEPARATOR	SEPARATOR THICKNESS	0.081 INCH
INSULATION	0.020" GLASS MAT	
TERMINALS	AUTO POST	

COLD CRANK	CCA	0ºF / -17.8ºC	1218	**RESERVE**	870
	MCA	32ºF / 0ºC	1523	**MINUTES AT 25A**	

CAPACITY 20 HR RATE 400

		CAP / AH	CURRENT / AMPS
CAPACITY AT THE 100 HOUR RATE	1.265 SP. GR.	532	5.32
CAPACITY AT THE 72 HOUR RATE	1.265 SP. GR.	504	7.00
CAPACITY AT THE 50 HOUR RATE	1.265 SP. GR.	476	9.52
CAPACITY AT THE 24 HOUR RATE	1.265 SP. GR.	412	17.2
CAPACITY AT THE 20 HOUR RATE	**1.265 SP. GR.**	**400**	**20.0**
CAPACITY AT THE 15 HOUR RATE	1.265 SP. GR.	376	25.1
CAPACITY AT THE 12 HOUR RATE	1.265 SP. GR.	356	29.7
CAPACITY AT THE 10 HOUR RATE	1.265 SP. GR.	340	34.0
CAPACITY AT THE 8 HOUR RATE	1.265 SP. GR.	320	40.0
CAPACITY AT THE 6 HOUR RATE	1.265 SP. GR.	296	49.3
CAPACITY AT THE 5 HOUR RATE	1.265 SP. GR.	280	56
CAPACITY AT THE 4 HOUR RATE	1.265 SP. GR.	260	65
CAPACITY AT THE 3 HOUR RATE	1.265 SP. GR.	236	79
CAPACITY AT THE 2 HOUR RATE	1.265 SP. GR.	204	102
CAPACITY AT THE 1 HOUR RATE	1.265 SP. GR.	144	144

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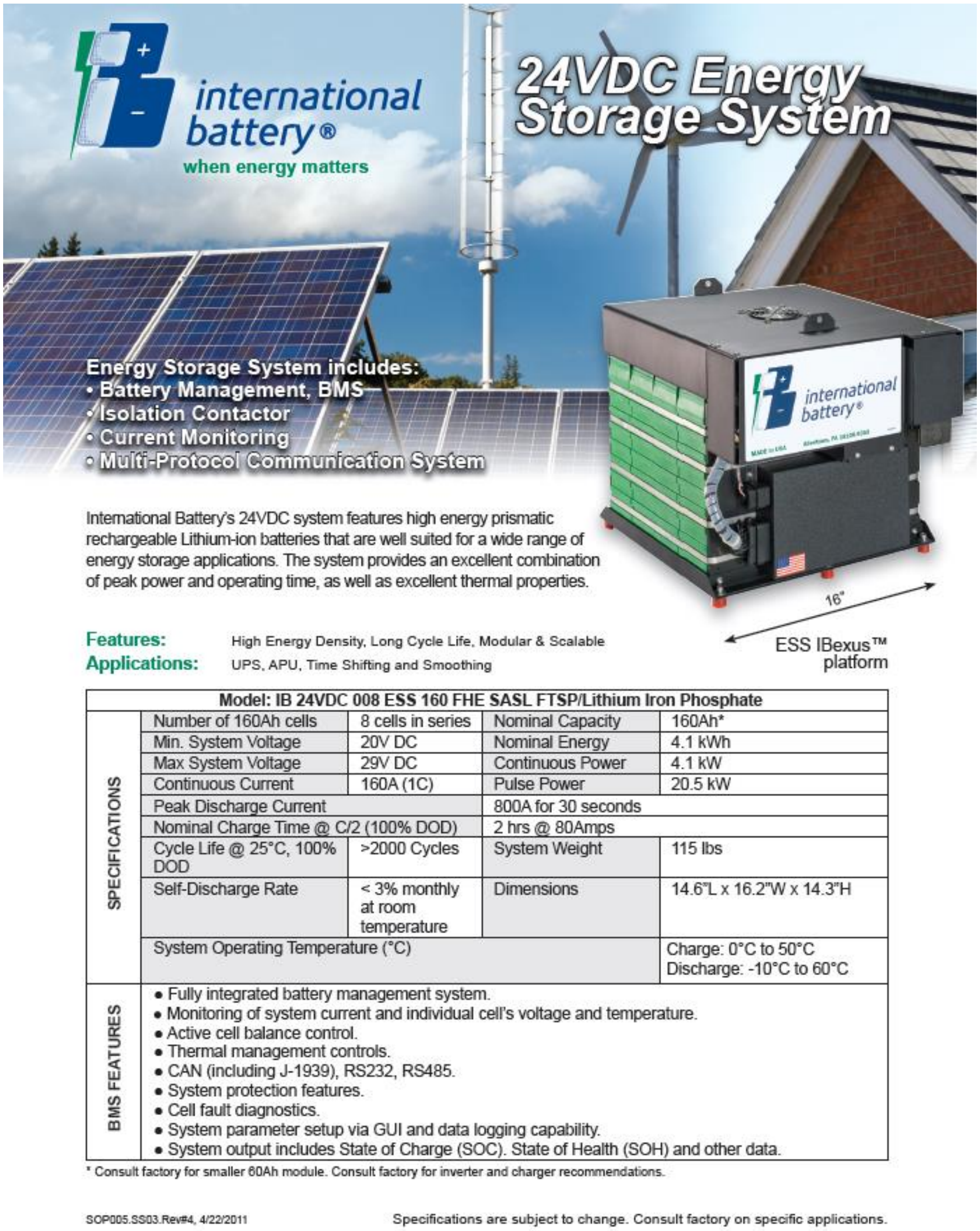
Appendix I: Specifications for Lithium Ion Battery in the Power Lab

The lead acid battery set described was available in the Drexel Power Lab. The configuration is a 24VDC configuration consisting of (8) 3V cells connected in series.



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- Isolation Contactor
- Current Monitoring
- Multi-Protocol Communication System

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16"

ESS IBexus™ platform

Features: High Energy Density, Long Cycle Life, Modular & Scalable
Applications: UPS, APU, Time Shifting and Smoothing

Model: IB 24VDC 008 ESS 160 FHE SASL FTSP/Lithium Iron Phosphate				
SPECIFICATIONS	Number of 160Ah cells	8 cells in series	Nominal Capacity	160Ah*
	Min. System Voltage	20V DC	Nominal Energy	4.1 kWh
	Max System Voltage	29V DC	Continuous Power	4.1 kW
	Continuous Current	160A (1C)	Pulse Power	20.5 kW
	Peak Discharge Current		800A for 30 seconds	
	Nominal Charge Time @ C/2 (100% DOD)		2 hrs @ 80Amps	
	Cycle Life @ 25°C, 100% DOD	>2000 Cycles	System Weight	115 lbs
	Self-Discharge Rate	< 3% monthly at room temperature	Dimensions	14.6"L x 16.2"W x 14.3"H
	System Operating Temperature (°C)			Charge: 0°C to 50°C Discharge: -10°C to 60°C
BMS FEATURES	• Fully integrated battery management system. • Monitoring of system current and individual cell's voltage and temperature. • Active cell balance control. • Thermal management controls. • CAN (including J-1939), RS232, RS485. • System protection features. • Cell fault diagnostics. • System parameter setup via GUI and data logging capability. • System output includes State of Charge (SOC). State of Health (SOH) and other data.			

* Consult factory for smaller 60Ah module. Consult factory for inverter and charger recommendations.

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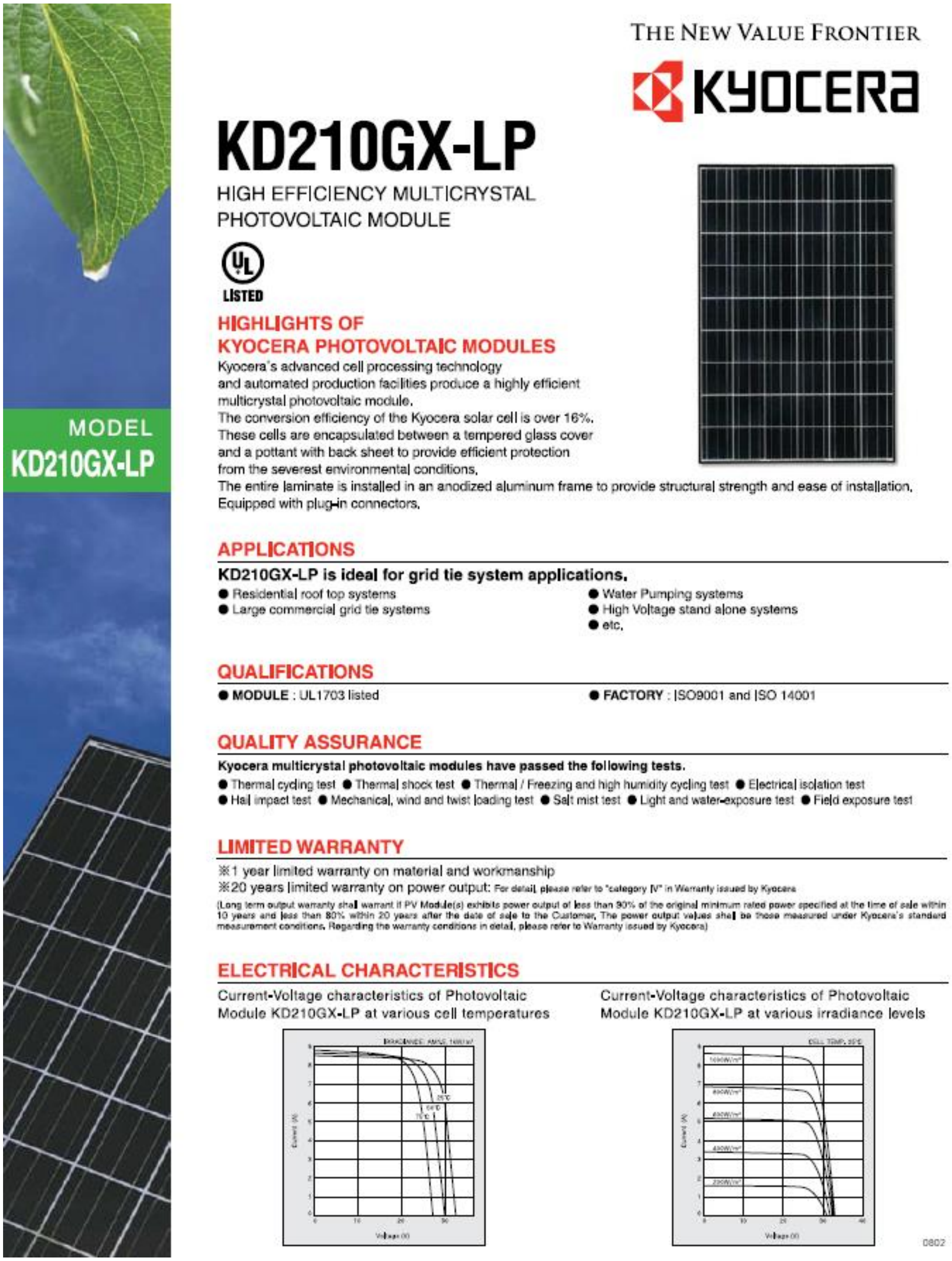
Specifications are subject to change. Consult factory on specific applications.

Appendix J: Specifications for Photovoltaic Module in the Power Lab

The photovoltaic module described was available in the Drexel Power Lab. The configuration is for (2) 72VDC arrangements producing 0.8kW consisting of (4) module parallel subarrays for a total of 1.6kW.



THE NEW VALUE FRONTIER

KYOCERA

KD210GX-LP

HIGH EFFICIENCY MULTICRYSTAL
PHOTOVOLTAIC MODULE

UL LISTED

MODEL
KD210GX-LP

HIGHLIGHTS OF KYOCERA PHOTOVOLTAIC MODULES

Kyocera's advanced cell processing technology and automated production facilities produce a highly efficient multicrystal photovoltaic module.
The conversion efficiency of the Kyocera solar cell is over 16%.
These cells are encapsulated between a tempered glass cover and a pottant with back sheet to provide efficient protection from the severest environmental conditions.
The entire laminate is installed in an anodized aluminum frame to provide structural strength and ease of installation.
Equipped with plug-in connectors.

APPLICATIONS

KD210GX-LP is ideal for grid tie system applications.

- Residential roof top systems
- Large commercial grid tie systems
- Water Pumping systems
- High Voltage stand alone systems
- etc.

QUALIFICATIONS

- **MODULE** : UL1703 listed
- **FACTORY** : ISO9001 and ISO 14001

QUALITY ASSURANCE

Kyocera multicrystal photovoltaic modules have passed the following tests.

- Thermal cycling test
- Thermal shock test
- Thermal / Freezing and high humidity cycling test
- Electrical isolation test
- Hail impact test
- Mechanical, wind and twist loading test
- Salt mist test
- Light and water-exposure test
- Field exposure test

LIMITED WARRANTY

※1 year limited warranty on material and workmanship

※20 years limited warranty on power output: For detail, please refer to "category IV" in Warranty issued by Kyocera

(Long term output warranty shall warrant if PV Module(s) exhibits power output of less than 90% of the original minimum rated power specified at the time of sale within 10 years and less than 80% within 20 years after the date of sale to the Customer. The power output values shall be those measured under Kyocera's standard measurement conditions. Regarding the warranty conditions in detail, please refer to Warranty issued by Kyocera)

ELECTRICAL CHARACTERISTICS

Current-Voltage characteristics of Photovoltaic Module KD210GX-LP at various cell temperatures

Current-Voltage characteristics of Photovoltaic Module KD210GX-LP at various irradiance levels

0802

Appendix K: Block Diagram of Drexel's System for Hardware Testing

This block diagram shows the current lab set up in the Drexel Center for Electric Power Engineering (CEPE). It shows the connections between the solar panels, the two available battery banks, the load, and the power from the utility (PECO). The current set up is a single phase system, but standard commercial customers would use a 3-phase system.

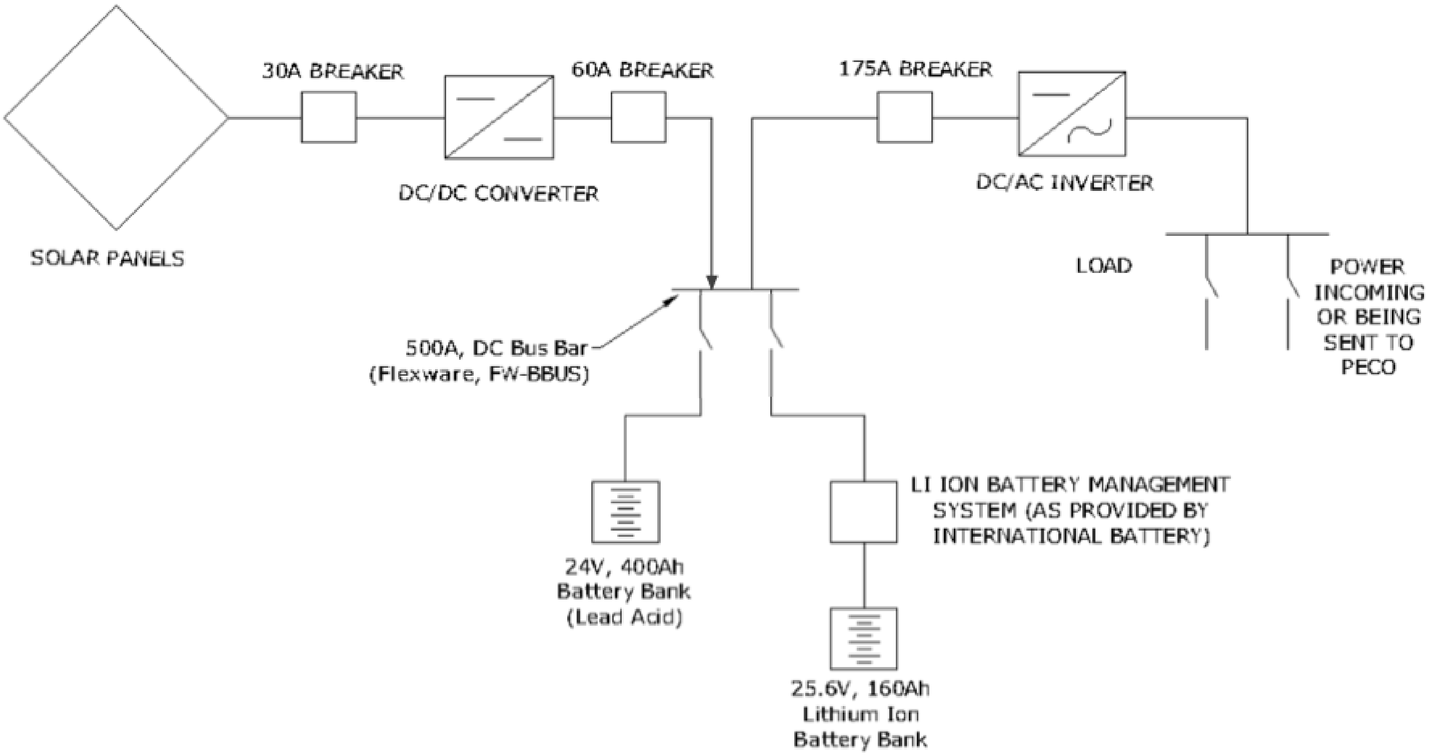


Figure 22. System Block Diagram.

Appendix L: Battery Diagnostic Testing Plan

Note: This plan can be adapted into a lab plan for a power class, such as ECEP-354 or ECEP-451 as an introduction to the varying characteristics of the batteries over time.

1. **Objective**:

The purpose of this experiment is to obtain the characteristic curves for the Lithium Ion and Lead Acid batteries in the CEPE lab to ensure that they are still functioning properly. These tests have not been performed in a year since the previous senior design group worked on them. Because our project's results will be compared with theirs, it is important to confirm that the batteries are functioning on the same level they were when the previous team performed their experiments.

2. **Experimental Set Up**:

2.1. Circuit Diagram

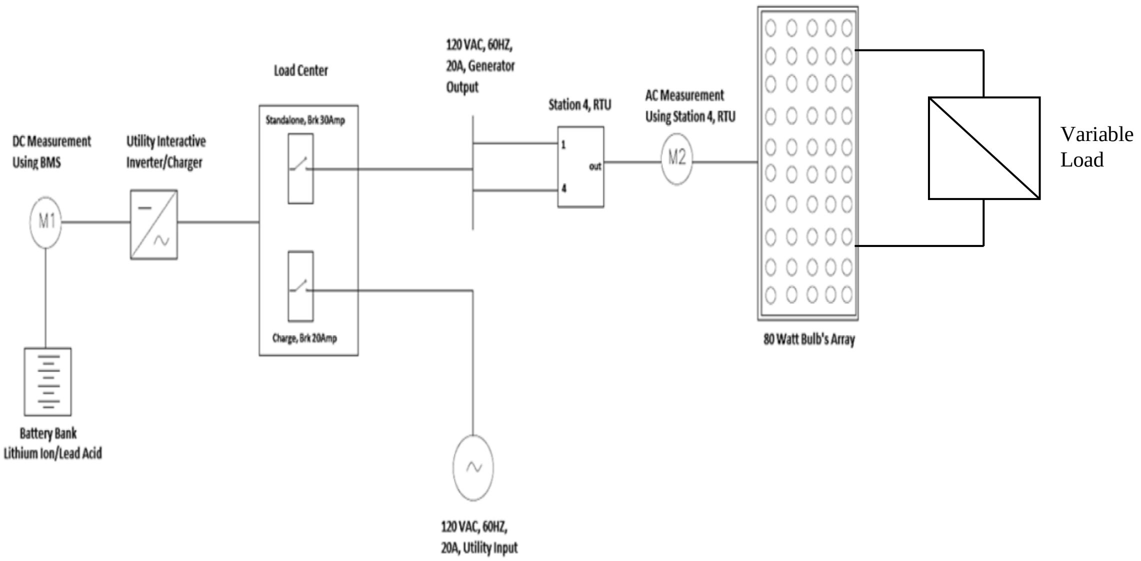


Figure 23. Circuit diagram for battery testing.

2.2. Meters:

Measurements will be taken from the AC and DC side of the system. At the point labeled M1, the MATE3 will be used to record the voltage, current, and battery state of charge (%SOC) on the DC side. At the point labeled M2, the Remote Terminal Unit (RTU) station will be used to record the voltage and current on the AC side.

3. **Experimental Plan:**

3.1. Scenarios

Two tests will be performed on the batteries: the constant load test and the variable load test. The constant load test will connect a constant load to the batteries and observe them as time passes. The variable load test will examine the batteries response to a load that changes to mimic a real world commercial load.

Additionally, each of these tests will be performed on both the Lead Acid and Lithium Ion batteries for comparison.

3.2. Step-by-step Plans

Constant Load Test

1. Verify that battery state of charge is at 100% on the MATE3
2. Open 20A "charger" breaker on Load Center
3. Verify that 175A "battery" breaker on DC panel is closed
4. Verify that battery is connected to inverter via Anderson Connector
5. Closer 30A "standalone" breaker
6. Turn on power to lab station
7. Turn on 25 light bulbs to serve as load
8. Record Measurements:
    a. Take recordings every 5 minutes
    b. Record Voltage, Current, and SOC on DC side using MATE3
    c. Record Voltage and Current on AC side using Remote Terminal Unit (RTU)
9. Stop discharging at 50% SOC
10. Turn off light bulbs and turn off power to lab station
11. Open 30A "standalone" breaker
12. Verify battery connection via Anderson Connector for charging
13. Close 60A "charge controller" breaker on DC panel
14. Close 20A charger breaker on Load Center
15. Repeat process, switching out Lithium Ion battery with Lead Acid battery
16. Recharge batteries when finished

Variable Load Test

1. Verify that battery state of charge is at 100% on the MATE3
2. Open 20A “charger” breaker on Load Center
3. Verify that 175A “battery” breaker on DC panel is closed
4. Verify that battery is connected to inverter via Anderson Connector
5. Closer 30A “standalone” breaker
6. Turn on power to lab station
7. Vary controllable load every 5 minutes according to schedule in Table L.1.
8. Record Measurements:
    a. Take recordings every 5 minutes
    b. Record Voltage, Current, and SOC on DC side using MATE3
    c. Record Voltage and Current on AC side using Remote Terminal Unit (RTU)
9. Stop discharging at 50% SOC
10. Turn off light bulbs and turn off power to lab station
11. Open 30A “standalone” breaker
12. Verify battery connection via Anderson Connector for charging
13. Close 60A “charge controller” breaker on DC panel
14. Close 20A charger breaker on Load Center
15. Repeat process, switching out Lithium Ion battery with Lead Acid battery
16. Recharge batteries when finished

4. Predict the results

For each test, the variables measured (voltage, current, state of charge) will be plotted over time. The results are expected to be comparable to the plots shown in last year’s senior design final report [6]. This will confirm that the batteries are functioning on the same level and that the results our load leveling tests are able to be compared with theirs.

Table L.1. Variable load test loads.

Interval	Total Load (W)
1	1221
2	1187
3	1169
4	1165
5	1192
6	1272
7	1406
8	1477
9	1473
10	1462
11	1452
12	1422
13	1394
14	1375
15	1358
16	1354
17	1373
18	1421
19	1472
20	1462
21	1437
22	1382
23	1296
24	1210

Appendix M: Battery Diagnostic – Constant Load Test Results

These results are compared against the previous year's results to highlight the slightly lower performance, along with the earlier cut off time.

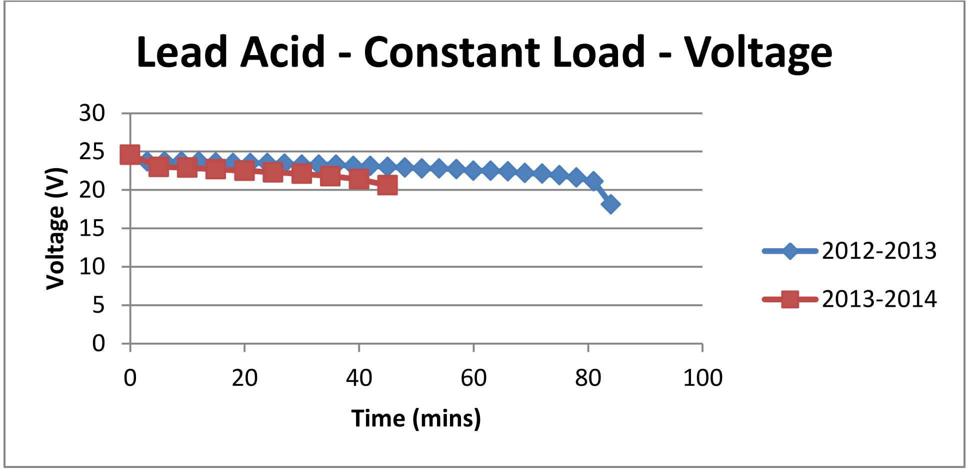


Figure 24. Comparison of voltage for lead acid with constant load.

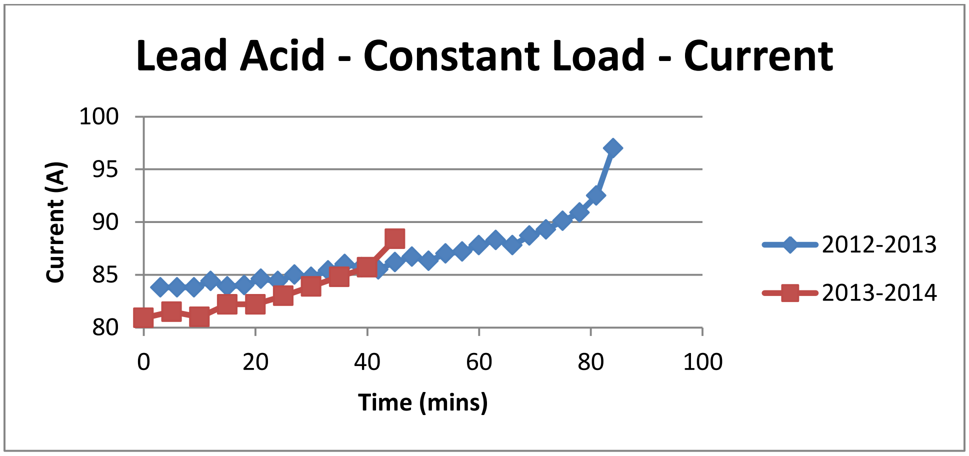


Figure 25. Comparison of current for lead acid with constant load.

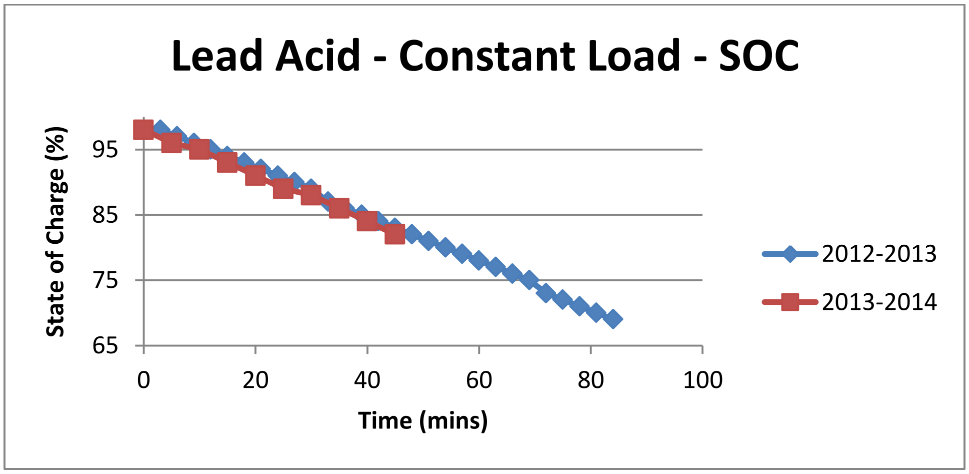


Figure 26. Comparison of state of charge for lead acid with constant load.

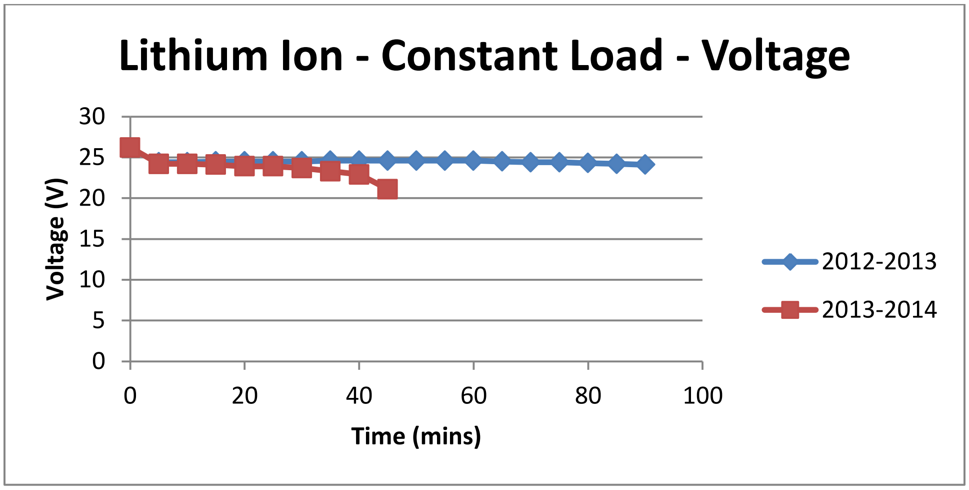


Figure 27. Comparison of voltage for lithium ion with constant load.

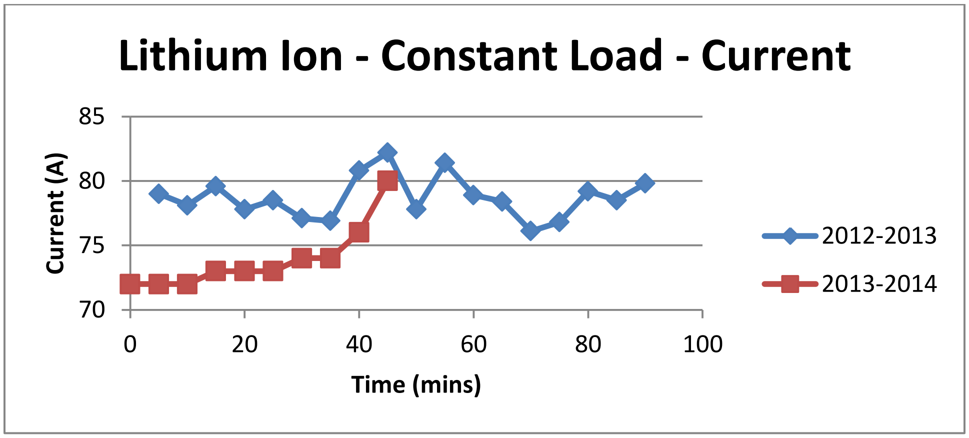


Figure 28. Comparison of current for lithium ion with constant load.

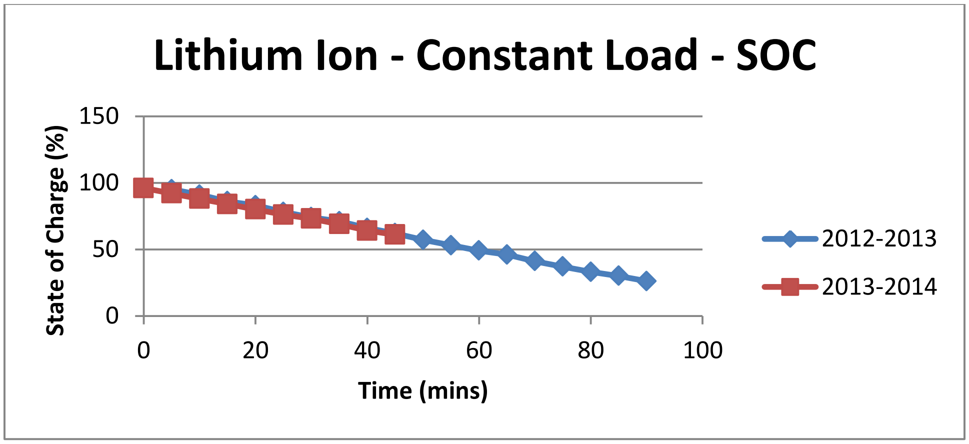


Figure 29. Comparison of state of charge for lithium ion with constant load.

Appendix N: Battery Diagnostic – Variable Load Test Results

These tests show the batteries responses to a varying load as described in Appendix L.

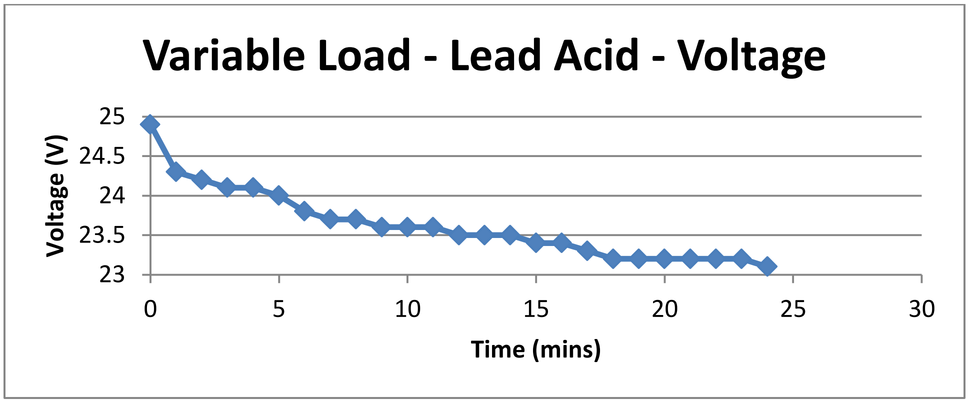


Figure 30. Voltage for lead acid with variable load.

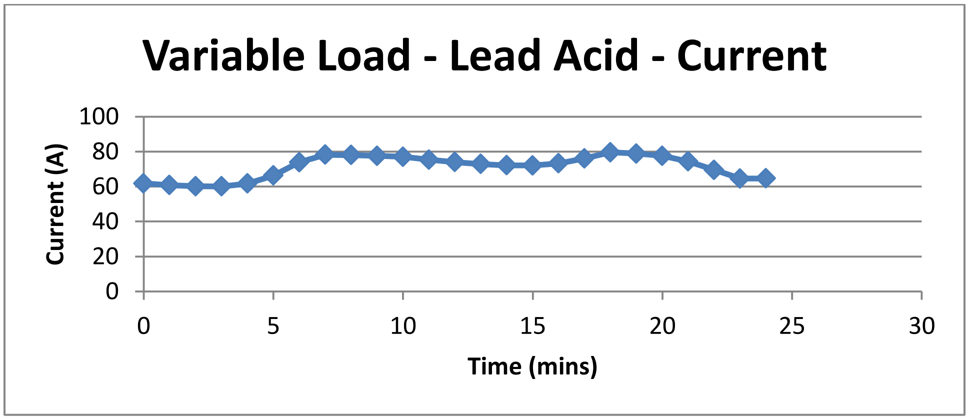


Figure 31. Current for lead acid with variable load.

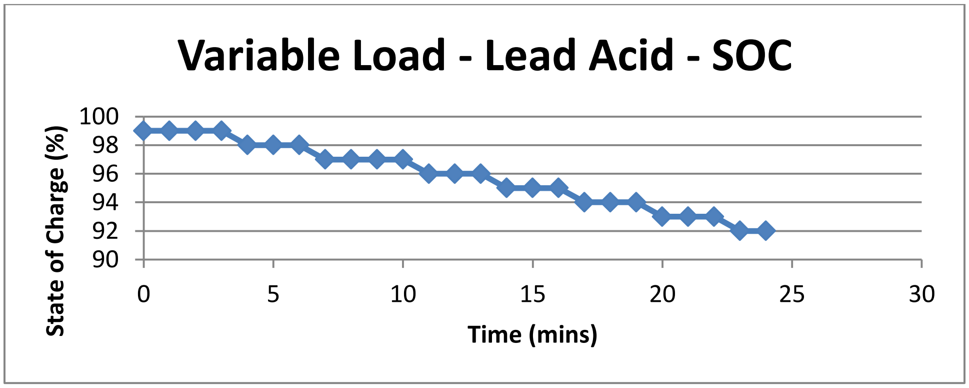


Figure 32. State of charge for lead acid with variable load.

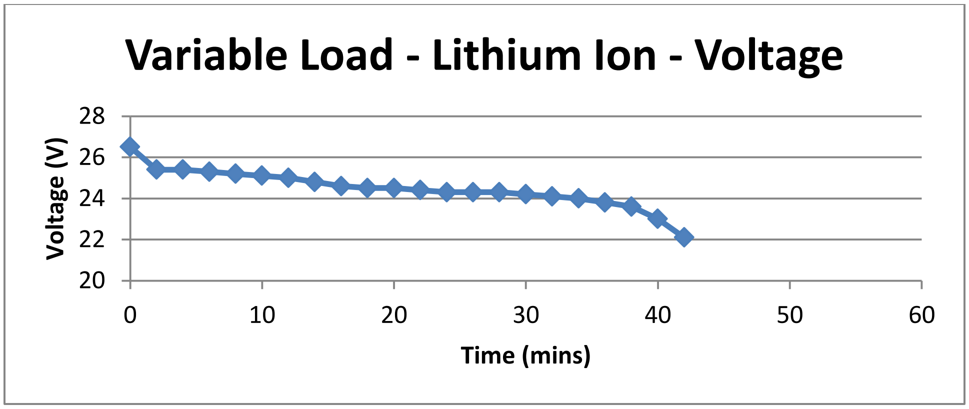


Figure 33. Voltage for lithium ion with variable load.

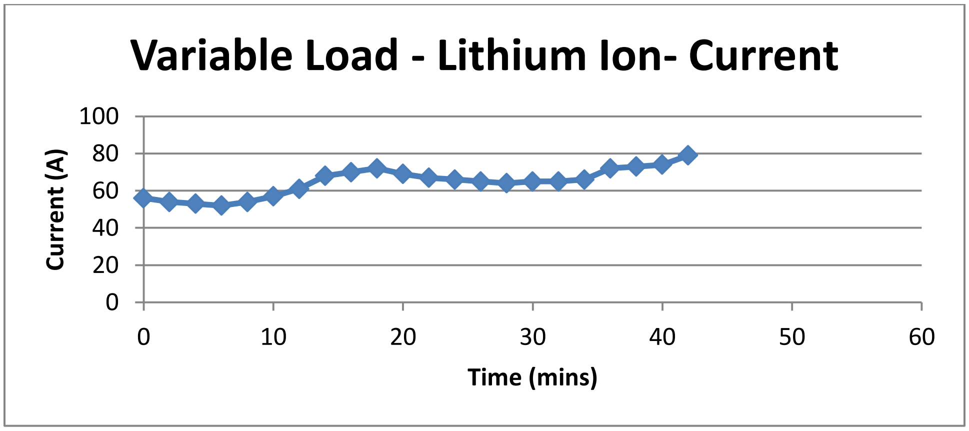


Figure 34. Current for lithium ion with variable load.

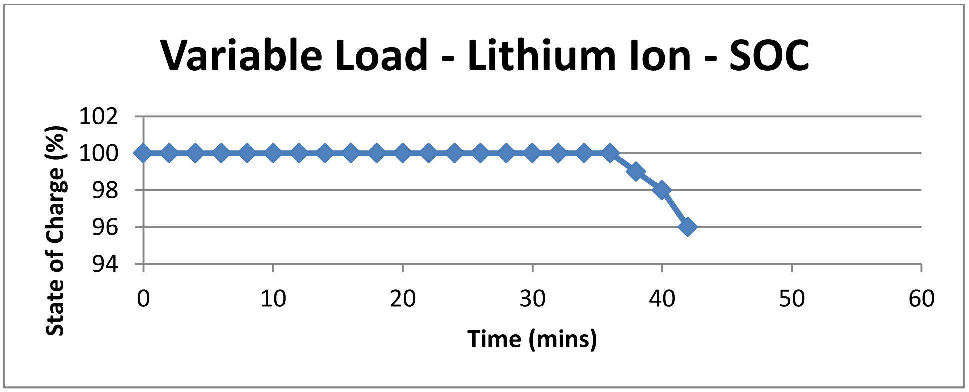


Figure 35. State of charge for lithium ion with variable load.

Appendix O: MPPT Testing Lab Plan

Note: This plan can be adapted into a lab plan for a power class, such as ECEP-354 or ECEP-451 as an introduction to the Renewable Resource Center and the way in which MPPT is determined.

1. Objective:

The purpose of this experiment is to manually determine the maximum power point of operation for the solar array in the Drexel Interconnected Power Systems Laboratory (IPSL).

The power that is flowing from a solar array can be determined by the following:

$$P = I * V$$

P = power, I = current, V = voltage

The relationship between current and voltage for photovoltaic modules mimics a "knee" curve seen below in Figure 1. The power that is delivered from the solar arrays to the battery banks in IPSL is dictated and controlled by the charge controller, to be discussed later.

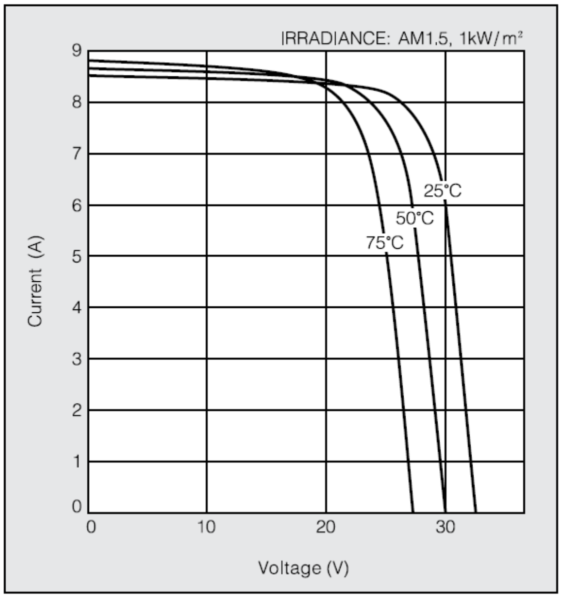


Figure 36. I-V Curve of Photovoltaic Module KD210GX-LP at various cell temperatures [Appendix J]

Any point along the solid curves that are shown in Figure 1 can be considered as an operating point for the solar arrays. In order to make sure that the maximum possible power flow is attained, the correct operating point must be chosen by the charge controller for the solar array.

For example, if an operating point of I = 8.5A and V = 2V is chosen, you are only producing 17W of power. If you choose the optimal power point at the "knee" of the curve, occurring at I = 7.9A and V = 26.6V. This produces the maximum power, per cell, of 210W. Since the current configuration in the Drexel Power Lab has 8 solar cells, a maximum power of 1.6kW can be produced.

This maximum power point is automatically selected, based on the current conditions, by the FLEXmax60 Maximum Power Point Charge Controller. For the purposes of this lab, you will manually change settings on the charge controller to determine what the maximum power point will be.

2. **Experimental Set Up**: Showing:

2.1. Simplified single line diagram

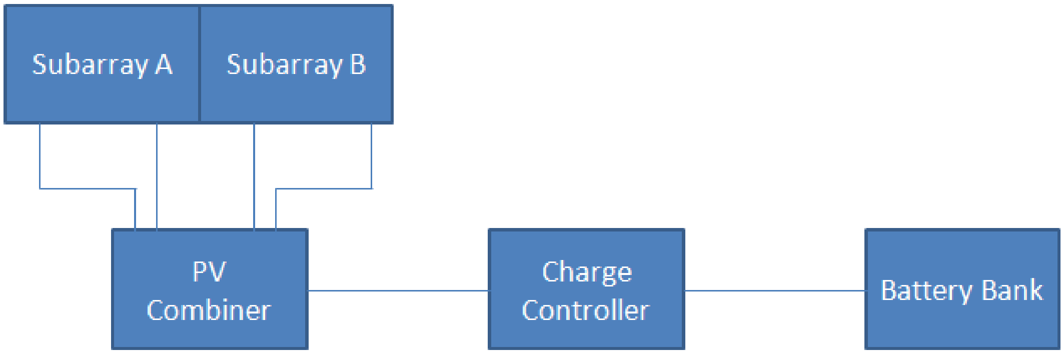


Figure 37. Single line diagram for MPPT testing

Equipment Used:

- Subarray A and Subarray B:
    - (4) Kyocera KD210GX-LP High Efficiency Multicrystal Photovoltaic Modules connected in series configuration
- PV Combiner
    - Outback FWPV8 PV Combiner Box
- Charge Controller
    - Outback FLEXmax 60 Maximum Power Point Tracking Charge Controller
- Lead Acid Battery Bank:
    - (4) 6V Rolls s-530, Lead-Acid, Deep Cycle, Solar Batteries connected in series

2.2. Meters to be used

The only two measurements necessary for this experiment are the % of Open Circuit Voltage and the Power of the PV arrays. Both of these measurements will be taken directly on the Charge Controller Display.

3. Experimental Plan:

3.1. Variable to be measured

During the course of this experiment, the power that is flowing from the PV arrays to the battery bank will be measured.

3.2. Scenarios

In order to speed up maximum power point tracking time, there are limits set for the minimum and maximum percentage of the open circuit voltage that can be selected as an operating point for the charge controller. The lower limit is defaulted to 50% of the open circuit voltage. The upper limit is set to 90% of the open circuit voltage, partially because the open circuit voltage can never exceed 150VDC for this charge controller.

3.3. Step-by-step Procedure

1) Before starting, ensure that the PV and Charge Controller (CC) breakers are OPEN.
2) Adjust the set points on the MATE3 as specified in Appendix P
3) Next, CLOSE the CC breaker. At this point, the battery voltage should power on the charge controller display. Verify that the correct battery voltage (24VDC) has been detected before proceeding. The charge controller will show the system voltage in the upper right corner of the display.
4) You should now be viewing the Status screen shown below:

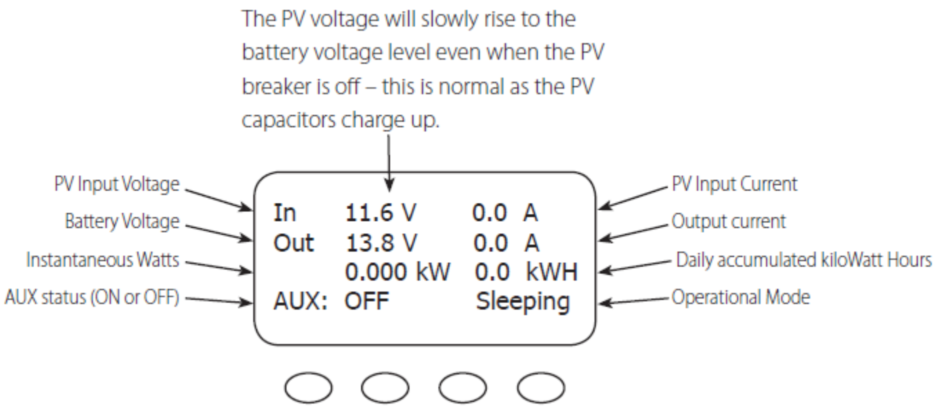
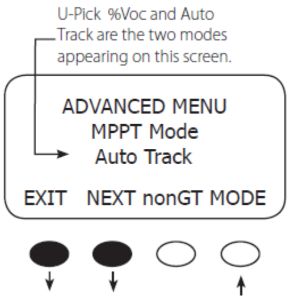

The PV voltage will slowly rise to the battery voltage level even when the PV breaker is off – this is normal as the PV capacitors charge up.

Figure 38. Charge Controller Status Screen [14]

5) Press the left-most soft button on the charge controller to access the Main Menu screen
6) From the Main Menu, move the arrow and select the Advanced tab.
7) Once in the Advanced menu, select the “next” arrow until you arrive at the MPPT Mode screen shown below:

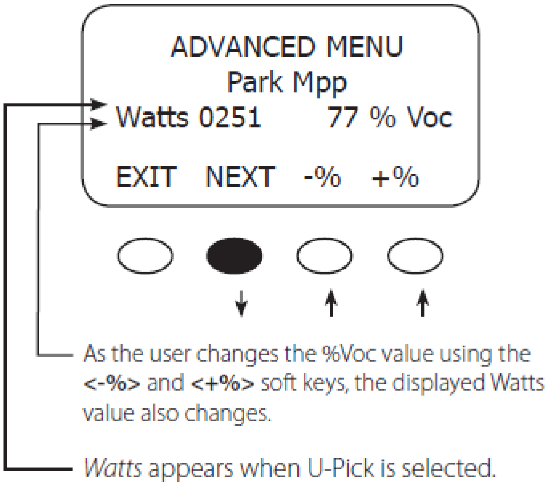


U-Pick %Voc and Auto Track are the two modes appearing on this screen.

Figure 39. MPPT Mode Screen of Charge Controller [14]

8) From the MPPT Mode Screen, select the "MODE" button until "U-Pick % (Voc)" is shown.

9) Once this is completed, select the "NEXT" button to proceed to the Park MPP screen shown below:



As the user changes the %Voc value using the **<-%>** and **<+%>** soft keys, the displayed Watts value also changes.

Watts appears when U-Pick is selected.

Figure 40. Park MPP Screen on Charge Controller [14]

10) This screen is where the measurements for this experiment will be taken. Start with a %Voc near 50%, the minimum value and record the power (in Watts).

11) Next, select a %Voc near 90% and record the power output from the PV arrays.

12) With these values as a starting point, change the % of the open circuit voltage that you are operating the charge controller at in order to determine the maximum possible power output. The max possible output of the PV array in IPSL is 1.6kW, but will not be attained when conditions are less than optimal.

13) Record multiple values of %Voc and power in order to prove that you have found the maximum power point manually using the charge controller.

Appendix P: MATE3 Set Point Adjustment Procedure

Follow this guide to put the Renewable Resource Center into the proper mode to text the MPPT tracking feature and perform load leveling tests.

Press LOCK Button, enter passcode ‘141’

Set up:

- AC Input
    - AC Input Mode → USE to DROP
- Settings
    - Inverter
        - Battery Charger
            - Absorb Voltage Time → 1h to 0h
            - Float Voltage Time → 1h to 0h
        - Grid Tie Sell
            - Grid Tie Capable→ N to Y
            - Sell Voltage → 26.2V to 25.2V
    - Charge Controller
        - Charger
            - Absorb Voltage Time → 1h to 0h
        - Grid Tie Mode
            - Grid Tie Enables → N to Y
- AC Input
    - AC Input Mode → DROP to USE

Load Leveling:

- Settings
    - Inverter
        - AC Input and Current Limit
            - AC Charger Limit → adjust as needed for CHARGING
        - Grid Tie Sell
            - Sell Voltage → adjust as needed for DISCHARGING

Appendix Q: Renewable Resource Center and MPPT Testing Results

These plots show the results of the Renewable Resource Center testing. Figure 41 shows the expected I-V curve for the PV system, while Figure 42 shows the experimentally produced I-V curve for the entire system. Finally, Figure 43 shows that the load and utility feeds add up to equal the inverter power.

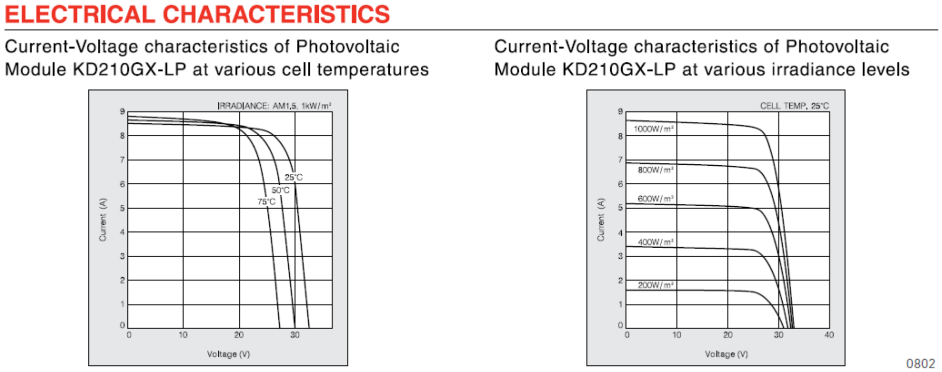


Figure 41. I-V curves for PV cells in renewable load center [Appendix J]

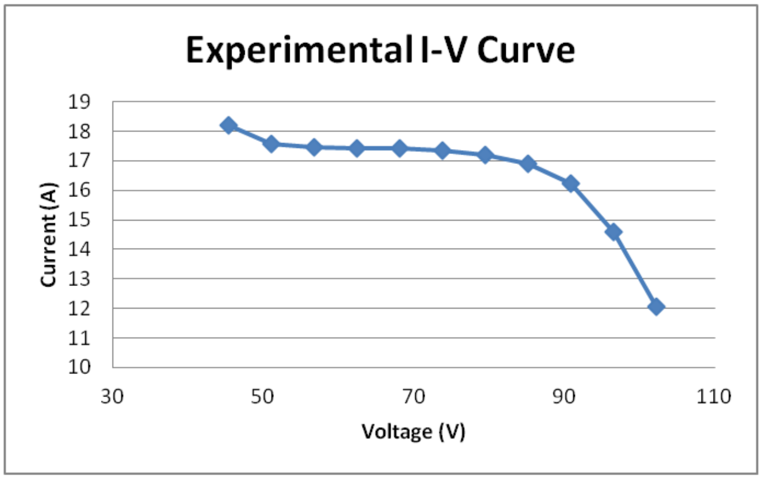


Figure 42. Experimental I-V Curve Created for Entire PV Array

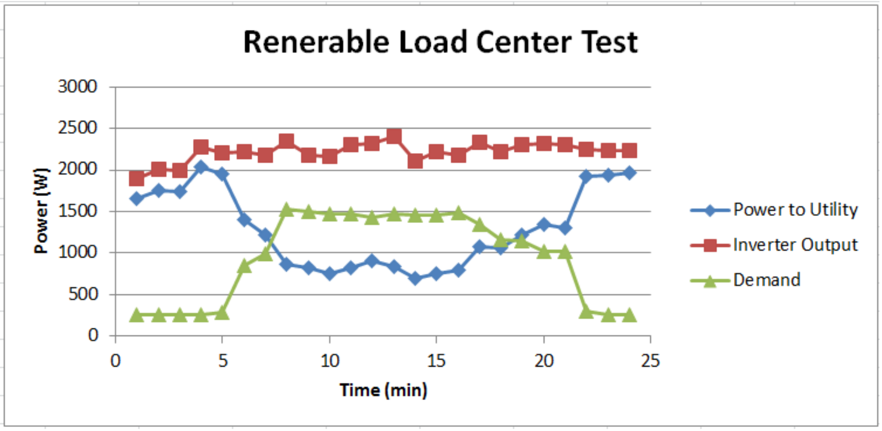


Figure 43. Renewable Load Center Testing Results

The following 3 plots are for further analysis of the Renewable Resource Center (RRC). Figure 44 shows that as the load increase, power sold to the load decreases. Figure 45 shows that as PV power decreases, battery power increases in response. Figure 46 shows that the power into the inverter (battery and inverter) and out of the inverter (utility and load) are approximately equal, within the limits of the inverter efficiency.

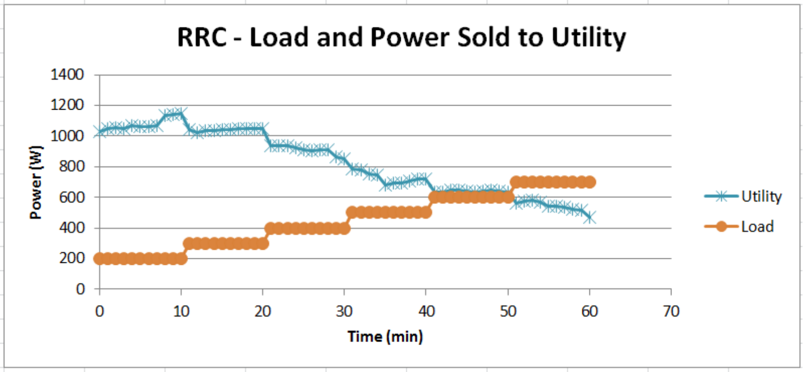


Figure 44. Renewable Resource Center – Load and Power Sold to Utility

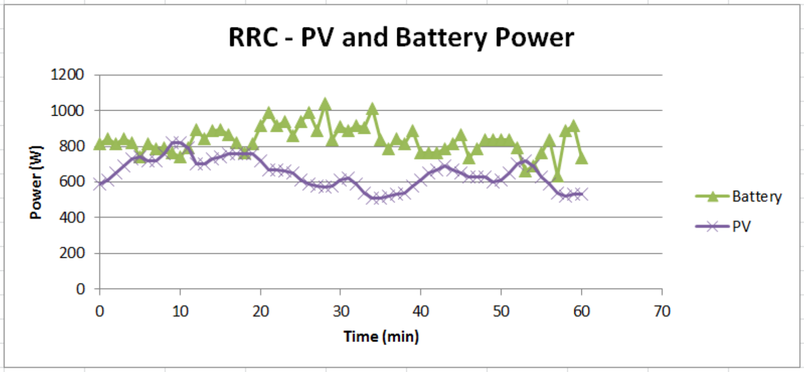


Figure 45. Renewable Resource Center – PV and Battery Power

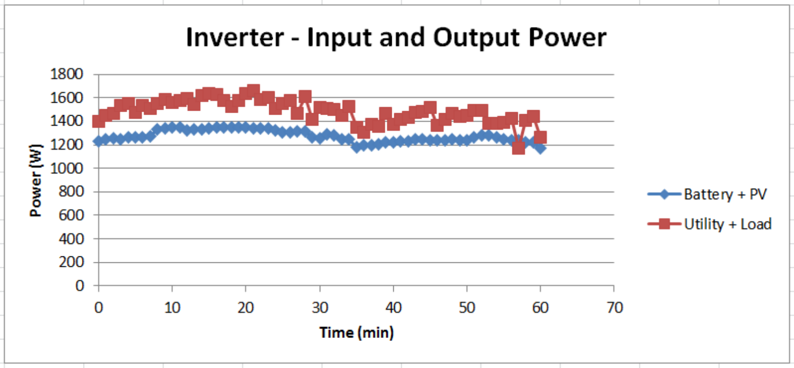


Figure 46. Renewable Resource Center – Comparison of Inverter Input and Output

Appendix R: Load Leveling Testing Plan

1. Objective:

The goal of this experiment is to perform the final load leveling test of the project, and determine if the results reflect the expectations determined from the software simulations. The results will be limited by the oversized batteries in the lab, coupled with the lack of an ability to control the rate of discharge in the batteries.

2. Experimental Set Up:

2.1. Single Line Diagram

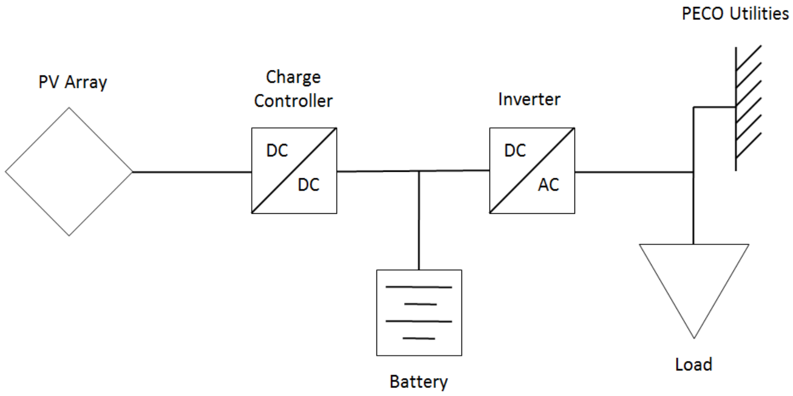


Fig. 47. Single Line Diagram for load leveling

2.2. Meters

Battery voltage, current, and state of charge is recorded through the BMS on a laptop. PV power production is shown on the charge controller screen. AC readings were taken on multimeters and RTUs at two points: immediately after the inverter, and on the utility side.

3. Experimental Plan:

3.1. Scenarios considered

For this experiment, the same load used in the Matlab simulation was intended to be used, but was scaled down to half size to function within the programmable load limits. Because discharge rate could not be controlled on the battery, results may have been skewed due to the battery handling too much of the load.

3.2. Step-by-step Plans

1. Input load profile shown in Table R.1 to programmable load with intervals of 2 minutes, and a max current value of 20A

Figure 48. Programmable load set up

2. Connect measurement equipment to utility side and inverter side as shown below

Figure 49. Utility feed measurements

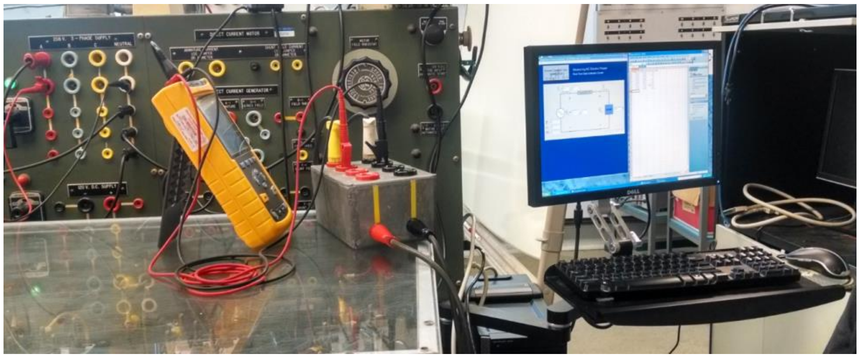


Figure 50. Inverter feed measurements

3. Connect laptop to lithium ion BMS as shown and run TeraTerm program to record battery data

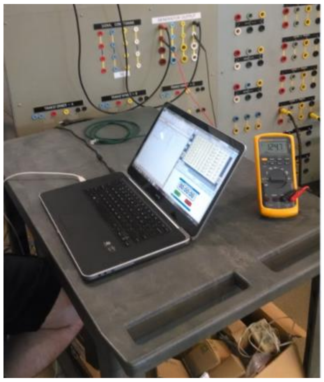


Figure 51. Battery measurements set up

4. Adjust MATE3 set points as shown in Appendix P.
5. Adjust the max charger amps in the MATE3 to 15A
6. Verify all system connections with lab personnel before proceeding
7. Discharge battery to at least 80%
8. Set Sell Voltage on MATE3 to below battery voltage to enter charge mode
9. Activate load profile, and take recordings at each station every minute
10. At Interval 7, adjust the Sell Voltage to above the battery voltage to enter discharge mode
11. At Interval 22, adjust the Sell Voltage to below the battery voltage to enter charge mode until end of test

Table R.1. Load data for load leveling test

Interval	Load (W)	Battery Setting
1	258.2	Charge
2	258.2	Charge
3	258.2	Charge
4	264.35	Charge
5	288.65	Charge
6	845.25	Charge
7	999.7	Discharge
8	1533.55	Discharge
9	1501.35	Discharge
10	1473.5	Discharge
11	1468.85	Discharge
12	1426.95	Discharge
13	1467.2	Discharge
14	1461.3	Discharge
15	1459	Discharge
16	1487.5	Discharge
17	1351.85	Discharge
18	1156.2	Discharge
19	1147.65	Discharge
20	1014.95	Discharge
21	1016.55	Discharge
22	299.3	Charge
23	264.35	Charge
24	258.2	Charge

Appendix S – Economic Analysis Calculation

The following load profile was the profile entered into the controllable load for the load leveling testing. In order to demonstrate economic analysis, it was scaled up 100 times. Based on the solar predictions in Appendix C, 75% PV power was used for 0900 through 1100 hours and again from 1600 hours to 1800 hours. 100% PV power was assumed for the hours in red.

Table S.1. Load Profile Used for Economic Analysis (Green = 75% PV and Red = 100% PV)

Interval	Demand (W)	Scaled Demand (KW)
0	258.2	25.82
1	258.2	25.82
2	258.2	25.82
3	264.35	26.435
4	288.65	28.865
5	845.25	84.525
6	999.7	99.97
7	1533.55	153.355
8	1501.35	150.135
9	1473.5	147.35
10	1468.85	146.885
11	1426.95	142.695
12	1467.2	146.72
13	1461.3	146.13
14	1459	145.9
15	1487.5	148.75
16	1351.85	135.185
17	1156.2	115.62
18	1147.65	114.765
19	1014.95	101.495
20	1016.55	101.655
21	299.3	29.93
22	264.35	26.435
23	258.2	25.82

Table S.2. Sizing of System Used in Calculations

System	System Type	PV Size (kWh)	Battery Size (kWh)
1	Lead Acid + PV	60	20
2	Lithium Ion + PV	60	20

PV Specifications for Calculations: 60 kWh with a standard 25 year lifespan

Lead Acid Battery Specifications for Calculations: 20 kWh **usable capacity** with 500 cycle lifetime (1 day = 1 cycle)

Lithium Ion Battery Specifications for Calculations: 20kWh **usable capacity** with 1900 cycle lifetime (1 day = 1 cycle)

Equipment	Cost for usable capacity ($/kWh)
PV Array	4520

Equipment	Cost for usable capacity ($/kWh/cycle)
Lithium Ion Battery	.5754
Lead Acid Battery	1.0412

PV Generation (Reducing Load)

Company	Reduced Load (kWh)	Summer Peak Rate (cents/kWh)	Winter Peak Rate (cents/kWh)	Summer Savings (cents)	Winter Savings (cents)	Total Yearly Savings ($)
PECO	210	15.95	N/A	1222567.5	N/A	12225.675
PG&E	330	23.6	15	1432992	64074	14970.66
NV	315	30.03	4.887	1154052.9	374075.415	15281.28315

Savings = (# of Summer Days * Summer Peak Rate * Daily Leveled Load) + (# of Winter Days * Winter Peak Rate * Daily Leveled Load)

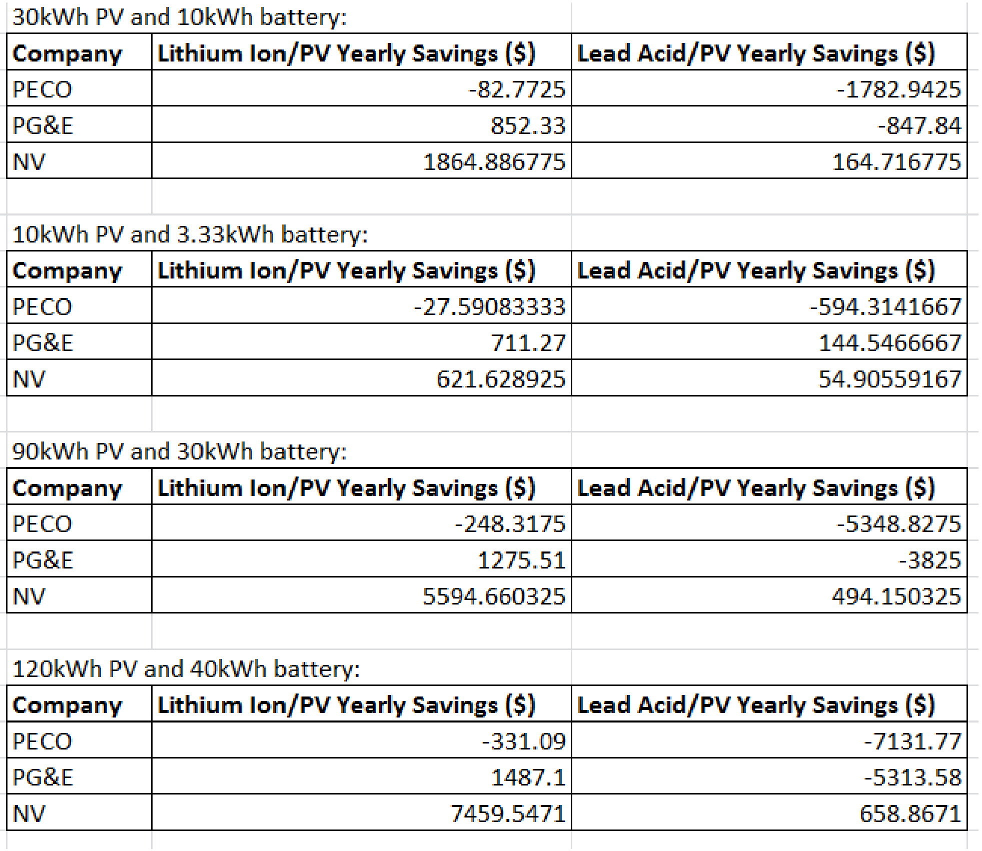
Battery Leveling (Leveled Load)

Company	Leveled Load (kWh)	Summer Peak Difference (cents/kWh)	Winter Peak Difference (cents/kWh)	Summer Savings (cents)	Winter Savings (cents)	Total Yearly Savings ($)
PECO	80	9.1	9.1	265720	N/A	2657.2
PG&E	120	3.4	1.8	75072	39096	1141.68
NV	120	23.886	0	349691.04	0	3496.9104

Savings = (# of Summer Days * Summer Peak/Off Peak Difference * Daily Leveled Load) + (# of Winter Days * Winter Peak/Off Peak Difference * Daily Leveled Load)

Company	Total Yearly Savings before Install Costs ($)	Lithium Ion + PV Yearly Cost ($)	Lead Acid + PV Yearly Cost ($)	Lithium Ion + PV Total Yearly Savings ($)	Lead Acid + PV Total Yearly Savings ($)
PECO	14882.875	15048.42	18448.76	-165.55	-3565.89
PG&E	16112.34	15048.42	18448.76	1063.92	-2336.42
NV	18778.19355	15048.42	18448.76	3729.77	329.43

Table S.3. Comparisons of savings for varying system sizes.



30kWh PV and 10kWh battery:

Company	**Lithium Ion/PV Yearly Savings ($)**	**Lead Acid/PV Yearly Savings ($)**
PECO	-82.7725	-1782.9425
PG&E	852.33	-847.84
NV	1864.886775	164.716775

10kWh PV and 3.33kWh battery:

Company	**Lithium Ion/PV Yearly Savings ($)**	**Lead Acid/PV Yearly Savings ($)**
PECO	-27.59083333	-594.3141667
PG&E	711.27	144.5466667
NV	621.628925	54.90559167

90kWh PV and 30kWh battery:

Company	**Lithium Ion/PV Yearly Savings ($)**	**Lead Acid/PV Yearly Savings ($)**
PECO	-248.3175	-5348.8275
PG&E	1275.51	-3825
NV	5594.660325	494.150325

120kWh PV and 40kWh battery:

Company	**Lithium Ion/PV Yearly Savings ($)**	**Lead Acid/PV Yearly Savings ($)**
PECO	-331.09	-7131.77
PG&E	1487.1	-5313.58
NV	7459.5471	658.8671

Appendix T: 24 Hour Load Factor Improvement versus Battery Size

One limit on effectiveness of this system is the size of the battery used. With a large enough battery, the load could be completely leveled. However, the benefits from this may not outweigh the costs of sufficiently large battery. Using the data for Philadelphia in the summer, the battery size was varied from 2kWh to 20kWh to see its effect on the improvement of the load factor. The results, shown in Figure 52 below, show a very linear improvement up to 10kWh , at which point increased battery size yields less return as it get closer to 100% leveling.

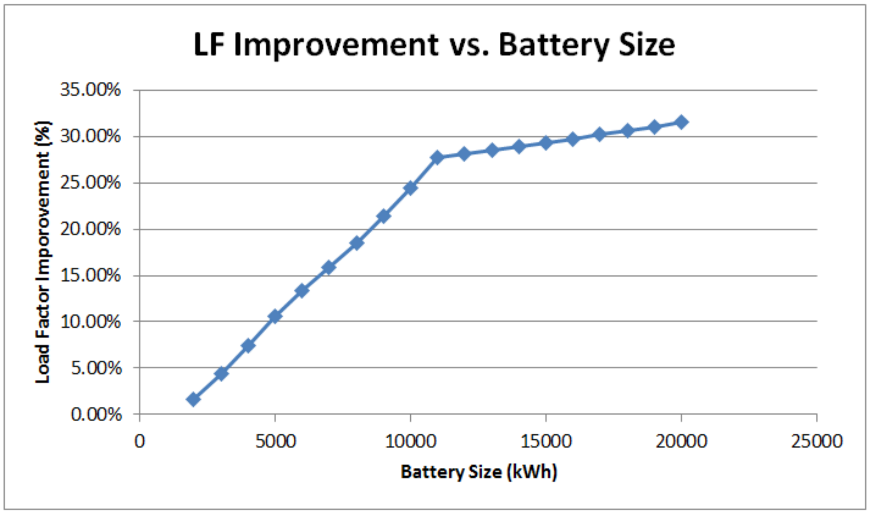
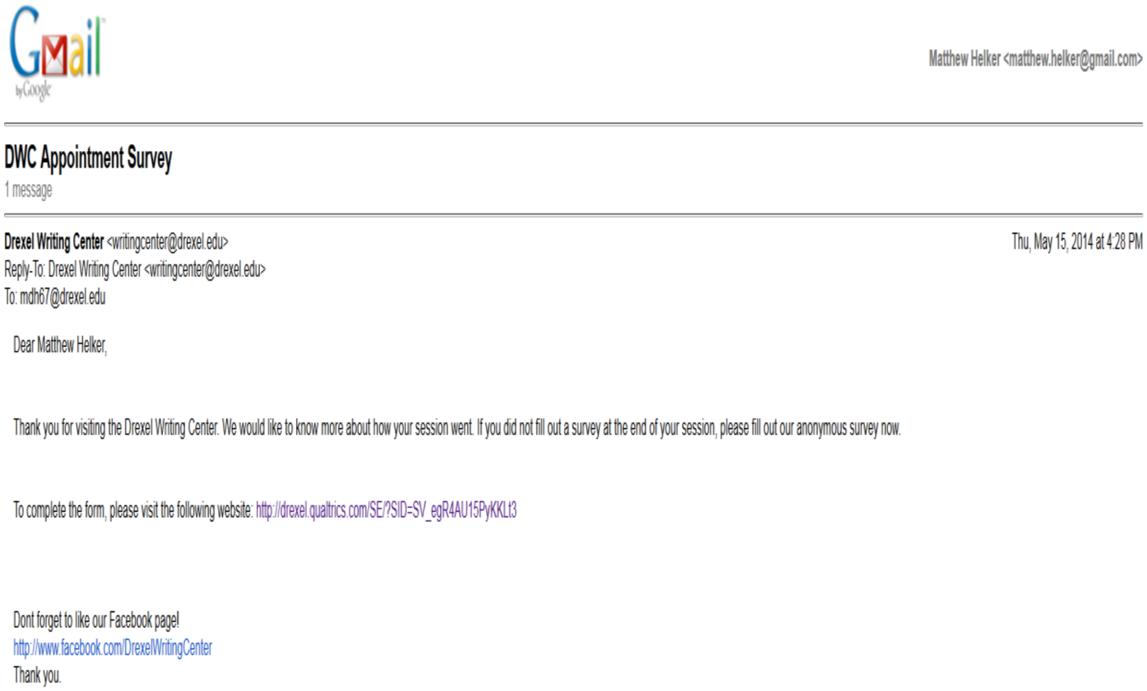


Figure 52. Comparison of battery size and load factor improvement.

Appendix U: Drexel Writing Center Confirmation



Matthew Helker <matthew.helker@gmail.com>

DWC Appointment Survey

1 message

Drexel Writing Center <writingcenter@drexel.edu>
Reply-To: Drexel Writing Center <writingcenter@drexel.edu>
To: mdh67@drexel.edu

Thu, May 15, 2014 at 4:28 PM

Dear Matthew Helker,

Thank you for visiting the Drexel Writing Center. We would like to know more about how your session went. If you did not fill out a survey at the end of your session, please fill out our anonymous survey now.

To complete the form, please visit the following website: http://drexel.qualtrics.com/SE/?SID=SV_egR4AU15PyKKLt3

Dont forget to like our Facebook page!
http://www.facebook.com/DrexelWritingCenter
Thank you.

Matthew David Helker

104 Brookthorpe Terrace
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484-574-5099
matthew.helker@gmail.com

Education

Drexel University, Philadelphia, PA
Bachelor of Science in Electrical Engineering, Anticipated Graduation - June 2014
Concentration - Power, **Cumulative GPA - 3.82**

Skills

- Proficient - Revit, AutoCAD, MATLAB, Microsoft Word, PowerPoint, Excel
- Adept - CYME, PSpice, AGI-LIGHT, LabVIEW

Experience

EwingCole, Philadelphia, PA
Electrical Engineering Co-op - Sports/Entertainment Team, March to September 2013

- Developed lighting, power, and telecommunications systems for sports stadiums and entertainment centers
- Managed and updated Revit and AutoCAD files of building schematics
- Streamlined Revit usage for teammates by setting up standards

PECO, Philadelphia, PA
Distribution Capacity Planning Co-op, March to September 2012

- Maintained and improved the reliability of PECO's power distribution network
- Analyzed circuits to determine impacts of upgrades to customers' services
- Reviewed customer cogeneration requests for approval

EwingCole, Philadelphia, PA
Electrical Engineering Co-op - Healthcare Team, March to Semptember 2011

- Assisted engineers and architects in the design of electrical system plans for hospitals and healthcare facilities
- Managed and updated AutoCAD files of building schematics
- Tested and selected lighting fixtures to find cost efficient lighting solutions

Senior Design Project

Load Leveling with BESS and Photovoltaic Generation, Drexel University
Team Captain, September 2013 to June 2014

- As Team Captain: organize meetings, assign tasks, coordinate efforts with advisers
- Utilize battery energy storage system (BESS) for load leveling of commercial customers
- Create and implement algorithm to regulate energy from batteries and photovoltaic array
- Perform hardware tests to confirm results of simulations
- Goal of reducing long term costs to both customers and utility providers

Honors and Awards

- Pennoni Honors College - Drexel University 2009 - Present
- AJ Drexel Academic Scholarship - 2009 - Present
- Drexel University Dean's List - 2009 - Present

Christopher Vaile
386 Anderson Avenue
Phoenixville, PA 19460
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cjv34@drexel.edu

Education

Drexel University, Philadelphia, PA
BS/MS in Electrical Engineering, Anticipated Graduation - June, 2014
Cumulative GPA: 3.42

Experience

PECO Energy, Philadelphia, PA
Central Reliability Engineering Intern, June 2013 - Present

- Developed a new statistical method of analyzing/comparing outage durations (CAIDI) above a calculated threshold
- Presented study aimed at developing best practices for manual switching opportunities and their effect on CAIDI
- Responsible for tracking and analyzing Recloser Operations used to quantify effectiveness of devices
- Assisted Engineers with analysis/suggestions of system enhancements to improve customer experience
- Managed the selection/review of Top Priority Circuits, as well as produced Quantitative Greenboard results detailing Community reliability

PECO Energy, Philadelphia, PA
Central Reliability Engineering Intern, March to September, 2012

- Responsible for management/analysis of Circuits out of Configuration (COOCs) database
- Reviewed all sustained outage events to verify scheme operations and system coordination
- Assisted in analysis and recommendations to improve reliability of Top Priority Circuits
- Developed and presented COOCs study aimed at developing best practices for reducing overall impact of COOCs

Philadelphia Department of Commerce (PHL Airport), Philadelphia, PA
Electrical Engineering Intern, March 2011 to September 2011

- Oversaw daily activities on the installation of a $3.6 million 2.0MW electric generator
- Attended project meetings and provided updates to a Resident Engineer
- Analyzed and reviewed multiple coordination studies for Airport Complex
- Field verified multiple single line diagrams that needed updating and revision

Senior Design Project: Load Leveling w/ BESS

- The goal is to utilize a battery energy storage system (BESS) for the purpose of load leveling
- A functional algorithm is being created so that load leveling will be automatic and sustainable for desired durations
- Hardware tests of Lead Acid and Lithium Ion batteries will be used to quantify effectiveness of algorithm
- Effects/Challenges of Distributed Generation on load leveling will be explored for future uses of this technology

Honors and Awards

- Eta Kappa Nu (HKN) Member 2012-present
- Engineering Learning Community, 2009-10
- The Rensselaer Medal Award, 2008
- Physics Olympics (President), 2007-09
- National Society of Collegiate Scholars, 2010-present
- Drexel University Dean's Scholarship, 2009-13
- National Honors Society, 2007-09

Skills

- Computer (PSpice, MATLAB, Pro-ENGINEER, Microsoft Excel, Word, PowerPoint, Maple 13)
- Technical (Single Line Diagrams, Construction Drawings, Circuit Prints, DMACs)

Matthew Yoder

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Philadelphia, PA 19104
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Education

Drexel University, Philadelphia, PA
Bachelor of Science in Electrical Engineering, Anticipated Graduation - June, 2014

Honors and Awards

AJ Drexel Academic Scholarship, 2009 - Present
Industrial Arts Award, Sponsored by The Kiwanis Club, 2009
Eagle Scout Award, 2008
National Honor Society, Milton Area High School, 2007 – 2009

Experience

Vineland Municipal Electric Utility, Vineland, NJ
Assistant Engineer, April to September 2013

- Assisted engineers with field and office tasks involved in design, maintenence, and construction
- Collaborated with work crews on projects
- Maintained distribution records and files
- Performed field observations
- Recorded and edited GIS system

Bruce Brooks & Associates, Philadelphia, PA
Assistant Engineer, April to December 2012

- Drafted designs made by engineers in AutoCad and Revit
- Designed lighting, power, telecommunication, security, and fire alarm plans of new construction and renovations
- Performed fire alarm calculations
- Assisted engineers with responsibilities

The Philadelphia Electric Company, Philadelphia, PA
Assistant Designer, March to September 2011

- Sketched designs for crews to follow out in the field
- Kept records of inventory of protective covering
- Assisted designer with responsibilities
- Scheduled jobs

Skills

Computer Skills - ArcMap GIS; Autodesk AutoCad, Revit, 3D Studio Max; Adobe Photoshop, Premiere, Dreamweaver, and Illustrator; MatLab; Microsoft Word, Excel, and PowerPoint

Relevant Coursework

Digital Logic Design
Electronic Devices
Energy Management Principles
Intro to Renewable Energy
Theory to Nuclear Reactors
Electric Circuits
Analog Electronics
Electric Motor Control Principles
Power Systems I

Activities

Boy Scout Troop 600 Spaghetti Dinner, New Columbia, PA, March 26, 2004-2009

- Participated as a waiter; served up to 50+ people; cleaned tables, dishes, and areas of food preparation; helped prepare food for 400+ people

Educate Cambodia, 2007 - 2008

- Volunteered to raise money for building a school in Cambodia

Eagle Scout Project - Ronald McDonald House, Danville, PA, May 2007

- Cleaned and beautified the exterior of building; cleaned 50+ windows, more than 13,000 square feet of siding, sidewalks, playground equipment, three cement porches, lighting around the building, outside of storage garage, exterior furniture, and eves over walkways