Experimental Study and Economic Impact Analysis of Battery Assisted Residential PV System

by

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ABSTRACT

Due to the increasing trend of electricity price for the future and the price reduction of solar electronics price led by the policy stimulus and the technological improvement, the residential distribution solar photovoltaic (PV) system's market is prosperous. Excess energy can be sold back to the grid, however peak demand of a residential customer typically occurs in late afternoon/early evening when PV systems are not a productive. The solar PV system can provide residential customers sufficient energy during the daytime, even the exceeding energy can be sold back to the grid especially during the day with good sunlight, however, the peak demand of a regular family always appears during late afternoon and early evening which are not productive time for PV system. In this case, the PV customers only need the grid energy when other customers also need it the most. Because of the lower contribution of PV systems during times of peak demand, utilities are beginning to adjust rate structures to better align the bills paid by PV customers with the cost to the utility to serve those customers. Different rate structures include higher fixed charges, higher on-peak electricity prices, on-peak demand charges, or prices based on avoided costs. The demand charge and the on-peak energy charge significantly reduced the savings brought by the PV system. This will result in a longer the customer's payback period. Eventually PV customers are not saving a lot in their electricity bill compare to those customers who do not own a PV system.

A battery system is a promising technology that can improve monthly bill savings since a battery can store the solar energy and the off-peak grid energy and release it later during the on-peak hours. Sponsored by Salt River Project (SRP), a smart home model consists 1.35 kW PV panels, a 7.76 kWh lithium-ion battery and an adjustable resistive load bank was built on the roof of Engineering Research Center (ERC) building. Solar data used in the analysis was scaled up by 6/1.35 times to simulate a real residential PV setup. The testing data had been continuously recorded for more than one year (Aug.2014 - Oct.2015) and a battery charging strategy was developed based on those data. The work of this thesis deals with the idea of this charging strategy and the economic benefits this charging strategy can bring to the PV customers. Part of this research work has been wrote into a conference paper which is accepted by IEEE PES General Meeting 2016. A new and larger system has been installed on the roof with 6 kW PV modules and 6 kW output integrated electronics. This project will go on and the method come up by this thesis will be tested.

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CHAPTER 1

A BACKGROUND ON BATTERY ASSISTED RESIDENTIAL PV SYSTEM

1.1 Background of Battery Assisted PV System

With the maturing of residential photovoltaic (PV) devices as well as their declining prices, a rapid expansion of the PV system market was seen especially in the recent five years. The U.S. cell and module market, measured by domestic shipment revenues, has grown in size from $3.3 billion in 2008 to $7.1 billion in 2012, reports the U.S. Energy Information Administration (EIA). Following an unprecedented period of growth, the number of PV systems in the United States reached more than 445,000 by the end of 2013, more than twice the total at the end of 2011[1].

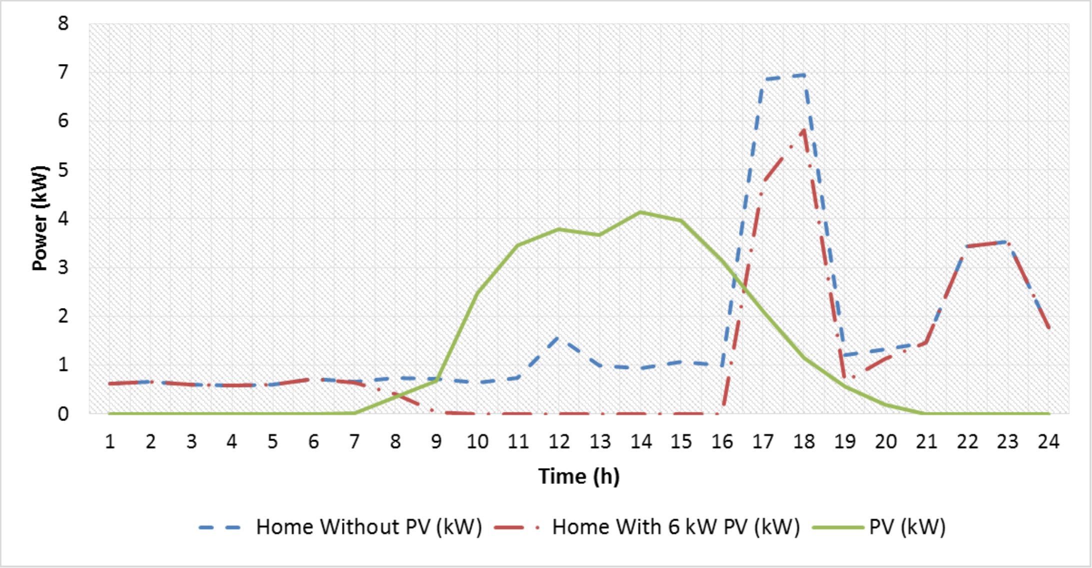


Figure 1.1 Load Demand Comparison Before and After PV Installation

The large scale application of the PV system created a significant amount of clean energy which contributes both the PV customers and greenhouse gas emission reduction, however, the utility companies' costs are not properly covered because of the low load factor created by those PV systems. Because solar energy is not so productive during the

$$f_{load} = \frac{\text{Average load}}{\text{Maximum load in given time period}} \tag{1.1}$$

late afternoon and the early evening which are typical the utility on-peak hours. In this case, PV customers' peak demand will almost keep the same as if they do not have PV. On the other hand, during the daytime PV customers' electricity demand are greatly covered by solar energy. This phenomenon can be seen in figure.1. Apply this phenomenon into equation 1.1, it can be concluded that the grid load factor is reduced after the installation of PV system. Low load factor indicates that the utility companies are not properly recovering their costs.

Since utility company's transmission and distribution systems are sized for the maximum load of the customers using the systems, the cost driver for providing transmission and distribution service is constant although the total energy transmission in the grid is reduced by PV system. In order to better align the costs of building and operating those systems with PV customers, a demand charge is applied to the maximum average load demand (kW) within 15 min or 30 min interval is recorded on a customer's meter during the month. This demand charge can be a significant part in regular customer's electricity bill. Like the E-27 price plan for PV customers launched by Salt River Project (SRP), it introduced tired demand charge, for example, in summer, the first 3 kW demand will be charged for \$9.59/kW and from 3 kW-10 kW, each kW will be charged for \$17.82, when the peak demand is over 10 kW, each kW will be charged for $34.19. Like the load profile shown in figure 1.1, the PV customer's peak demand in that days is 6 kW, so the demand charge will be $9.59/kW*3+$17.82/kW*3= $82.23. By doing the calculations based on several houses' annual load profiles which can be obtained from PecanStreet [2], it is can be concluded that the high demand charge results in a high electricity bill to PV customer. Considering the heavy cost of a PV system and the demand charge does not apply to the home without PV system, its economic benefits are not guaranteed.

For most people, the biggest motivation for having a PV system is to save electricity bill, but the demand charge reduces their enthusiasm of using solar energy.

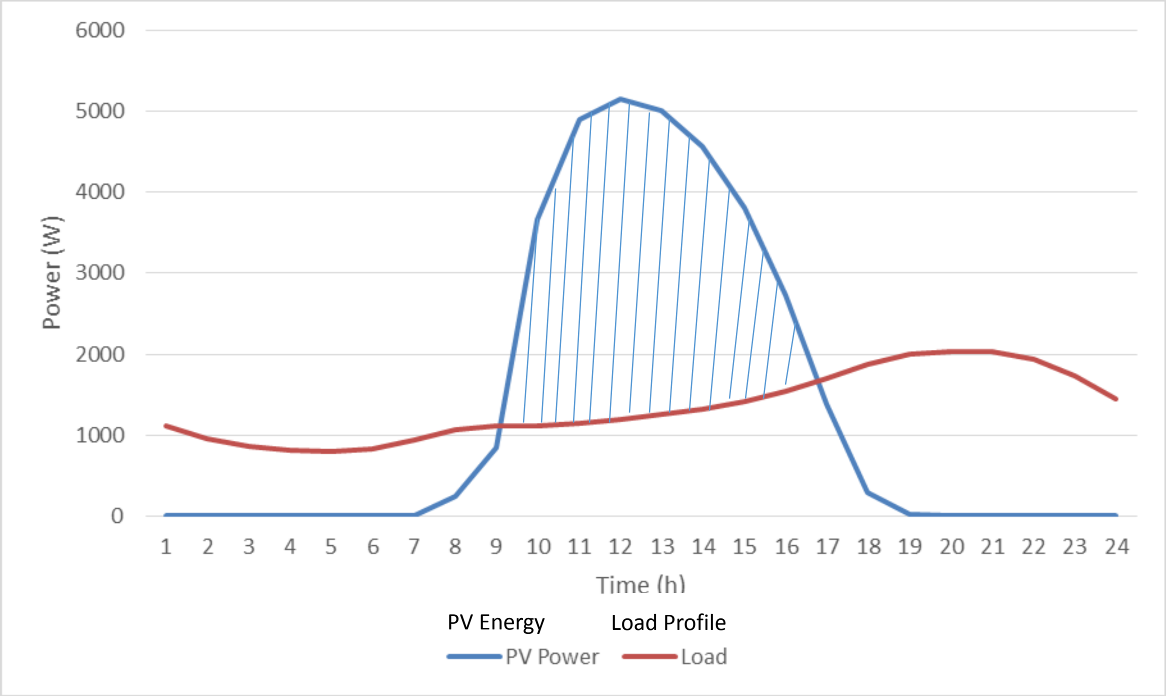


Figure 1.2 Daily PV Profile VS Daily Load Profile

To solve this contradiction, the best solution is to shave the peak demand by using solar energy. In other words, if the solar energy can be stored during the day time and be released during the on-peak hour, then the problem will be perfectly solved. Battery, as a reusable and relatively inexpensive energy storage device, can play the role. The feasibility of this idea is confirmed by the long-term observed tests data from Pecan Street. Figure 2 shows a typical PV-equipped house's load profile and the solar energy production profile during summer, this house's PV capacity is 6250 W. From 9:00 am-5:00 pm, the solar energy produced by the PV panels exceeded the load demand, the extra solar energy represented by the shadow area are wasted and during 5:00 pm-8:00 pm which are on peak hours, the solar energy is not enough to supply the load. If the solar energy represented by the shadow area can be moved to the on peak hours, then the PV customer can both achieve the maximum PV energy utilization and also avoid the on-peak demand charge.

The battery assisted PV system can be a win-win solution to both PV customer and the utility company. To PV customer:

- PV customers save on their electricity bills by reducing peak demand and achieve the maximum solar energy utilization.

To utilities, this system can provide one major benefit:

- Utilities reduce the operational cost of generating power during peak periods (reducing the need for peaking units).

Every coin has two sides, besides the advantages the battery storage system bring to both utilities and customers, it also brings disadvantages to the customers. In addition to the investment on battery, the PV customers also need to purchase a battery charging controller to manage the solar energy to supply the load, charge and discharge the battery. Thus, compare to the regular PV system, the battery assisted PV system's cost is higher. Between those two options, the one with higher long-term economic benefits will win the hearts of customers.

Since the battery assisted PV system is a new concept to the solar market, there is not that much evidence to prove its long-term economic benefits. In order to answer this question, ASU and SRP have been doing a series of studies on the battery assisted PV system since 2014. SRP invested a 20 kWh lithium battery, a battery charge controller (XW-MPPT-60-150V), an inverter/charger (XW+5548NA) and PV panels with 6.36 kW capacity, ASU built a controllable load bank, those devices were put together to form a mini house which equipped with the battery-assisted PV system. The specifications of the battery charge controller, load bank, PV panels and the inverter lists in Table 1.1.

Table 1.1 Equipment Specifications

Solar Charge Controller Specification	
Model	XW-MPPT60-150
Max PV Array Voltage	140 Vdc
Max PV Open Circuit Voltage	150 Vdc
Array Short Circuit Current	60 Adc Maximum
Maximum output Power	3500 W
Battery Specification	
Capacity	7.76 kWh
Nominal Battery Voltage	12,24,36,48,60 Vdc
Battery Voltage Range (operating)	10 Vdc to 80 Vdc
Maximum Output Current	60 A
PV Panel Specification	
Capacity	265 W/each
Number	6

Size	5.40 ft * 3.23 ft
Load Bank Specification	
Resistance Adjustable Range	6.90 Ω – 200 Ω
Applied Power Range	72 W - 2088 W

1.2 Motivation for the Research

Energy storage system provides fast response and emission-free operation, making it the optimal solution for the application of peak shaving. For example, power electronic device manufacturer ABB offers turnkey energy storage systems for power requirements ranging from hundreds of kilowatts to tens of megawatts, and including medium- or high-voltage grid connection. The same technology can be applied to small scale and low voltage applications. By combining the energy storage system with distributed PV system, there is a possibility that the residential PV customers can also enjoy the benefits from the peak shaving. Besides the peak shaving, the battery system can also ensure the PV customers to have the maximum solar energy utilization.

Different from the regular energy storage system, the battery assisted PV system stores the energy not only from the grid but also from the PV panels. In this case, the battery charge controller for this system has to be smart enough to manage when and how much the grid or the PV panels need to charge the battery. Because if too much energy from the grid been charged into the battery then part of the solar energy would be wasted, on the other hand, if the battery was not charged to the right level by the grid, the solar energy stored in the battery would not be enough to supply the load during the on peak hour.

A proper charging strategy which can balance the energy from the grid and the PV panels can be a possible solution for the application of the battery assisted PV system. Thus, the results of this research could be very valuable and practical.

1.3 Literature Review

Solar energy has gone through a rapid growth in past few years, this growth is contributed by both the cost reductions since the technological improvements and the government policies support of renewable energy development and utilization. However, even the cost of solar energy has declined rapidly, it still much higher compare to the cost of conventional energy sources like natural gas, coal etc. [3]. Traditional economic analysis of PV system is purely compare the value of its energy generation within the predicting life time with its initial cost. However, this comparison may not be accurate, because for most of the utility companies they provide PV customers a specific rate plan which is completely different from the regular customers', in those plans the electricity is always priced by Time-Of-Use (TOU) also the demand charge are always included. In this case, if the solar energy can be stored and used according to the load demand, then the demand charge can be avoided and PV customers can obtain the maximum economic benefits, for some PV rate plans, PV customers can even earn money by selling the solar energy back to the grid. The battery can play an important role in this task since it can store solar energy and release it at any time, there will be three major benefits [4] if the solar energy can be applied during the on-peak hour.

- The battery assisted PV system reduces the grid load, especially during the on-peak hours and therefore the network expansion schedule will be greatly delayed.

- The battery assisted PV system decreases the share of energy consumption from the grid and therefore reduces the energy expenses for PV customers.
- The battery assisted PV system is capable of providing the peak-shaving during the peak time and therefore further decreases the energy expenses.

The battery assisted PV system is not a new thing in the field of renewable energy application. The use of battery assisted PV systems can help to achieve the energy independence and continues electrical energy supply to a remote region which does not have stable grid energy [5]. Since the PV modules have the disadvantage of producing intermittent power especially during the night or cloudy day. Then, the PV systems is not able to supply electricity to the load side. Hence, the energy storage systems such as battery, fuel cells are introduces to improve the utilization of solar energy and the operability of PV [6]. However, this kind of battery-PV application in remote area is not connected into the grid, the goal for this system is to achieve the highest solar energy utilization. This charging strategy simply stores the exceeding solar energy into the battery and supply the load when the solar energy cannot cover the load demand. But for grid connected battery assisted PV systems, the charging strategy can be much more complicated, since the charging strategy has to consider two energy sources PV panels and the grid.

Considering the discontinuity of solar energy, use batteries to store exceeding solar energy during the daytime and supply it during the nighttime is a great idea. But if the load needs 24-7 continuous electricity supply, the PV and the battery size need to be extremely large, consequently, the cost for the whole system is expected to soar. To solve this problem, auxiliary power system (APS), shown in figure 1.3 [7], is came up by some researchers. The use of APS can greatly reduce the solar panels installation capacity, battery size and increase the stability of the power supply. Typical auxiliary power systems include gas generator, diesel generator, micro gas turbine and solid oxide fuel cell (SOFC). Those APS systems, solar panels and batteries can form a combination to provide load side a reliable and relatively cheap power supply [7]. However, if a customer is pursuing solar PV at least in part for environmental reasons and not purely based on economics, those solutions do not make much sense since emissions would be higher from a group of diesel generators than from an equivalent-sized natural gas power plant. In Nafeh's study [8], an optimal size of PV/Diesel generator hybrid energy system is discussed

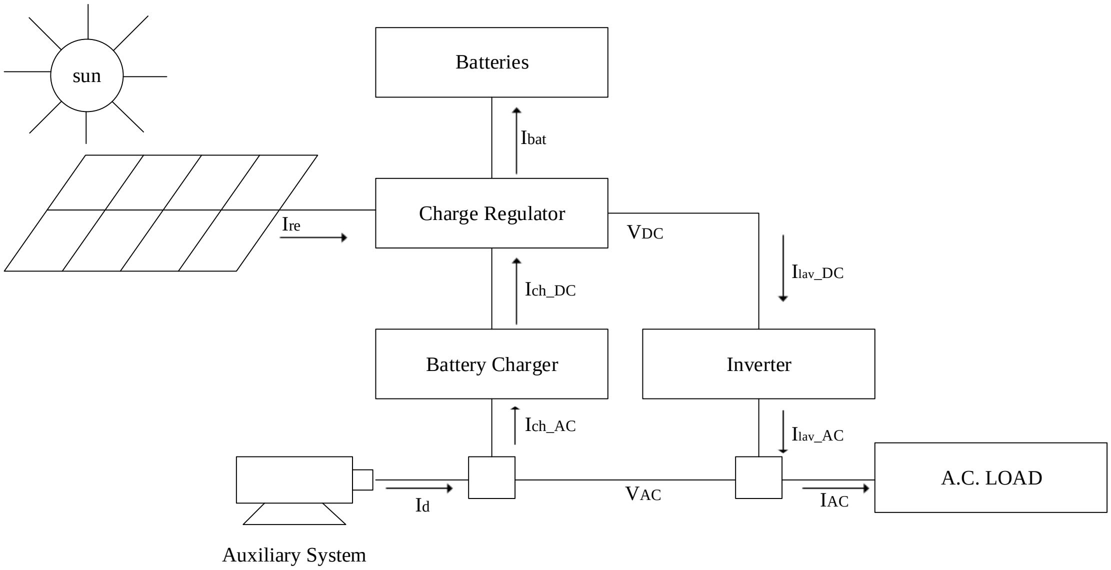


Figure 1.3 PV-Battery-APS System [7]

to provide continuous power supply for the load. The capacity of the PV modules and the size of the batteries were optimized according to a given load characteristic. The operation of the diesel generator is coordinated with the battery assisted PV to achieve a minimum operation cost, the depth of battery discharge is considered. In Dufo and Bernal's study [9], a HOGA program (hybrid optimization by genetic algorithms) is introduced to optimize a PV-Diesel system, a comparison is done between the designed system and a stand-alone PV system. The results showed the hybrid-PV system has big economic advantages. As for Baniasad and Ameri [10], they applied a PV diesel-battery power systems in a remote region in Iran to meet a typical load. They simply used a two-step optimization method, in the first step they found different system configurations with high reliability, and then in the second step, they compare those configurations and selected the cheapest system. In Iran, the natural gas (NG) is in low price and very easy to get, thus the use of gas generator is also reasonable. The combination of a gas generator and solar panels has not been considered yet. In their study, this new combination is compared with some other popular combinations, and the economic analysis are also presented. Degobert [11] discussed the possibility of combining a photovoltaic system with a high speed micro-turbine. They developed a simple and effective model of the PV-MTG hybrid system, through the simulation the confirmed the effectiveness of the designed hybrid system. In the end, they concluded that it is necessary for the proposed system to have a short-term energy storage, in case the sensitive loads has fast power fluctuations or power surge. Another study which is conducted by Costamagna [12] discussed the model of a hybrid system which couples the micro gas turbine and the solid oxide fuel cell. This model allows a comprehensive evaluation of the system design and the effectiveness of the designed hybrid system. Solid oxide fuel cell is a new energy storage concept which is still in developing, the SOFC has relatively high charging/discharging efficiency also it works at a low noise level and little emission. Unlike regular battery, the SOFC is able to work at high temperature, it combines together with gas turbine/micro gas turbine. In Lee's study [13], he mainly described a power management method, which can be applied to a UAV's hybrid electric propulsion systems. They discussed three electric propulsion systems, each of them has different APS, such as SOFC, fuel cells, and batteries. Unlike the single source battery assisted PV system discussed previously, combine the APS system with the battery-PV system requires the battery charge controller to manage the energy from both the PV modules and the APS system. However, since the system is normally used in remote area without the grid connection, this charging control strategy cannot be applied to the PV customers with grid connection. Because for the customers who have grid connected PV systems, the biggest challenge for them is not how to increase the solar energy share in their total electricity consumption but how to reduce the peak demand and how to reduce the on-peak grid energy utilization.

Some studies considered the situation when the battery assisted PV system is interconnected with the grid, but their focus is on how to increase the "Self-consumption rate”. The concept “Self-Consumption Rate” is defined in equation 1.2 [14]. Due to the decreasing FIT rate and increasing grid electricity price in the future and the cost decreasing of PV manufacturing, improving self-consumption rate becomes the first concern for the PV customer. With a battery installed together with the PV arrays, when the generated solar electrical energy is more than the load demand, the extra solar energy can be stored in a battery and used at later times when the solar

$$Self\ Consumption\ Rate = \frac{PV\ Electricity\ Consumed\ Locally}{Overall\ Electricity\ Generated\ by\ the\ Particular\ PV\ Generator} \qquad 1.2$$

energy is not sufficient to cover the load demand. Thereby the battery raises the Self-Consumption Rate for PV customers. This method is discussed in Ghada Merei’s research [15]. However, the improved self-consumption rate does not guarantee an economical electricity bill, because the stored solar energy may be exhausted before the end of utility peak time, then PV customers still need to pay for the demand charge and the expensive on-peak electricity.

Based on the discussion made above, it is not difficult to conclude that the optimal charging strategy for battery assisted PV system should take the electricity rate plan into the consideration. In Akihiro Yoza’s study [16], the economic analysis for the battery assisted PV system is done, but the price plan used in their research is a regular price plan not a typical PV customer’s price plan. Most of the price plans for distributed generation (DG) customers have four parts including demand charge, energy charge, metering charge and service charge [17]. Among those four parts demand charge is what PV customers need to concern about, because the demand charge is only for DG customer and the energy charge for them is usually lower than regular customer who doesn't have a PV system, the metering charge and service charge are almost the same for everybody. Demand–related charges usually represent 30 to 70 percent of most DG customers' electric bills [18]. Demand charges are based on the amount of energy consumed in a specified period of time known as a demand interval. Demand intervals are usually 15 or 30 minutes [19]. Since the demand charge only exists during the utility peak hours, so the optimal charging strategy presented in this study used the battery as an energy bank to store the solar energy and cheap off-peak grid energy to provide the PV customer on-peak energy supply and peak shaving.

1.4 Objective and Scope of Research

As the primary objective of the thesis, an optimal battery charging strategy for the battery assisted PV system is developed based on the data analysis results using *Matlab Software*, those data includes one year solar energy input data collected from the PV panels with a resolution of 1 minute, one year load profile data provided by SRP with a resolution of 15 minutes and the SRP E-27 price plan. Those data used in the analysis is continuously recorded from Dec. 2014-Dec. 2015. This charging strategy is able to rational allocate the PV customers' energy consumption from both the grid and the PV panels, at the same time, achieve the best economic benefits for PV customers and provide peak shaving for the utility companies.

Besides to find out the optical battery charging strategy, it is also important to know if the system has the ability to cope with various conditions of use, because once this system is installed, it supposes to work 24/7. In order to test the system's reliability and the ability to deal with the extreme conditions, a series of performance tests to the battery assisted PV system has been done, including power smoothing test, frequency regulation test, voltage stability test when AC starts and battery aging study.

At the last part of the thesis, an economic analysis for the battery assisted PV system through its predicting lifespan is done and compared with the overall economic benefits of a regular PV system without battery storage. Besides, the best battery size for different PV size is analyzed based on the economic analysis result. The credibility of this analysis is ensured because it incorporates the solar energy data and the load data from a real house in Austin, Texas, those data is available on PecanStreet.

1.5 Thesis Outline

Chapter 1 provides the background, motivation for the research, also the literature review of the battery assisted PV system and the objective of the thesis.

Chapter 2 deals with the designing introduction of the devices used in the project, also demonstrates the performance tests mentioned above and the results of those tests.

Chapter 3 deals with the primary objective of the thesis, optimal charging strategy for the battery assisted PV system. Detailed data analysis is presented in this section, and the charging strategy is programmed in *Matlab*, the running results of this program is also presented.

Chapter 4 deals with the economic analysis of the system. The financial model used in the analysis is introduced. The lifespan economic benefits of this system is calculate and compared with the regular PV system without battery storage. The analysis also suggests a most profitable combination of PV size and battery size.

Chapter 5 includes all the important conclusions from the study and it refers to the other steps that can be considered for the selection process.

CHAPTER 2

PROJECT DESIGNING INTRODUCTION AND PERFORMANCE TEST OF THE DEVICES

In order to better conduct this research, a mini-house model has been built to simulate a residential house equipped with a battery assisted PV system. For this system, the DC solar energy collected by PV panels supplied the load through an inverter, which can convert the DC power into 120 V AC power, in addition, the DC solar energy can also charge the battery when solar power is larger than the load demand. Same as the solar energy, the energy from the grid can also supply the load and charge the battery through an AC-DC converter. In this system, the grid energy is a supplemental energy source of solar energy. With the assistance of battery, the cheap off-peak grid energy can be used during the on-peak hour. The single line diagram for this system connection is shown in figure 2.1. The grid power comes from an existing switchboard on the roof of ERC rated at 120/208V, 3P and 600A, and then the 208V power is converted into 120/240V split phase power for the grid. In addition, the grid power can charge the battery through the inverter. The PV power is firstly been sent to the charge controller, the output power of the controller can either directly charge the battery or supply the load through the DC/AC inverter.

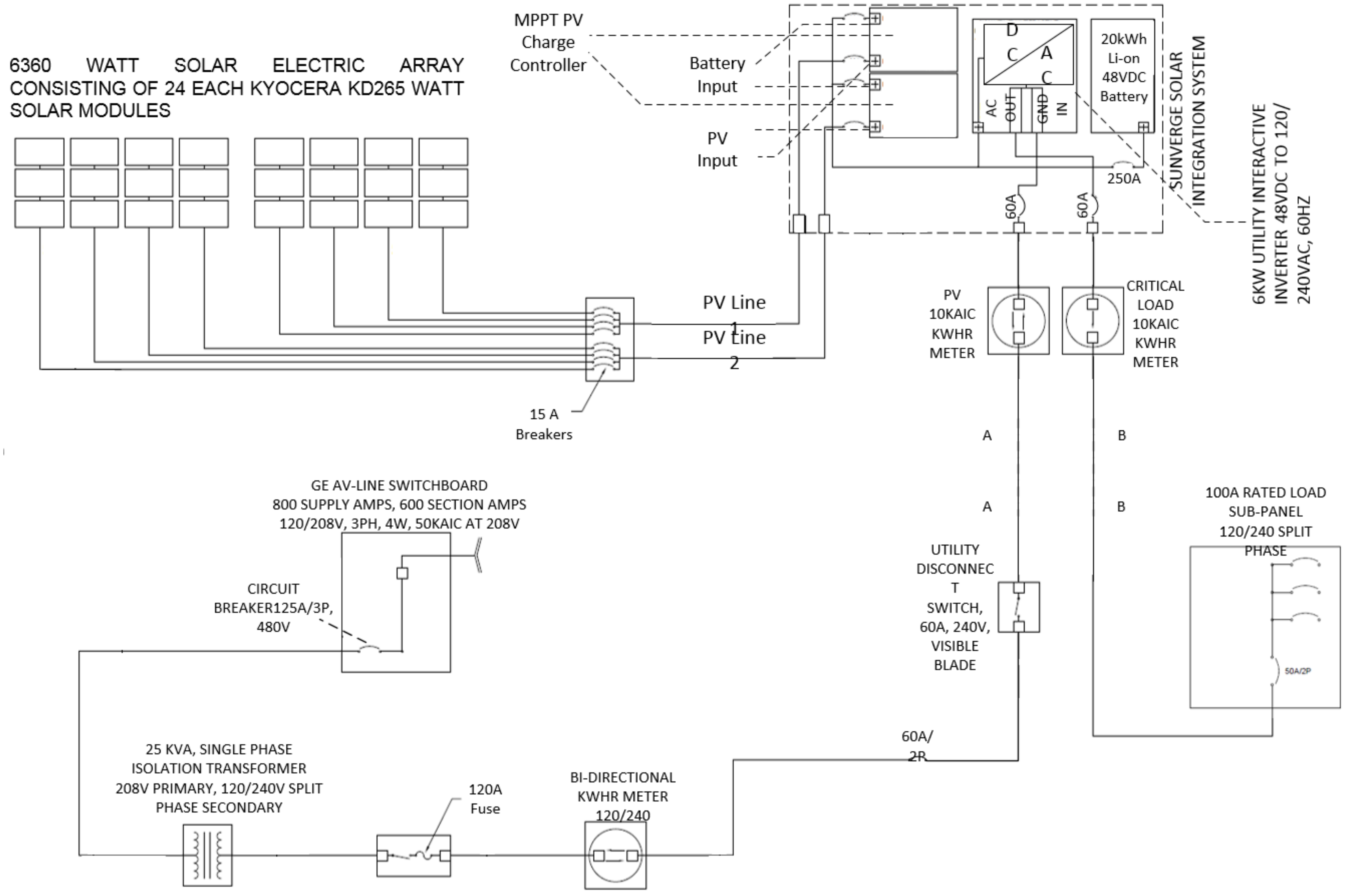
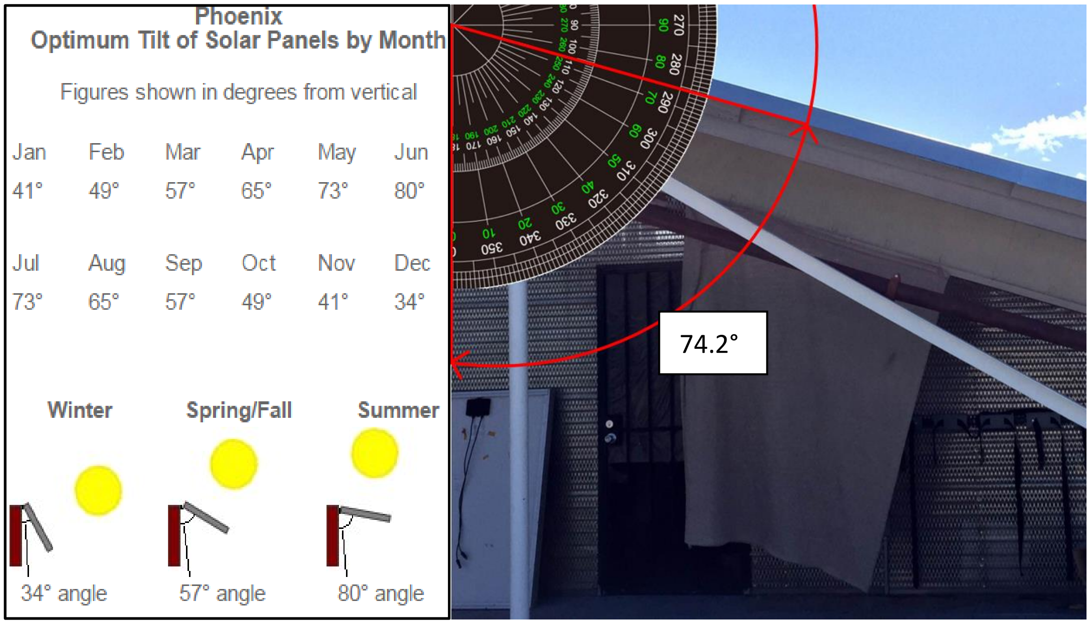


Figure 2.1 Single Line Diagram of the Battery Assisted PV System Installed on the Roof of ERC Building

2.1 Introduction to the Mini-house Designing

The six PV panels used in the model were connected in series, each of them had a power capacity of 265 W. Total PV capacity was 1.35 kW, but this 1.35 kW solar data has been scaled up to 6 kW when conducting the mathematic analysis, since 6 kW is the average capacity of US residential solar customers [20]. The power output voltage of the PV panels was 48 V with 8 V on each panel. Figure 2.2 [21] shows the best solar panel angel for each month in Phoenix area. In our research the tilt angle is 74.2° which is close to the May's and July's optimum tilt 73°, for April, June and August it will also provide a pretty good performance.



Phoenix
Optimum Tilt of Solar Panels by Month

Figures shown in degrees from vertical

Jan	Feb	Mar	Apr	May	Jun
41°	49°	57°	65°	73°	80°
Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
73°	65°	57°	49°	41°	34°

Figure 2.2 Tilt of Solar Panels Installed

The electronics including battery, XW4548 120/240-60 hybrid inverter and XW-MPPT60-150 charge controller, they were made and integrated by *Schneider*. Figure 2.3 shows the integrated system. XW4548 120/240-60 hybrid inverter has two DC-AC inverters and one AC-DC converter in it. One of the inverter is used to convert the 48 V DC from PV into 120 V AC for the load, the other inverter is used to convert the 60 V DC from the battery into 120 V AC. The converter is used to convert the 120 V AC into 48V DC to charge the battery. The battery was set to be charged by 48 V DC and discharge at 60 V DC. The XW-MPPT60-150 is a photovoltaic (PV) charge controller that tracks the maximum power point of a PV array to deliver the maximum available current for charging batteries. When charging, the XW-MPPT60-150 regulates battery voltage and output current based on the amount of energy available from the PV array and state-of-charge of the battery.

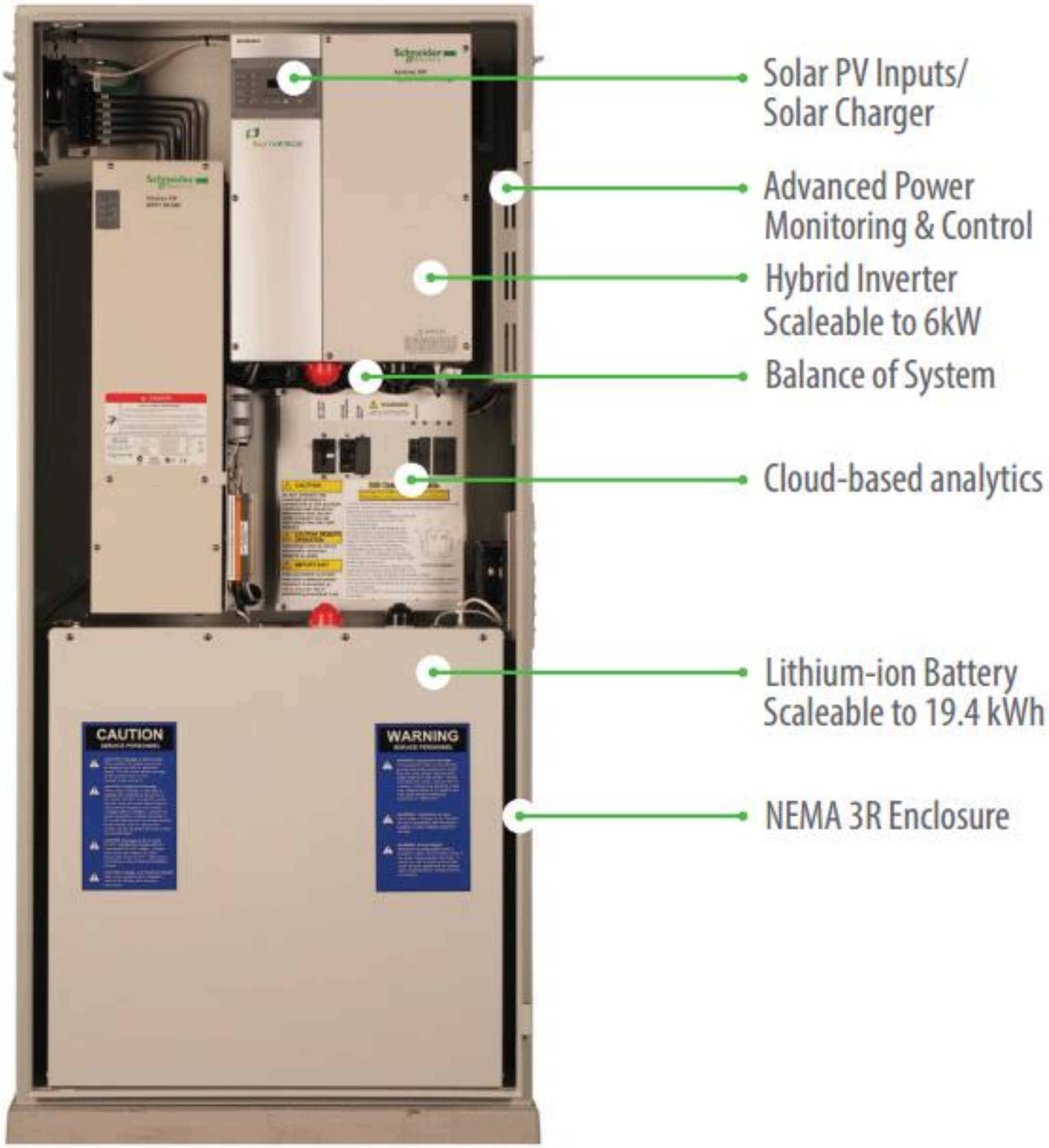


Figure 2.3 Integrated Unit Used in This Research [22]

The last part of the mini-house is the load bank. There are two load banks been designed, one is a small load bank with maximum load of 2.088 kW, the other one is a big load bank with maximum load of 10 kW. The single line diagram of the load banks are shown in figure 2.4a and figure 2.4b. As shown in figure 2.4a, the smaller load bank consists 29 of 72W heating units connected in parallel to each other. Each heating unit was connected in series with a relay switch except switch B8, C8 and D8. Since each digital relay board only has 8 relays and 3 relay boards were installed, in order to connect 29 heating units with 24 relays, 3 heating units were connected in parallel to a single relay B8, another 3 heating units were connected in parallel to relay C8 and 2 heating units were connected in parallel to relay D8. In the physical load unit, the rating of the resistance is marked on the surface of the resistance, which is 200Ω. Figure2.4b shows the single line diagram of a bigger load bank, which had 10 kW maximum load demand. The circuit connection of this load bank was in the same manner as the smaller load bank, but this load bank had ten 1kW heating unit and only ten relay switches were used. The relays shown in the figure can be controlled with the help of the control signals from the Microcontroller "PIC 18F 97J60" shown in Figure 2.5. In figure 2.4, B1 to B8, C1 to C8, and D1 to D8 represent the control signal from the Microcontroller used to control the state of the relay.

The load unit can be controlled by switching the relay switches ON and OFF as required. The relays used are NC type of relays and are rated for 5V. These relays are normally in a closed state, i.e., when no signal is given to the relay, the relay connection will be closed and when a signal of 5V is given to the relay, the relay will be on and remove its corresponding resistance branch out of the circuit. Therefore, by switching any particular relay OFF, the resistor(s) connected in series to those relay is removed from the system. By switching a particular relay ON, the resistors connected to that relay get included in the system. Thus, by varying the net resistance of the system by switching the relays ON and OFF, the total current flowing through the system can be varied and thus the load can be varied.

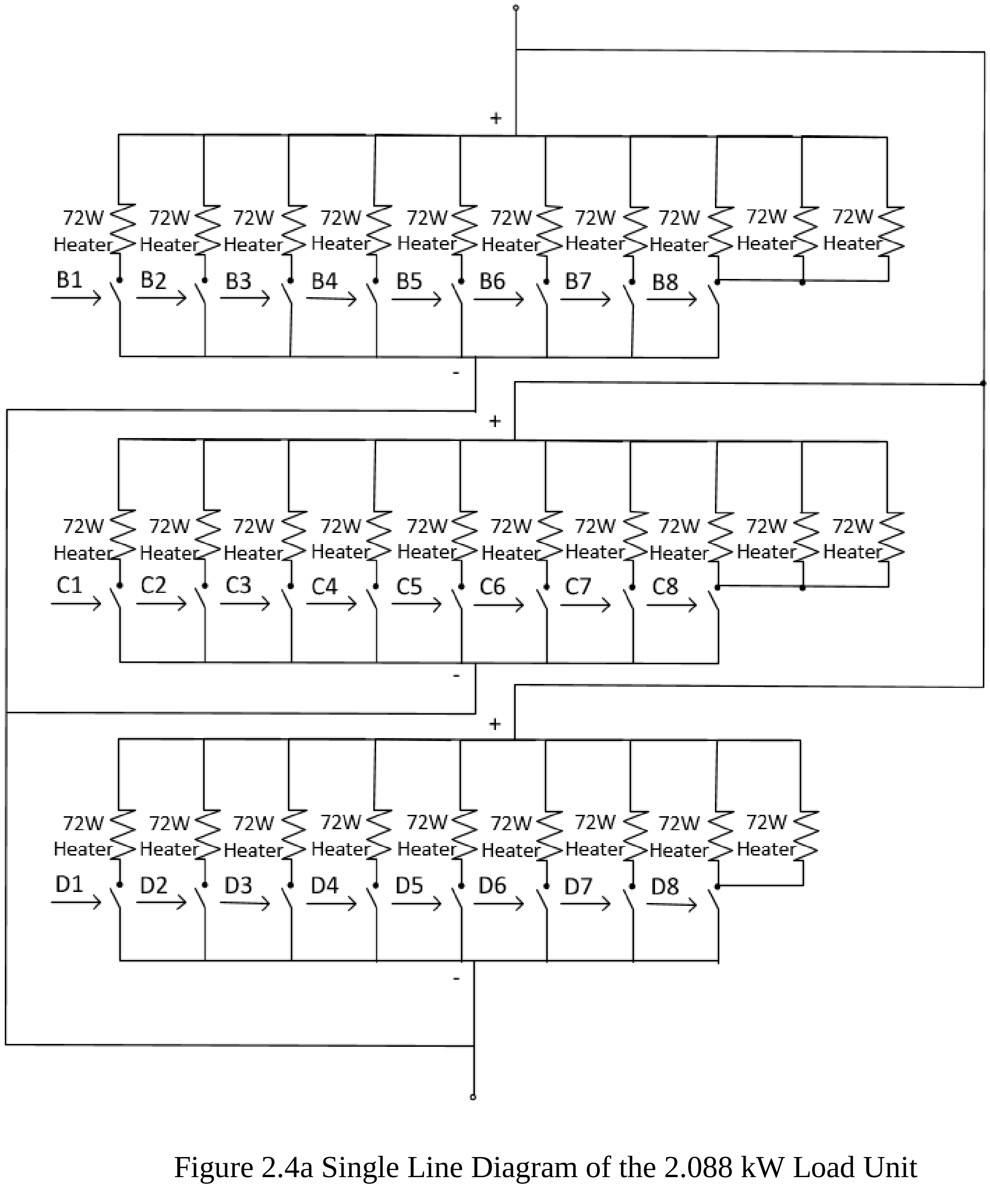


Figure 2.4a Single Line Diagram of the 2.088 kW Load Unit

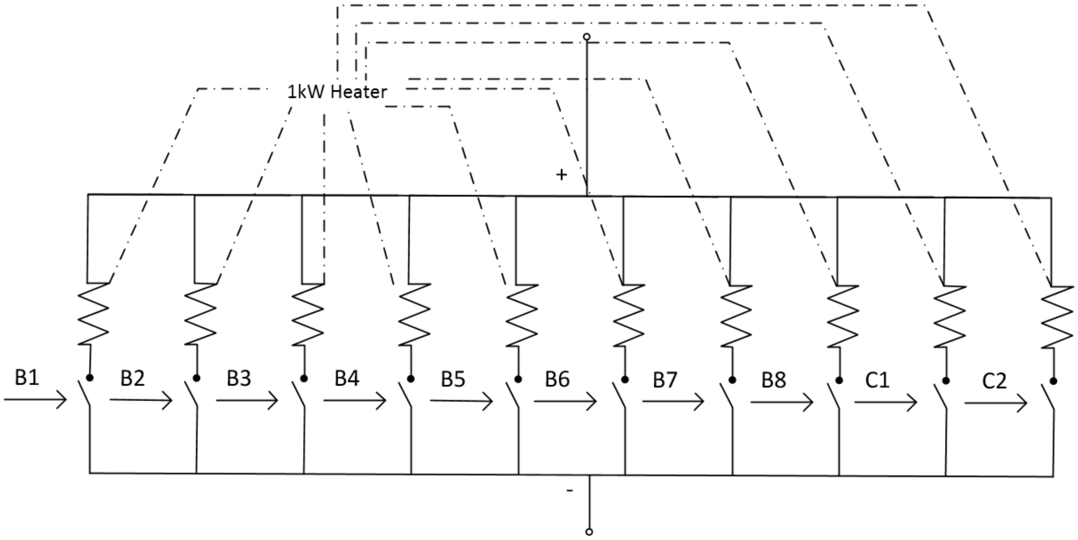


Figure 2.4b Single Line Diagram of the 10 kW Load Unit

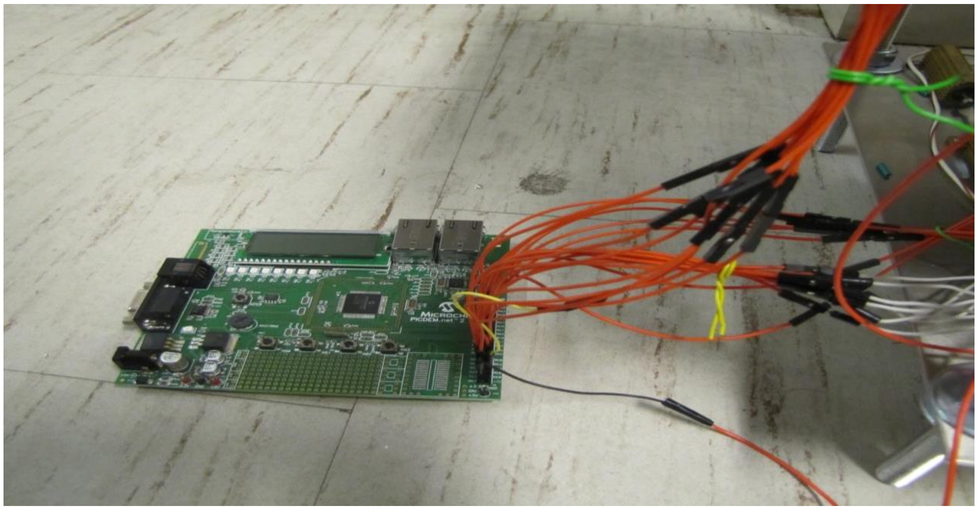


Figure 2.5 Microcontroller "PIC 18F 97J60"

To perform the switching operation of the relays, two microcontroller had being used. The microcontroller can be programmed to control the switches. This microcontroller was mounted on a standard board “MICROCHIP PICDEM.net 2” designed by “Microchip Technology Inc”.This board "MICROCHIP PICDEM.net 2" has a standard circuit designed on the board and can be controlled with the help of the Microcontroller "PIC 18F 97J60".

64 pins was used on this Microcontroller, they are controlled through coding. These 64 pins are grouped into 8 sets each having 8 pins and each set is called as a PORT. The 8 PORTS are named as Port A, Port B, Port C, Port D, Port E, Port F, Port G, Port H. The 64 pins which can be controlled through the MPLAB coding are named as {RA1, RA2,...RA8};{RB1, RB2,...RB8};{RC1, RC2,...RC8}; {RD1, RD2,...RD8}{RE1, RE2,...RE8};{RF1, RF2,...RF8};{RG1, RG2,...RG8} ; {RH1, RH2,...RH8}. The control action is written as a program and this program is coded using MPLAB coding with the help of the software "MPLAB X IDE v8.92". MPLAB X IDE v8.92 is software developed by the organization "Microchip Technology Inc.". According to the required load curve, the microcontroller is coded so that the relays are switched in such a way that the load is being varied according to the load curve. This Microcontroller board was mounted on the ventilated enclosure inside which the Load Unit is placed. The finished design of the load banks are shown in figure 2.6a and figure 2.6b.

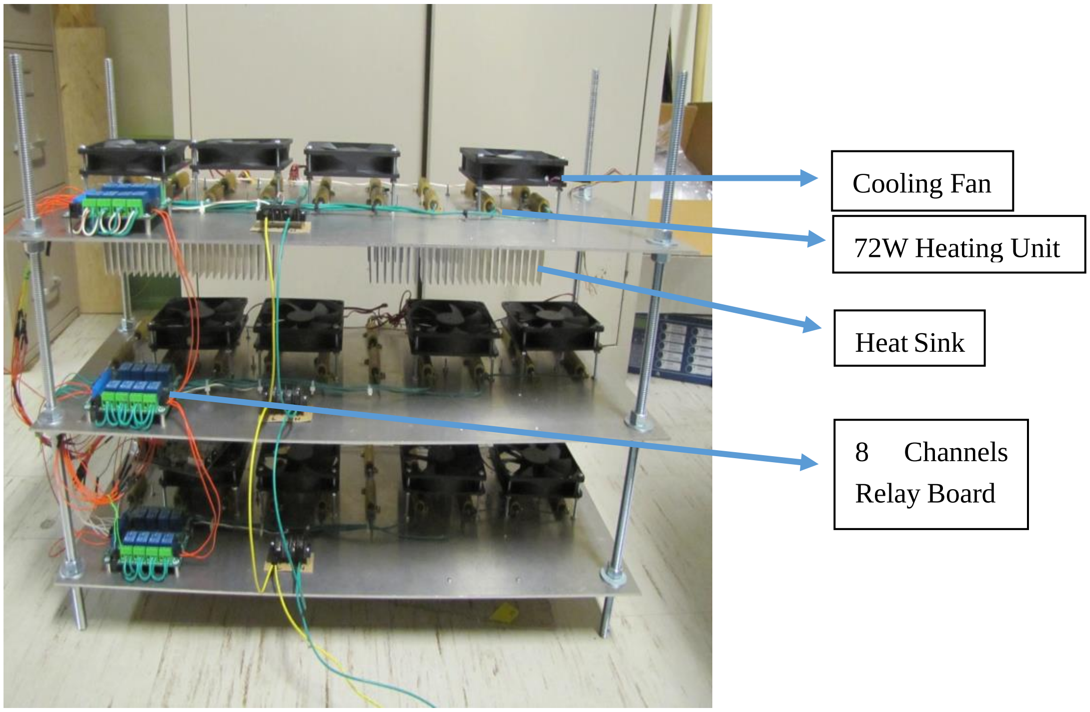


Figure 2.6a Design of the 2.088kW Load Bank

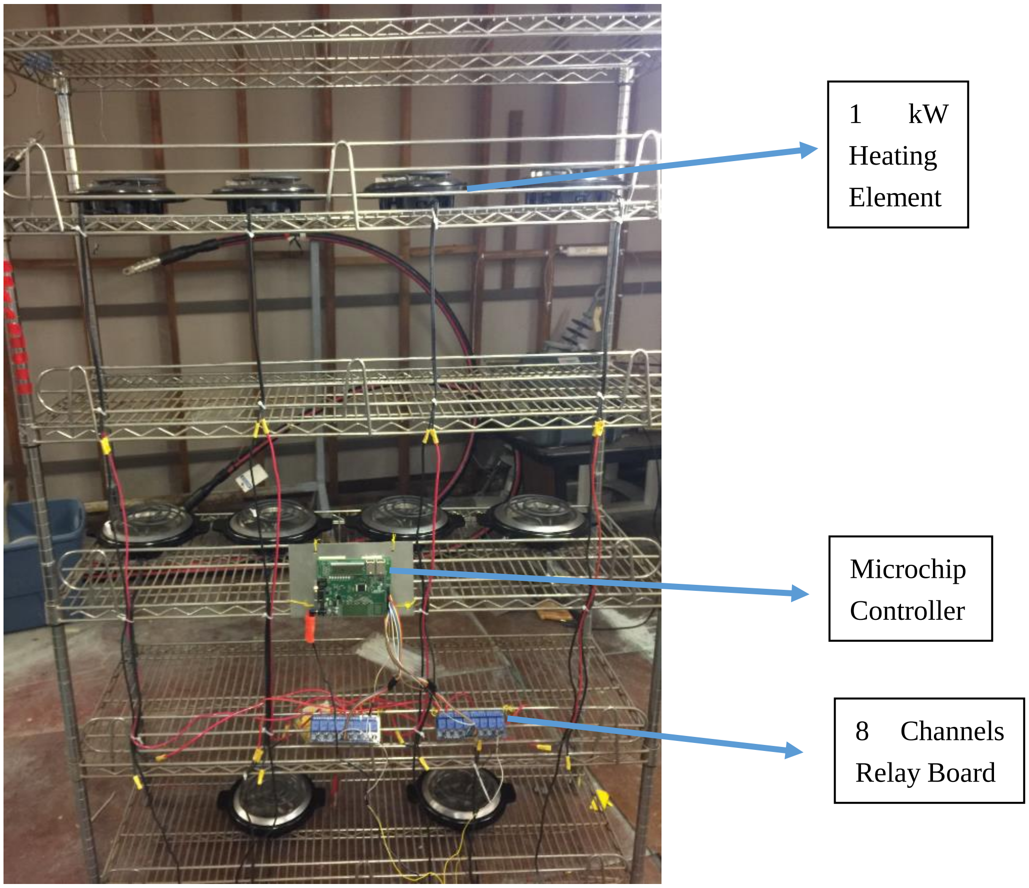


Figure 2.6b Design of the 10kW Load Bank

Last year only the small load bank has been used, so the load adjusting range is from 72 W-2088 W with a step of 72 W, in next year the two load banks will be used so the load can be adjusted from 72 W- 12088 W. Figure 2.7 shows an example of one day hourly load curve simulation.

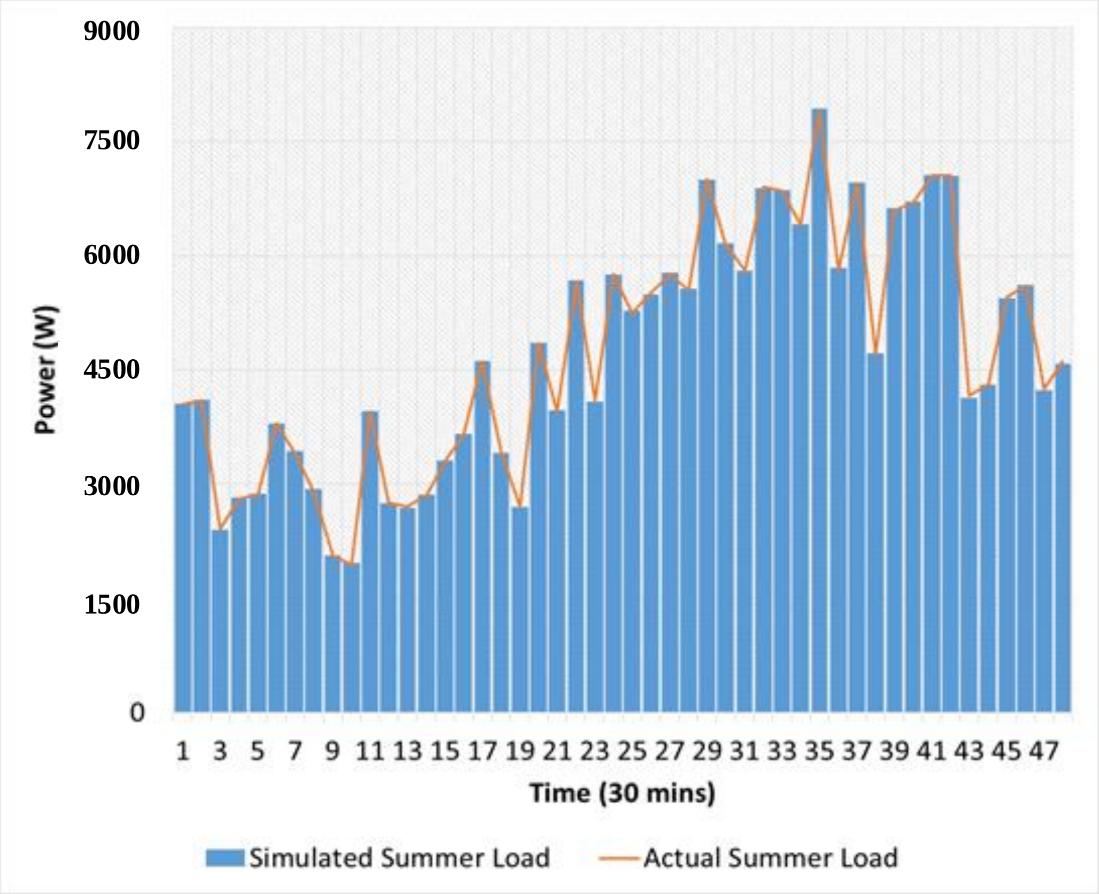


Figure 2.7 24-Hour Load Simulation

2.2 Smooth Operation Test of the PV System

Regular PV system installed on residential roof always cooperate with the grid to supply the home load, the controller manages the energy come from the grid and the solar panels, the grid is a supplemental energy source during the daytime, but during the night the grid will be the only energy source for the load. However the battery assisted PV system has three energy sources, PV modules, battery and the grid, so not only the grid but also the battery become the supplemental energy source for the load. So the switch between each energy sources has to be seamless to make sure the energy supply will not be interrupted. As figure 2.1 shows, the load can be supplied by three sources, PV, battery and the grid. During the daytime, when the solar energy is greater than the load demand, the solar energy will supply the load and charge the battery at the same time. When the solar energy is lower than the load demand, the battery will pick up the load to supply together with the PV panels, if the battery is exhausted, the grid will pick up the load to help the PV panels. During night time, the battery will supply the load until the battery died, after that, the grid will continue to supply the load. Those cooperation and switching between those three sources has to be seamless in case a brief of power outage happens, this is also called PV smooth operation ability. The real time data like PV power output, battery charge/discharge power, the grid power input and the load demand can be tracked by the system, those data has been downloaded and used for this test. As figure 2.8 shows, during A section the solar power was higher than the load demand, so the solar power both charge the battery and supply the load. In B section, the sun was suddenly covered by the cloud so the solar power was not sufficient to supply load, at this moment, the battery switched from charging mode into discharging mode and the load was supplied both by the battery and the solar. During C section, when the sunlight was uncovered, the battery stop discharging and switch into charging mode.

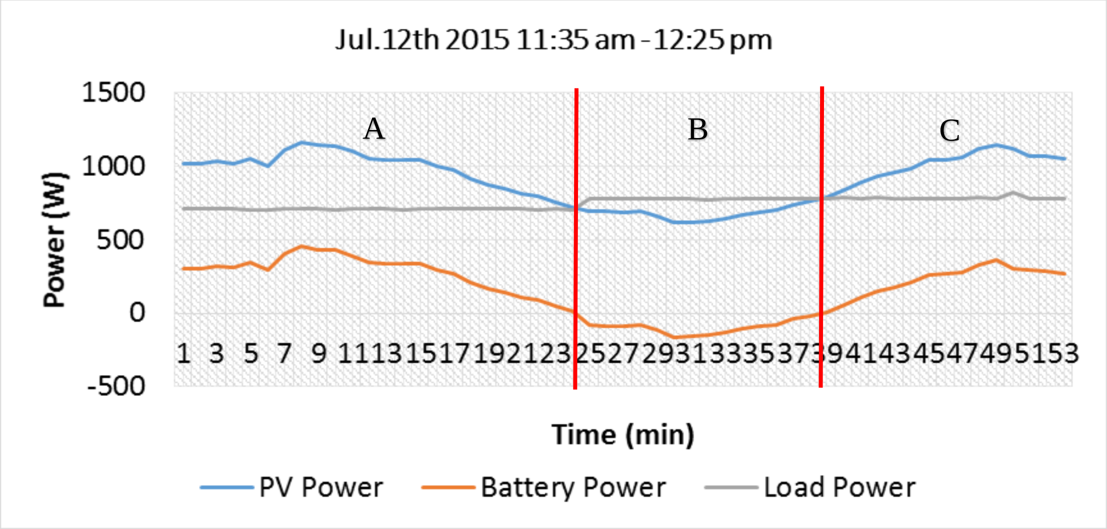


Figure 2.8 PV Intermittent Operation Example A

Another situation happens when the battery was exhausted around early morning then the grid picked up the load. As figure 2.9 shows the battery was exhausted at the 7th minute and the grid began to supply the load after the 5th minute when battery was low.

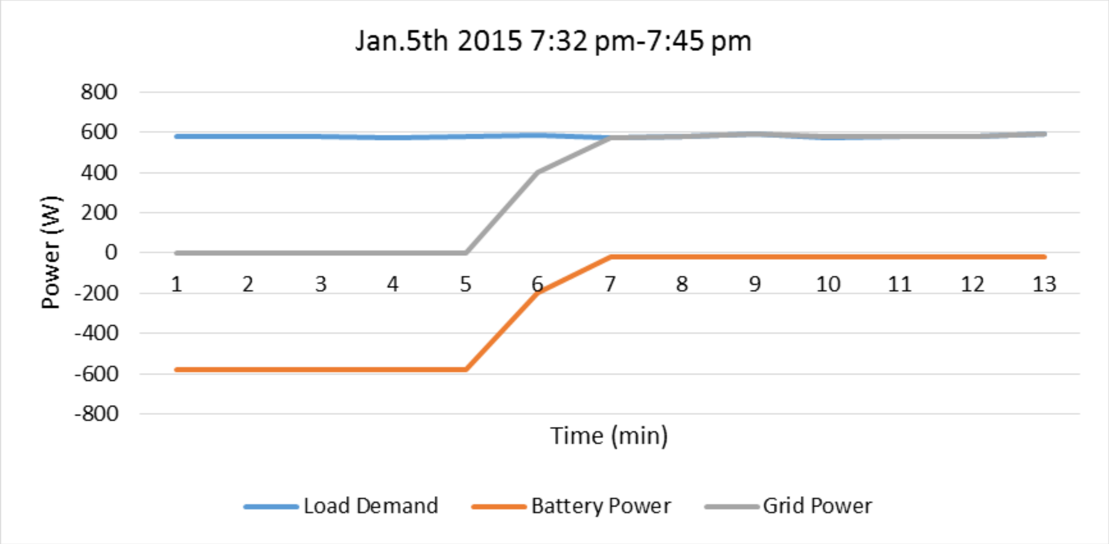
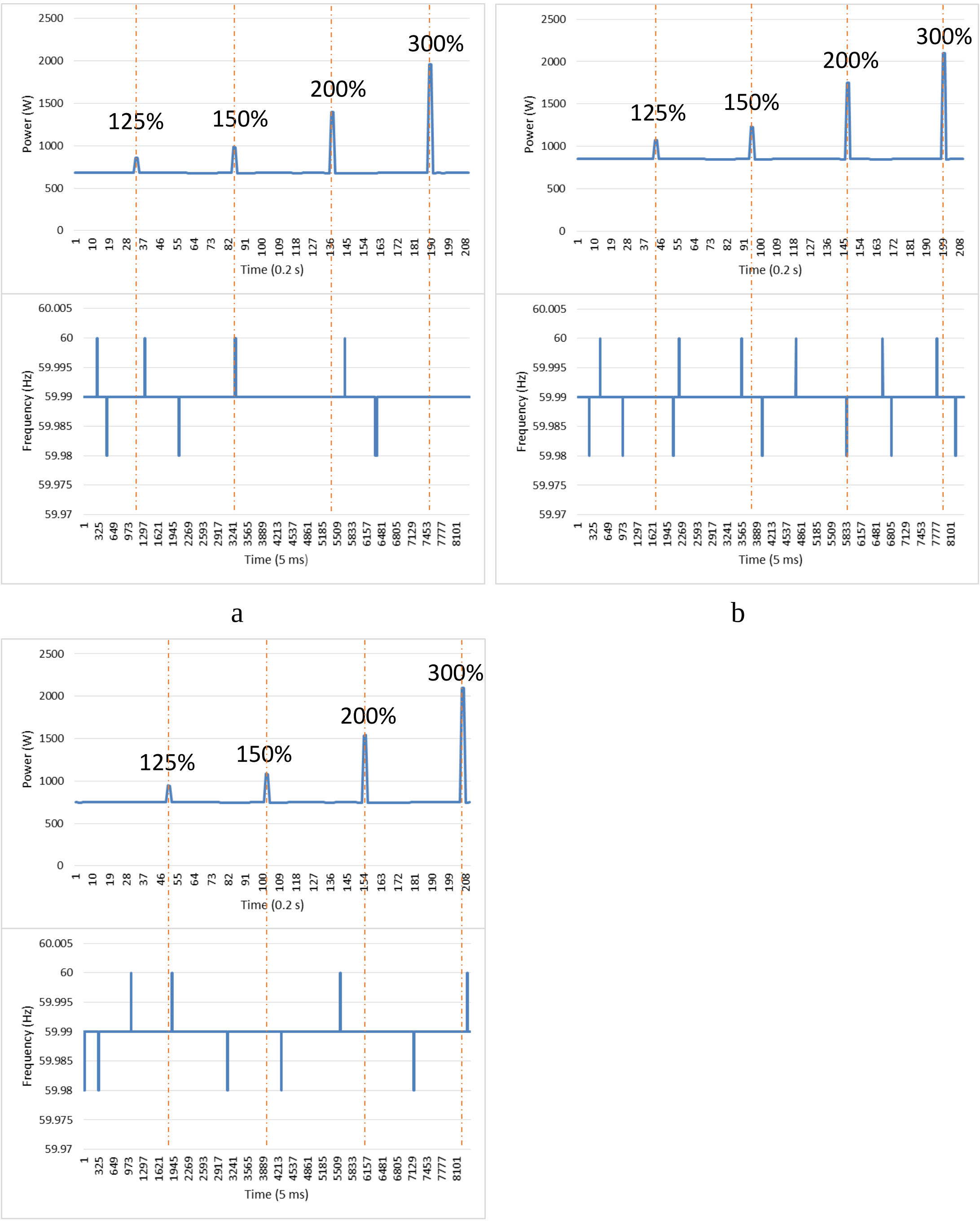


Figure 2.9 PV Intermittent Operation Example B

From the two situations mentioned above, it can be concluded that the system is able to operate smoothly those weather situations and ensure the reliable and uninterrupted electricity supply for the PV customers.

2.3 Frequency Regulation Ability Test

The system output power was 120 V AC which was converted from the 48 V DC PV power and the 60 V DC battery power. Consequently the AC frequency was decided by the inverter. So the inverter’s frequency regulation ability is concerned, to test this ability several power surges were applied. 125%, 150%, 200% and 300% overloads which last for 0.5s were programmed into the load bank, each overload was set to be 10 s apart. The system’s real time output power and frequency data was monitored by the system, the sampling frequencies are 5 Hz and 200 Hz respectively. The same test was conducted 3 times. The first test was conducted when only PV panels supplied the load, the second test was conducted when only battery supplied the load, the last test was conducted when the battery and the PV panels supplies the load together. This test determined the ability of the PV system electronics to maintain 60 Hz frequency when power surge happens.



a

b

c

Figure 2.10 Frequency Measurement During the Power Surge Test

The data used to plot the figure 2.10 a was receored at 1:55 pm on Jul.10th 2015. The reason to choose the noon to conduct this experiment was because the PV was the only power source supplying the load. So the frequency reflected the performance of the inverter for PV panels. Figure 2.10 b was plotted according to the data collected by 7:10 pm on Jul.10th 2015, because during this period the battery was the only power source supplying the load, so the output power frequency reflected the performance of the inverter for battery. Figure 2.10 c was plotted according to the data collected by 4:40 pm on Jul.10th 2015, because at this time the PV panels and the battery were supplying the load together. So the power output of the system combined the power from both the PV inverter and the battery inverter. From those three figures, it can be seen that the system output power frequency always stablelized between 60 Hz and 59.98 Hz (within the system rate range shown in figure 2.3) no matter if there is power surge or not. So the power surges did not create any frequency disturbance to the output power. In this case, the conclusion is that the system is capable of maintaining the frequency stable when power surge occurs.

2.4 AC Starting Test Using the System

For residential battery assisted PV system the biggest challenge would be the AC. When the AC starts, the compressor which is an induction motor will induce a few cycles of inrush current which is typically 4 times higher than the normal operation current, this process will last until the compressor accelerate to the normal operation speed. This process is very short, but it still might cause a big problem. As equation 2.1 and 2.2 show, if the inrush current by 120 V plus the power demand of the rest unit is higher than the inverter power output limit

$$I_{inrush} * V_{normal} + P_{rest} = P_{total} > P_{capacity} \qquad 2.1$$

$$V_{drop} * I_{inrush} + \frac{V_{drop}^{2}}{R_{load}} = P_{capacity} \qquad 2.2$$

then subject to the maximum power output rating, the output voltage will automatically drop, if the system stays on this full load operation status too long the system overload protection will be triggered. Then the PV customer will encounter a power outage. Also this might damage the electronics inside the PV system and even trigger other equipment to do under voltage protection. In order to test this influence, an experiment was done with the help of a Thru-the-Wall Air Conditioner, and this test was done without the grid connection. Considering the size of the PV system and the load bank, an AC with cooling capacity of 0.575 ton is selected. The AC's specifications are in Table 2.1.

Table 2.1 AC Specification

AC General Information	
Brand	LG
Model	LWHD6500SR
Style	Window Air Conditioner
Voltage Rating	115 V
Cooling Capacity	6500 Btu
Energy Efficiency Ratio	9.7
Power Consumption	196 W

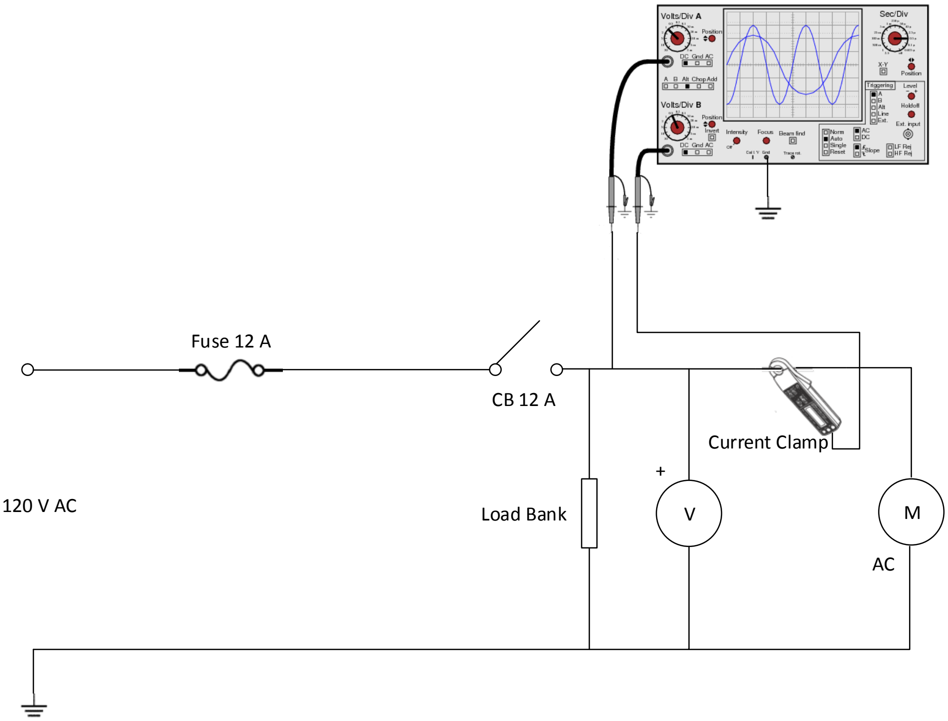


Figure 2.11 AC Starting Test Simulation Circuit

Figure 2.12 AC Starting Actual Testing Circuit

Figure 2.11 shows the drawing of the testing circuit. Figure 2.12 is the photo of the testing circuit. The induction motor and oscilloscope were protected by a 12 A fuse and a 12 A circuit breaker. The oscilloscope measured the voltage across the AC and a current clamp measured the current. The oscilloscope’s sample frequency was set to be 200 kHz.

To get the result of the worst situation, this test had been repeated for 10 times and each test was completed when the load bank was working at 2088 W, which is close to the output limit of the inverter and within the range of SRP average residential peak load [23]. Ten groups of the AC starting current and voltage data had been recorded by oscilloscope “LeCroy Waverunner 104mxi-a”. By comparing the ten groups of data it can be seen that the starting of AC will cause a high inrush current last for 11.5 cycles.

In figure 2.13, the curve is separated into three stages A, B and C. During stage A, the AC was in standby mode, there was a small current taken by the control panel display screen and indicator light. During stage B, the AC was started and the starting current suddenly went up to 15.56 A in one cycle and reached the maximum current 16.97 A at the third cycle (624.4 W overload), this maximum starting current lasted 6 cycles and then within 3 cycles the starting current gradually dropped to the normal operation current. For the voltage, during stage A the voltage across the AC or the load bank was 120 V, during stage B when the AC starts the voltage across the AC suddenly dropped to 109.62 V, this voltage drop lasted for 11.5 cycles and the PV system’s overload protection has not been triggered.

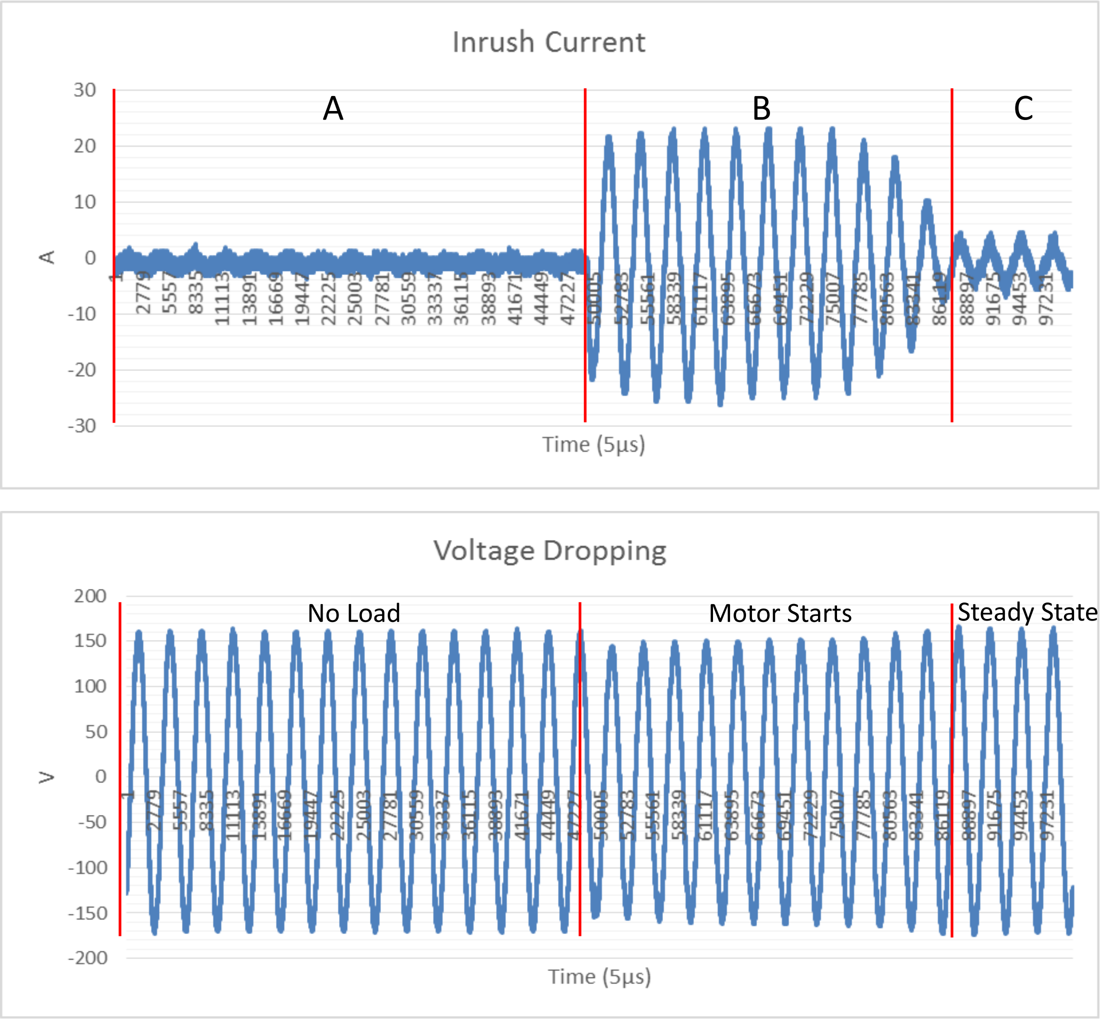


Figure 2.13 AC Starting Current and Voltage Wave

After the starting, the AC began to operate normally. The operating current was I_{ac}=1.6333+i1.6051A, so the AC's apparent power was S_{ac}= $\overline{I_{ac}}$ *V_{ac}= $\overline{1.6333 + i1.6051}$ A*120V =196.00W-192.61Var, so the AC's power consumption was P_{ac}=196W, the AC was working at a power factor of $p.f._{ac}$= P_{ac}/S_{ac}=71.32%, lagging. Since load banks were resistive load so the system's real power was P_{sys}= P_{ac}+P_{load_bank}=196W+2088W=2284W, the system's reactive power was the same as the AC's so Q_{sys}=Q_{ac}=192.61Var, system's apparent power was $S_{sys}=(P_{sys}^2+Q_{sys}^2)^{1/2}$=2292.11VA, system's power factor was $p.f._{sys}= P_{sys}/ S_{sys}$=99.65%. So the system is capable of starting this 274.80VA AC.

This size A/C unit is much smaller than what would be representative for a typical residential home in Phoenix, so further testing is planned in a subsequent phase of the project that is not covered in this thesis.

2.5 Battery Round Trip Efficiency Analysis

Most of the energy storage system, including battery, typically store energy from the grid or other energy sources in some manners, and then hands it back to the demand side when needed. During this process, round trip efficiency indicates in the percent the quantity of electricity, which can be recovered from the electricity used to charge and discharge the device.

Round trip efficiency is certainly a critical factor in the usefulness of a storage technology. A higher round trip efficiency means less energy loss. In power systems, a round trip efficiency higher than 80% is considered good for an energy storage systems [24]. Table 2.2 [24] shows the typical round trip efficiency for different energy storage technology.

Table 2.2 Round Trip Efficiency Range for Different Storage System

Storage technologies	Round trip efficiency
Hydro	From 65% in older installations to 75-80% for modern deployments

Flywheels	80% to 90%
Batteries	75% to 90%
Electrothermal (ETES)	65% to 75%
Compressed air (CAES)	65-75%

A standard battery round trip efficiency should be tested under a constant temperature environment, fully charge and discharge the battery for numerous cycles. However for a battery works together with the PV system, it is not possible to maintain the environment temperature constant since the battery is always been put in outdoor. In addition, the PV modules cannot guarantee the battery to be fully charged and fully discharged every day. Thus, a practical and realistic method was came up and used to test the round trip efficiency.

In this research the battery input power and output power were automatically recorded by the charge controller at the frequency of 5 Hz, those data can be downloaded and used for round trip efficiency analysis. According to the definition of round trip efficiency, it can be obtained by equation 2.3-2.6.

$$Round\_Trip\_Efficiency\ (n) = 1 - \frac{Energy_{loss}(n)}{Energy_{Charged}(n)} \tag{2.3}$$

$$Energy_{loss}(n) = E_{battery_{start}}(n) + E_{charged}(n) - E_{discharged}(n) - E_{battery\_end}(n) \tag{2.4}$$

$$E_{charged}(n) = \int_{0}^{24} P_{input}(t)\ dt \tag{2.5}$$

$$E_{discharged}(n) = \int_{0}^{24} P_{output}(t)\,dt \qquad 2.6$$

Where, $E_{battery\_\mathrm{start}}(n)$ is the energy left in the battery before the charging starts on the nth day, $E_{charged}(n)$ is the nth day's energy charged into the battery, $E_{discharged}(n)$ is the nth day's discharged energy from the battery, $E_{battery\_\mathrm{end}}(n)$ is the energy left in the battery before the charging starts on the n+1th day. Equation 2.3 shows that the round trip efficiency equals to 1 minus the energy loss rate. Equation 2.4 defines the energy loss rate equals to the energy left in the battery from the last day plus the energy been charged during this day minus the energy discharged from the battery during this day and the energy left in the battery during the end of this day. The start of the battery charging varies from 6 am-11 am depending on the weather conditions. For example if the battery started to be charged from 2kWh, during that day the total charged energy is 4 kWh, that day's total discharge is 3kWh and in the end of the day the battery level is 1.7kWh, then that day's energy loss is 2+4-3-1.7=0.3 kWh, so the battery efficient is $1 - \frac{0.3kWh}{4kWh} =$ 92.5%.

For the whole years operation the system has recorded the battery charge/discharge power data (in W) for 7972 hours (332 days), 792 hours data was missing due to the SIS data base upgrade. The battery round trip efficiency was calculated and the result was plotted and shown in figure 2.14.

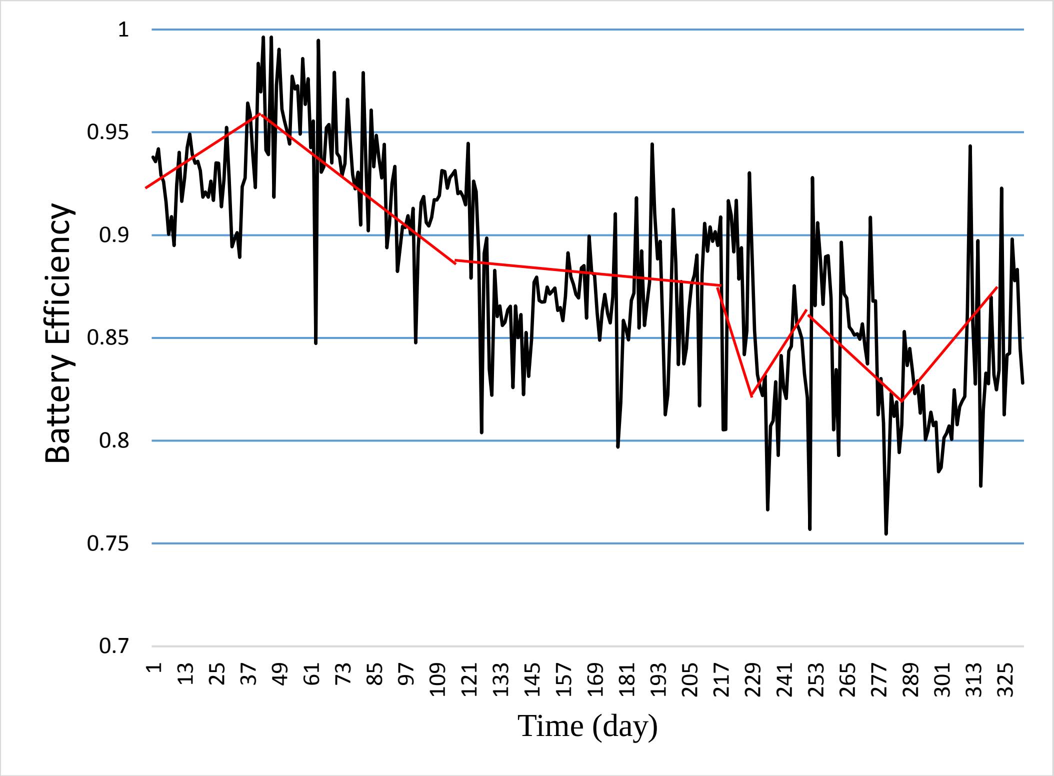


Figure 2.14 Battery Round Trip Efficiency Profile

Figure 2.14 shows the battery round trip efficiency profile for the 332 operation days. Every measuring equipment has random instrument errors so does the sensors used to collect those data, this error can be more influential to the results in those days when solar energy charged into the battery is less. This error can either increase or decrease the battery round trip efficiency depends on if the errors are positive or negative. However, the general battery round trip efficiency trend still can be observed. In the first three month, the battery round trip efficiency was around 90%-95%. In the end of this experiment, the battery round trip efficiency gradually dropped to 83%-85%. The efficiency dropped around 10% during the past one year, this efficiency loss not only came from the battery aging but also from the sunlight. In this experiment, the battery system was placed at a spot, which was exposed to the direct sunlight, thus, the battery was always working in high temperature environment during the summer, which might cause efficiency loss. In Phoenix area, summer starts from April and last until the beginning of November. This weather condition matched the round trip efficiency shown in figure 2.14. The round trip efficiency stop dropping at around the 131th day, which was in the mid-April. During summer, the system surface temperature can reach to 141℉， according to specifications of the battery system, it shows that the battery will not operate normally if the outside temperature is over 122℉, thus, if the battery was placed in a shade or garage to avoid the direct sunlight or even be placed into a place with AC on, the round trip efficiency is believed to be better. From figure 2.14, it can be observed that the whole year’s round trip efficiency of the battery are always higher than 75% and mostly over 80% which is within the reasonable range indicated in table 2.2. So the li-ion battery is capable of providing high efficiency energy storage in this battery assisted PV system application.

CHAPTER 3

DEVELOPMENT OF THE OPTIMAL CHARGING STRATEGY FOR THE BATTERY ASSISTED PV SYSTEM

Since the part of PV power higher than the load demand will be wasted or feed into the grid, so if a battery can store this part of solar energy and release them when load needs, then the solar energy's self-consumption rate can be greatly increased, this application is discussed in Akihiro's research [23]. By using the same load profile, a 20 years economic analysis is done by him under three scenarios, in scenario one no PV and no battery is used, in scenario two 10 kW PV was used and in scenario three 10 kW PV and 30 kWh battery is used., . The result shows that compare to scenario one, the 20 years overall cost of scenario two and scenario three is 5% and 1.4% less respectively . However, this comparison was not accurate because it was based on a unit electricity price plan, but most utility companies provide PV customer a unique price plan, which is completely different from the regular price plan. For example, an Arizona local utility company Salt River Project (SRP) provides their PV customers a price plan called E-27, the detail of this price plan is shown in Table 3.1. The regular price plan is shown in Table 3.2.

Table 3.1 SRP E-27 Price Plan

	On-peak kWh	Off-peak kWh	On-peak Demand Charge (per kW)			Monthly Service Charge
			0-3 kW	>3-10 kW	>10 kW	
Summer	$0.0486	$0.0371	$8.03	$14.63	$27.77	$30.94
Sum_pk	$0.0633	$0.0423	$9.59	$17.82	$34.19	$30.94
Winter	$0.0430	$0.0390	$3.55	$5.68	$9.74	$32.44

Table 3.2 SRP Basic Price Plan

	May-Jun and Sep-Oct (per kWh)	**Jul-Aug (per kWh)**	**Nov-Apr (per kWh)**
First 700 kWh	$0.1102	$0.1168	$0.0803
701-2000 kWh	$0.1121	$0.1180	$0.0803
2000+ kWh	$0.1226	$0.1331	$0.0803
Service Charge	$18.50/Month	$18.50/Month	$20/Month

From table 3.1 and table 3.2, it can be seen that the rate structures for regular customer and the PV customer are different. For regular customers, their electricity bill includes the energy charge and the service charge, for PV customers, their electricity bill contains one more part called demand charge, demand–related charges usually represent 30 to 70 percent of most customers' electric bills [24]. . The demand charge only applies to weekdays not weekends. In next part the yearly electricity bill comparison between regular customer and PV customer will be conduct again based on SRP’s price plans, a generic typical load profile of residential home was provided by SRP and the PV power profile was obtained by the PV panels.

3.1 Simulated Residential Yearly Load Profile with 30 Minutes Resolution

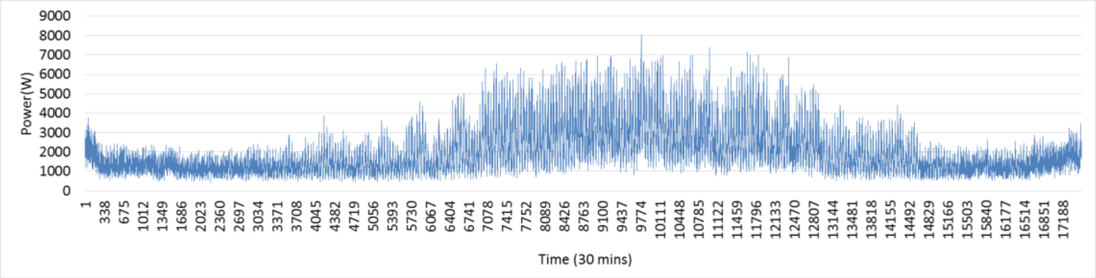


Figure 3.1 Simulated Load Profile with 30 min Resolution

SRP generated an average load profile with 30 min resolution based on 1000 residential house’s load profiles the load profile is shown in figure 3.1.

This load profile starts from 00:00 at Jan.01.2014 and lasts to 23:59 at Dec.31.2014. From figure 3.1, it can be seen that the electricity consumption is more intense during the summer and the summer peak load is about 3 times higher than the winter peak. Combine this load profile with Table 3.2, if there is no PV been installed for this simulated home, then its monthly electricity bill can be calculated by equation 3.1 and 3.2. Where, *m* is the number of month, *n* is number of how many 30 minutes certain month contains, *P(t)* is the average power demand in any 30 minutes, *Electricity* is the total electricity consumption in certain month, $Electricy_{bill}$ is certain month's electricity bill, *a* is the electricity price for the first 700 kWh, *b* is the electricity price for the part over 700 kWh but less than 2000 kWh, c is the electricity price for the part higher than 2000 kWh and *S* is the monthly service charge.

$$Electricity(m) = \int_0^{30*n} P(t)dt \qquad 3.1$$

$$Electricity_{bill}(m) = (Electricity(m) \leq 700) * a(m) + (700 < Electricity(m) \leq 2000) * b(m) + \big(2000 < Electricity(m)\big) * b(m) + S(m) \qquad 3.2$$

For example, this house's April electricity consumption is 999.462 kWh, then the bill would be 700kWh*0.0803\$/kWh+(980kWh-700kWh)*0.0803\$/kWh +20\$/mon=\$100.26. In this way, the electricity consumption and the electricity bill for each month is calculated by Matlab and shown in table 3.3, the code for the calculation in attached in APPENDIX A.

Table 3.3 Monthly Bill by Basic Plan

Month	kWh	Elec_bill ($)	Service ($)	Total_bill ($)
Jan	1075.807	86.39	20.00	106.39
Feb	793.2655	63.70	20.00	83.70
Mar	959.1052	77.02	20.00	97.02
Apr	999.462	80.26	20.00	100.26
May	1467.711	163.20	18.50	181.70
Jun	2072.893	239.98	18.50	258.48
Jul	2453.416	349.02	18.50	367.52
Aug	2154.598	273.98	18.50	292.48
Sep	1878.429	209.25	18.50	227.75
Oct	1261.977	140.14	18.50	158.64
Nov	902.2239	72.45	20.00	92.45
Dec	1106.501	88.86	20.00	108.86
Annual	17125.388	1844.25	231	2075.25

From table 3.3, it can be observed that the energy cost is 88.87% of the electricity bill, service fee takes 11.13% of the total bill.

3.2 Annual Electricity Bill for the Simulated House with 6 kW PV Modules

In fact, more than 92% of present PV customers do not have battery storage system [25]. Thus, directly obtain solar energy from the PV modules are the only way for them to use the solar energy, if the solar energy exceeds the load demand, then the exceeding part will be send back to the grid without any cashback according to the SRP rate plan. In addition, the peak shaving is very weak in this kind of simple application. Figure 3.2 is a typical 24-hour solar and load profile, it shows the details of the energy distribution for both the load and the solar. The PV customer is going to pay the energy of part D, part E and part F. For part D, the PV customer is also going to pay the demand charge for 3 kW. The PV energy covers the energy demand of part B. Energy part A and part C will be sent back to the grid. Figure 3.3 is the whole year's 6/1.35 times scaled up PV power profile with the resolution of 1 hour and 8760 hours in total. Considering the whole year, each day's solar energy and load profile has been analyzed as it is shown in figure 3.2. Equation 3.3-3.6 are the calculations for the PV customer's electricity bill.

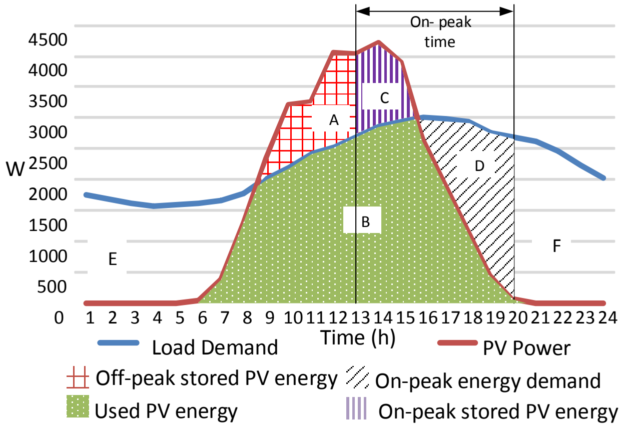


Figure 3.2 Detailed Daily Solar Energy Distribution

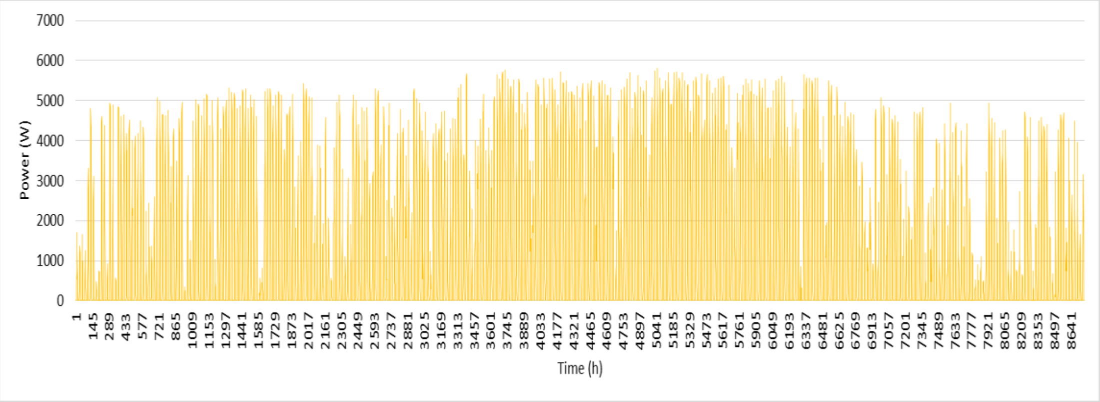


Figure 3.3 One-year Solar Energy Profile with 1-Hour Resolution

$$E_{on}(n) = \int_{13}^{20} P_{on}(t) - P_{pv}(t)dt, (if\ P_{on}(t) - P_{pv}(t) < 0, use\ 0) \tag{3.3}$$

$$\begin{aligned} E_{off}(n) = \int_{0}^{13} P_{off}(t) - P_{pv}(t)dt + \int_{20}^{24} P_{off}(t) - P_{pv}(t)dt\,, \\ (if\ P_{off}(t) - P_{pv}(t) < 0, use\ 0) \end{aligned} \tag{3.4}$$

$$Peak_n = \max\left(\lceil P_{on}(t) - P_{off}(t) \rceil\right), 13 < t < 20\ \ with\ step\ of\ 30\ min \tag{3.5}$$

$$\begin{aligned} &Peak_{charge}(m) \\ &= \begin{cases} \max(Peak_n) * a, if \max(Peak_n) \leq 3 \\ 3a + (\max(Peak_n) - 3)) * b, if\ 3 < \max(Peak_n) \leq 10 \\ 3a + 7b + (\max(Peak_n) - 7)) * c, if\ 10 < \max(Peak_n) \end{cases} \end{aligned} \tag{3.6}$$

$$\begin{aligned} Bill(m) = \sum_{1}^{n} (E_{on}(n) * Price_{on}(m) + E_{off}(n) * Price_{off}(m)) \\ + Peak_{charge}(m) + S(m) \end{aligned} \tag{3.7}$$

Where, *n* is the nth day in a certain month, *m* is a certain month, in equation 3.3 the integral domain is from 13-20, this is because the on-peak time is from 1:00pm-8:00pm, the rest of the day s off peak time. For example, this house's Apr on-peak energy consumption is 262.4324 kWh, and off-peak energy consumption is 381.1966 kWh, the highest peak during on-peak time is 4.7 kW, so the electricity bill for this month is 262.4323kWh*0.0430\$/kWh+381.1966kWh*0.0390\$/kWh+3Kw*3.55 \$/kW+$\lceil$4.7kW − 3kW$\rceil$*5.68\$/kW+\$32.44=\$80.70 the Matlab code using for analyzing the whole years electricity bill month by month is written and attached in APPENDIX B. The detailed electricity bill for each month are calculated and presented in table 3.4.

Table 3.4 Electricity Bill with 6 kW PV Installed

Month	On_peak (kWh)	Off_peak (kWh)	Energy Charge ($)	Peak(kW)/Charge ($)	Service Fee ($)	Total ($)
Jan	223.6421	562.0357	31.54	3.837276/16.33	32.44	80.31
Feb	159.6409	353.6922	20.66	2.607524/10.65	32.44	63.75
Mar	226.4324	381.1966	24.61	4.025352/22.01	32.44	79.06
Apr	264.2824	381.6162	26.25	4.704155/22.01	32.44	80.70
May	457.4067	510.1574	41.16	6.876783/82.61	30.94	154.71
Jun	693.0876	668.3563	58.48	7.738725/97.24	30.94	186.66
Jul	785.814	876.3646	86.82	8.556871/135.69	30.94	253.45
Aug	679.5495	736.7579	74.18	8.058391/135.69	30.94	240.81
Sep	611.7435	661.0685	54.26	7.475154/97.24	30.94	182.44
Oct	406.4933	449.8393	36.45	5.025664/67.98	30.94	135.37
Nov	232.5319	401.6955	25.67	3.155231/16.33	32.44	74.44
Dec	257.59	557.1252	32.81	3.859843/16.33	32.44	81.58
Total	4998.22	6539.91	512.84	720.11	380.28	1613.3

Table 3.4 shows that in PV customer’s electricity bill, the demand charge is $720.11/year which is even higher than the energy charge $512.84/year. With the help of the PV modules the customer electricity consumption from the gird decreased 32.63%, however the electricity bill only decreased by 22.26%. The savings on the bill was not proportional to the energy savings. This contradiction was caused by the demand charge. Considering the big investment been put on the PV system, the customer might encounter longer payback period under this rate plan and this will make them unsatisfied. The key to reduce their electricity bill is to control their peak demand.

3.3 Battery Charging Strategy Development for PV System

Part 3.2 illustrated why PV customers are paying high electricity bills. The best way to solve this problem is to store the exceeding solar energy during the day, and then use them during the on peak time. As it is shown in figure 3.4 the energy in part A can be used to supply the on-peak demand part D. If $E_A > E_D$ than the on peak demand will be eliminated, and there will be no demand charge. If $E_A < E_D$, than the grid energy has to pick up the load and the peak demand is still exist, but if the battery been pre-charged during the off-peak time by the grid energy, then there will be no peak demand. However every day's E_A-E_D are different, to make sure there is no peak demand all over the year, the battery need to be pre-charged to a very high level which is enough to cover the worst day. According to the one year data, this pre-charge level was too high to be realistic, also it will cause a lot of PV energy being wasted. In order to eliminate the peak demand and also increase the PV energy self-consumption, a charging methods is came up, the basic idea is following, the biggest daily negative E_A+E_C-E_D among the year can be set as the bench mark of the battery pre-charging level. It will ensure zero energy consumption from the grid unless the load demand is higher than the system maximum output limitation.

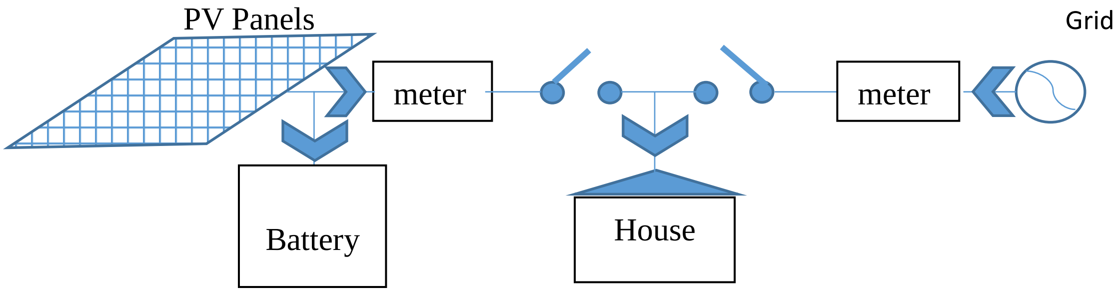


Figure 3.4 System Connection Typology Diagram

Like Figure 3.4 shows, both the PV system and the grid can supply the house and charge the battery. If the battery is fully charged, the PV energy will be fed into the grid. During the on-peak hours, the grid will become a supplemental energy source.

The biggest negative $E_A+E_C-E_D$ value is the Critical Charging Level (CCL). The grid will maintain the battery at this CCL level every day, and then the PV energy will charge the battery first, the PV energy will not supply the load until the peak hour comes, in this case even in the worst situation, during the on-peak hour the load still can be supplied without using the grid energy. During the on peak hour the PV will continue to charge the battery if the PV energy is higher than the load demand, when the battery is fully charged the extra PV energy will be fed back to the grid.

Assume a residential house’s 24-hour load profile is the blue line shown in figure 3.5. The detailed charging strategy explanation shows in figure 3.6.

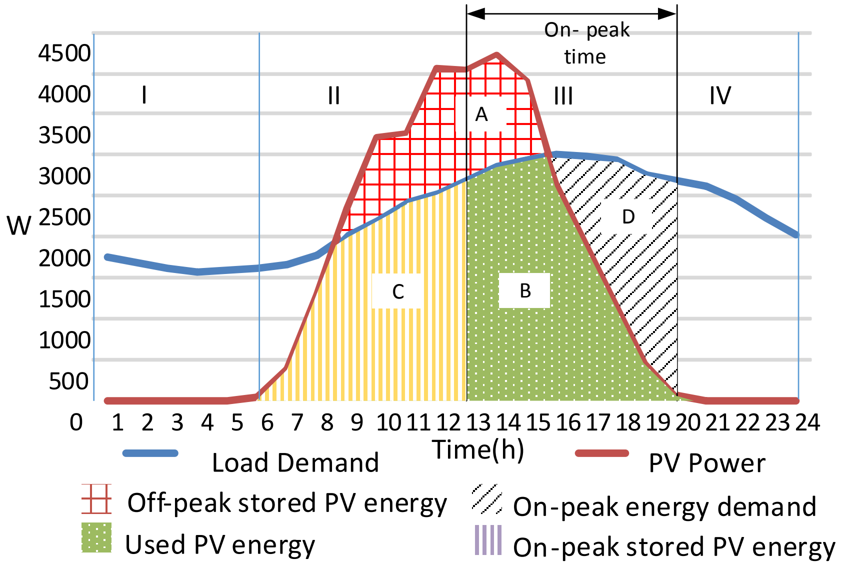
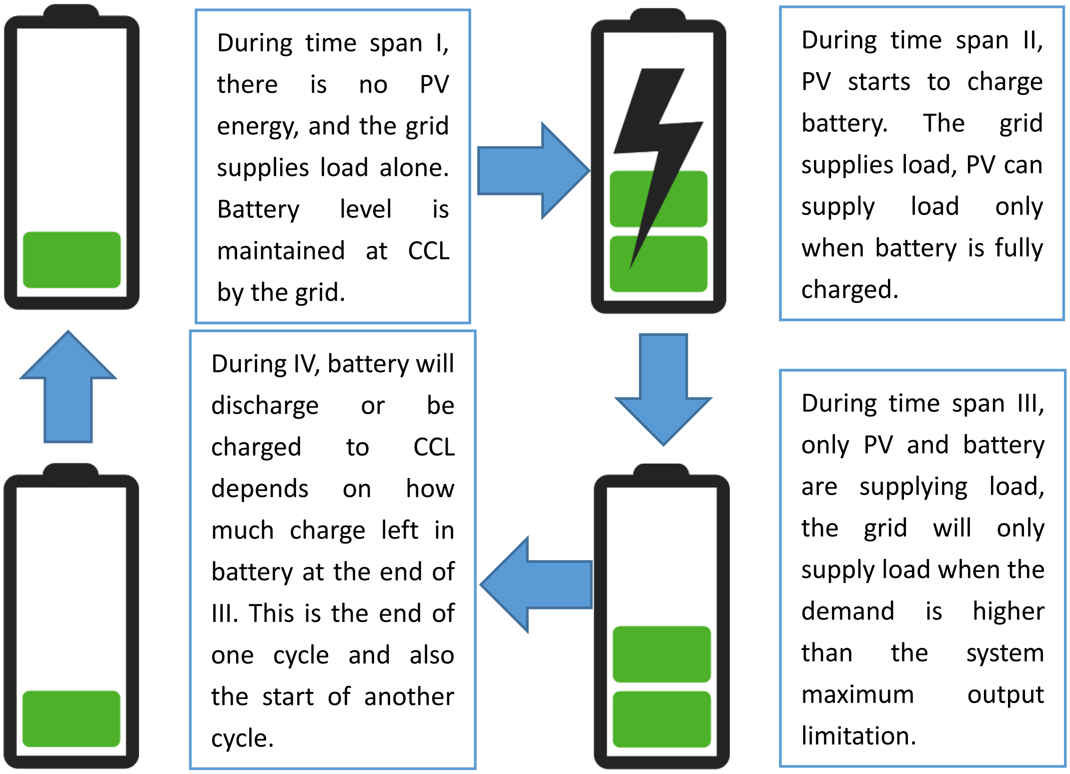


Figure 3.5 Solar Energy Distribution



During time span I, there is no PV energy, and the grid supplies load alone. Battery level is maintained at CCL by the grid.

During time span II, PV starts to charge battery. The grid supplies load, PV can supply load only when battery is fully charged.

During time span III, only PV and battery are supplying load, the grid will only supply load when the demand is higher than the system maximum output limitation.

During IV, battery will discharge or be charged to CCL depends on how much charge left in battery at the end of III. This is the end of one cycle and also the start of another cycle.

Figure 3.6 Charging Strategy Explanation

By analyzing the one-year data, each day's $E_A+E_C-E_D$ was calculated and listed in table 3.5. Part D, shown in figure 3.5, is the amount of energy needed from the battery to cover the on peak demand on each day, the minimum battery size was D_{min}=28.075 kWh. A+C-D is the difference between the PV energy and the on peak demand, when A+C-D>0 that means no off peak charge is needed so 0 is been filled in the blank, the biggest negative A+C-D is -14.504 kWh which is on 09/20/2014, so the CCL is 14.504 kWh. Thus, if the off-peak grid energy charge the battery to 14.504 kWh every day, then the whole years on peak demand would be zero. The value of CCL is found by a program written in Matlab, the basic logic of the program is shown in figure 3.6, the code is in the APPEDIX C.

Table 3.5 CCL and Battery Needed for Each Day

Date	A+C-D (CCL)	A+C	D (Battery)	Within 30kWh	Date	A+C-D (CCL)	A+C	D (Battery)	Within 30kWh
2014/1/1	-8078.51	4860	12938.51	yes	2014/7/3	-4765.69	21780.35	26546.04	yes
2014/1/2	-4923.19	5790	10713.19	yes	2014/7/4	-3308.52	16551.6	19860.12	yes
2014/1/3	-6238.76	5720	11958.76	yes	2014/7/5	-2935.89	20677.15	23613.03	yes
2014/1/4	-7718.05	3860	11578.05	yes	2014/7/6	-3893.82	19949.79	23843.61	yes
2014/1/5	-82.3191	6673.914	6756.233	yes	2014/7/7	-4567.12	20497.35	25064.48	yes
2014/1/6	0	9225.998	9225.998	yes	2014/7/8	-11122.5	14340	25462.51	yes
2014/1/7	0	7762.202	7762.202	yes	2014/7/9	-2122.29	17223.7	19345.99	yes
2014/1/8	-7203.61	1520	8723.612	yes	2014/7/10	-5177.48	18649.71	23827.19	yes
2014/1/9	-4823.51	2380	7203.509	yes	2014/7/11	-3795.02	21309.79	25104.81	yes
2014/1/10	0	9584.766	9584.766	yes	2014/7/12	-3940.42	21817.35	25757.77	yes
2014/1/11	0	8703.369	8703.369	yes	2014/7/13	-3749.65	21871.42	25621.07	yes
2014/1/12	-5156.23	1980	7136.229	yes	2014/7/14	-7555.15	15944.74	23499.89	yes
2014/1/13	0	7244.045	7244.045	yes	2014/7/15	-10420.8	12620	23040.79	yes
2014/1/14	0	7053.196	7053.196	yes	2014/7/16	-6670.63	17907.21	24577.84	yes
2014/1/15	-5795.97	1880	7675.966	yes	2014/7/17	-13000.4	14813.72	27814.16	yes
2014/1/16	0	8360.005	8360.005	yes	2014/7/18	-5201.21	16972.85	22174.06	yes
2014/1/17	0	10003.7	10003.7	yes	2014/7/19	-4294.51	19086.5	23381.01	yes
2014/1/18	0	9855.641	9855.641	yes	2014/7/20	-7763.71	16997.55	24761.26	yes
2014/1/19	0	8358.479	8358.479	yes	2014/7/21	-6254.61	17511.44	23766.06	yes
2014/1/20	0	8292.949	8292.949	yes	2014/7/22	-10536.9	17241.2	27778.10	yes
2014/1/21	0	7383.48	7383.48	yes	2014/7/23	-8587.3	17194.16	25781.46	yes
2014/1/22	0	7271.594	7271.594	yes	2014/7/24	-10142.3	15629.29	25771.59	yes
2014/1/23	0	6706.447	6706.447	yes	2014/7/25	-3631.78	22131.24	25763.01	yes
2014/1/24	0	8666.753	8666.753	yes	2014/7/26	-7279.94	19182.97	26462.9	yes
2014/1/25	0	7574.153	7574.153	yes	2014/7/27	-14488.5	9480	23968.54	yes
2014/1/26	-3025.48	3190	6215.483	yes	2014/7/28	-7172.6	18993.54	26166.14	yes
2014/1/27	-1319.43	4601.661	5921.092	yes	2014/7/29	-6377.09	21262.61	27639.7	yes
2014/1/28	-2238.99	4292.829	6531.818	yes	2014/7/30	-7063.19	20031.88	27095.07	yes
2014/1/29	-1922.73	4175.052	6097.778	yes	2014/7/31	-6197.22	20255.25	26452.47	yes
2014/1/30	0	7946.824	7946.824	yes	2014/8/1	-1643.84	16740.97	18384.81	yes
2014/1/31	0	9590.625	9590.625	yes	2014/8/2	-683.019	17173.57	17856.59	yes
2014/2/1	0	10345.75	10345.75	yes	2014/8/3	-1729.76	19118.17	20847.93	yes
2014/2/2	0	8510.459	8510.459	yes	2014/8/4	-7394.27	16758.11	24152.38	yes

2014/2/3	0	8031.904	8031.904	yes	2014/8/5	-4982.09	18365.32	23347.4	yes
2014/2/4	-320.569	5190.295	5510.864	yes	2014/8/6	-6447.92	17340.99	23788.9	yes
2014/2/5	0	7556.652	7556.652	yes	2014/8/7	-5547.8	16535.97	22083.77	yes
2014/2/6	0	5559.231	5559.231	yes	2014/8/8	-4606.05	18236.72	22842.77	yes
2014/2/7	0	6471.779	6471.779	yes	2014/8/9	-2998.89	19840.9	22839.79	yes
2014/2/8	0	8642.665	8642.665	yes	2014/8/10	-5545.9	20269.77	25815.67	yes
2014/2/9	-6798.2	1640	8438.204	yes	2014/8/11	-6291.92	18733.19	25025.1	yes
2014/2/10	-1097.75	4645.915	5743.664	yes	2014/8/12	0	18243.03	18243.03	yes
2014/2/11	-3324.37	3750	7074.367	yes	2014/8/13	-2847.08	14357.41	17204.49	yes
2014/2/12	-307.697	4831.963	5139.66	yes	2014/8/14	-7193.21	17880.49	25073.7	yes
2014/2/13	0	7317.84	7317.84	yes	2014/8/15	-7646.79	16821.43	24468.22	yes
2014/2/14	0	8260.958	8260.958	yes	2014/8/16	-7969.19	17876.72	25845.91	yes
2014/2/15	0	8009.231	8009.231	yes	2014/8/17	-5463.5	22611.72	28075.23	yes
2014/2/16	0	7987.564	7987.564	yes	2014/8/18	-2450.62	16913.5	19364.13	yes
2014/2/17	0	7294.316	7294.316	yes	2014/8/19	0	14679.15	14679.15	yes
2014/2/18	-1155.48	4038.051	5193.535	yes	2014/8/20	-3937.33	15210.39	19147.72	yes
2014/2/19	0	7456.913	7456.913	yes	2014/8/21	0	12415.34	12415.34	yes
2014/2/20	-4905.71	2690	7595.707	yes	2014/8/22	-2398.6	12635.84	15034.44	yes
2014/2/21	0	7672.857	7672.857	yes	2014/8/23	-3599.83	16512.32	20112.16	yes
2014/2/22	0	7874.359	7874.359	yes	2014/8/24	-9980.3	15189.58	25169.88	yes
2014/2/23	0	7064.89	7064.89	yes	2014/8/25	-6564.1	16504.46	23068.55	yes
2014/2/24	0	7670.249	7670.249	yes	2014/8/26	-8924.98	14055.27	22980.25	yes
2014/2/25	0	7629.41	7629.41	yes	2014/8/27	-14504.1	11080	25584.05	yes
2014/2/26	0	7952.923	7952.923	yes	2014/8/28	-6033.57	16814.93	22848.51	yes
2014/2/27	0	7065.438	7065.438	yes	2014/8/29	-7640.82	17248.71	24889.53	yes
2014/2/28	0	7675.87	7675.87	yes	2014/8/30	-7994	18149.47	26143.47	yes
2014/3/1	0	8805.807	8805.807	yes	2014/8/31	-5234.01	19425.64	24659.65	yes
2014/3/2	0	8058.683	8058.683	yes	2014/9/1	-8029.28	18580.15	26609.43	yes
2014/3/3	0	8315.419	8315.419	yes	2014/9/2	-8525.5	16801.05	25326.55	yes
2014/3/4	0	7049.066	7049.066	yes	2014/9/3	-7757.54	17429.35	25186.88	yes
2014/3/5	0	7985.381	7985.381	yes	2014/9/4	-8362.22	17162.91	25525.14	yes
2014/3/6	0	8185.52	8185.52	yes	2014/9/5	-4546.55	16712.01	21258.56	yes
2014/3/7	0	7757.864	7757.864	yes	2014/9/6	-7361.09	18453.57	25814.66	yes
2014/3/8	-7651.91	770	8421.908	yes	2014/9/7	-6156.27	20404.84	26561.11	yes
2014/3/9	-4735.5	2530	7265.497	yes	2014/9/8	-3407.41	12404.99	15812.4	yes
2014/3/10	0	6717.859	6717.859	yes	2014/9/9	-1831.55	15062.42	16893.97	yes
2014/3/11	0	7741.018	7741.018	yes	2014/9/10	-5935.41	14076.96	20012.37	yes
2014/3/12	0	7747.047	7747.047	yes	2014/9/11	-4770.39	14718.5	19488.9	yes
2014/3/13	0	7861.139	7861.139	yes	2014/9/12	-6566.93	15849.11	22416.04	yes

2014/3/14	0	8735.756	8735.756	yes	2014/9/13	-4150.14	17544.41	21694.55	yes
2014/3/15	0	8782.633	8782.633	yes	2014/9/14	-6635.92	17956.36	24592.28	yes
2014/3/16	-815.463	7123.77	7939.234	yes	2014/9/15	-9724.21	15753.6	25477.81	yes
2014/3/17	-1423.57	6564.407	7987.975	yes	2014/9/16	0	13750.64	13750.64	yes
2014/3/18	0	7964.887	7964.887	yes	2014/9/17	-1221.44	12563.14	13784.58	yes
2014/3/19	0	7845.048	7845.048	yes	2014/9/18	-3470.11	14641.15	18111.26	yes
2014/3/20	0	6436.017	6436.017	yes	2014/9/19	-8545.17	11643.23	20188.41	yes
2014/3/21	0	8680.751	8680.751	yes	2014/9/20	-8000.87	12440.65	20441.52	yes
2014/3/22	-345.075	8050.759	8395.835	yes	2014/9/21	-5474.17	15268.77	20742.94	yes
2014/3/23	-1727.8	5571.46	7299.257	yes	2014/9/22	-3987.03	15899.11	19886.14	yes
2014/3/24	0	7746.091	7746.091	yes	2014/9/23	-4693.99	15010.97	19704.96	yes
2014/3/25	0	7873.814	7873.814	yes	2014/9/24	-6955.37	14643.99	21599.37	yes
2014/3/26	0	8096.99	8096.99	yes	2014/9/25	-5536.64	16489.55	22026.18	yes
2014/3/27	-239.614	8233.506	8473.12	yes	2014/9/26	-1070.93	17213.54	18284.47	yes
2014/3/28	-4650.08	7473.728	12123.8	yes	2014/9/27	-755.073	13447.68	14202.75	yes
2014/3/29	-4551.77	8562.617	13114.39	yes	2014/9/28	-3844.32	12023.04	15867.36	yes
2014/3/30	-4218.24	7074.841	11293.08	yes	2014/9/29	-7600.66	6806.137	14406.8	yes
2014/3/31	-7463.65	6930.889	14394.54	yes	2014/9/30	-2269.25	9634.741	11903.99	yes
2014/4/1	-993.89	8939.767	9933.657	yes	2014/10/1	-4168.22	8160.048	12328.27	yes
2014/4/2	-4880.81	6240.468	11121.28	yes	2014/10/2	-4910.15	8095.469	13005.62	yes
2014/4/3	-9591.42	1990	11581.42	yes	2014/10/3	-4724.33	9297.212	14021.55	yes
2014/4/4	-1688.99	7149.782	8838.776	yes	2014/10/4	-4620.28	11199.32	15819.6	yes
2014/4/5	0	10375.09	10375.09	yes	2014/10/5	-5334.71	11502.88	16837.59	yes
2014/4/6	-446.917	7284.13	7731.046	yes	2014/10/6	-1863.28	10152.73	12016.01	yes
2014/4/7	-1392.66	5582.228	6974.891	yes	2014/10/7	-765.198	9869.863	10635.06	yes
2014/4/8	-3390.4	4350	7740.403	yes	2014/10/8	0	9683.075	9683.075	yes
2014/4/9	-1270.62	4592.21	5862.83	yes	2014/10/9	-493.566	9718.903	10212.47	yes
2014/4/10	-2035.79	4386.884	6422.672	yes	2014/10/10	-1605.98	10595.12	12201.1	yes
2014/4/11	0	8861.125	8861.125	yes	2014/10/11	-6951.97	8682.662	15634.63	yes
2014/4/12	0	9284.372	9284.372	yes	2014/10/12	-2823.32	11502.51	14325.83	yes
2014/4/13	-2045.41	8655.317	10700.73	yes	2014/10/13	-9903.18	5444.115	15347.29	yes
2014/4/14	-2265.74	8167.442	10433.18	yes	2014/10/14	-9173.88	5051.032	14224.91	yes
2014/4/15	0	6856.817	6856.817	yes	2014/10/15	-2954.98	8452.455	11407.44	yes
2014/4/16	0	7564.075	7564.075	yes	2014/10/16	-11738.6	4000	15738.56	yes
2014/4/17	-1665.3	6542.118	8207.415	yes	2014/10/17	-2088.91	8031.909	10120.82	yes
2014/4/18	-2146.91	5774.438	7921.352	yes	2014/10/18	-8682.49	7265.712	15948.21	yes
2014/4/19	-981.04	9915.056	10896.1	yes	2014/10/19	-2524.94	11771.24	14296.19	yes
2014/4/20	-1408.94	9241.709	10650.64	yes	2014/10/20	-2401.34	9610.241	12011.58	yes
2014/4/21	-468.795	8708.621	9177.416	yes	2014/10/21	-3890.69	8951.505	12842.19	yes

2014/4/22	-808.483	7946.664	8755.147	yes	2014/10/22	-3007.6	9619.48	12627.08	yes
2014/4/23	-2718.96	6090.649	8809.605	yes	2014/10/23	-3017.59	9567.224	12584.81	yes
2014/4/24	0	7751.458	7751.458	yes	2014/10/24	-3744.21	9709.41	13453.62	yes
2014/4/25	0	8367.842	8367.842	yes	2014/10/25	-5037.87	11504.59	16542.45	yes
2014/4/26	-2027.47	6275.711	8303.18	yes	2014/10/26	-5068.4	11113.95	16182.34	yes
2014/4/27	-1702.63	7021.757	8724.386	yes	2014/10/27	-5752.46	7058.093	12810.55	yes
2014/4/28	-1225.62	9181.608	10407.23	yes	2014/10/28	-4646.03	6307.862	10953.89	yes
2014/4/29	-2755.82	9123.853	11879.67	yes	2014/10/29	-4815.6	7028.5	11844.1	yes
2014/4/30	-4062.04	9528.891	13590.93	yes	2014/10/30	-4881.57	6007.829	10889.4	yes
2014/5/1	-1862.45	8312.154	10174.6	yes	2014/10/31	-3605.11	8099.672	11704.78	yes
2014/5/2	-9528.51	6247.703	15776.21	yes	2014/11/1	0	10393.77	10393.77	yes
2014/5/3	-2983.27	12045.76	15029.03	yes	2014/11/2	0	8910.959	8910.959	yes
2014/5/4	-3087.61	13406.88	16494.5	yes	2014/11/3	0	7405.233	7405.233	yes
2014/5/5	-1517.59	11881.96	13399.55	yes	2014/11/4	-4295.66	3922.861	8218.522	yes
2014/5/6	0	10121.73	10121.73	yes	2014/11/5	-2148.92	6310.541	8459.46	yes
2014/5/7	0	8450.7	8450.7	yes	2014/11/6	-2362.18	5242.969	7605.152	yes
2014/5/8	-1788.26	6475.831	8264.089	yes	2014/11/7	-508.108	7423.269	7931.377	yes
2014/5/9	-8406.21	4513.862	12920.07	yes	2014/11/8	-1094.39	7457.486	8551.872	yes
2014/5/10	-4567.6	9599.407	14167.01	yes	2014/11/9	-4524.93	6258.476	10783.41	yes
2014/5/11	0	10779.5	10779.5	yes	2014/11/10	-3130.79	5460.466	8591.252	yes
2014/5/12	-212.559	9278.152	9490.711	yes	2014/11/11	-529.7	7634.313	8164.014	yes
2014/5/13	-261.825	9381.767	9643.592	yes	2014/11/12	-2172.35	5204.581	7376.928	yes
2014/5/14	-1667.58	10161.57	11829.15	yes	2014/11/13	0	7306.879	7306.879	yes
2014/5/15	-8778.63	7133.72	15912.35	yes	2014/11/14	0	7087.234	7087.234	yes
2014/5/16	-7242.44	9673.382	16915.82	yes	2014/11/15	0	7210.06	7210.06	yes
2014/5/17	-4105.14	14582.53	18687.66	yes	2014/11/16	-1449.86	7109.746	8559.606	yes
2014/5/18	-3448.82	13593.74	17042.57	yes	2014/11/17	-201.451	6242.022	6443.473	yes
2014/5/19	-4600.36	12155.91	16756.28	yes	2014/11/18	0	6839.744	6839.744	yes
2014/5/20	-2537.43	11693.16	14230.59	yes	2014/11/19	0	7618.617	7618.617	yes
2014/5/21	-4891.18	9387.807	14278.98	yes	2014/11/20	-2123.61	4777.016	6900.631	yes
2014/5/22	-1042.25	10571.49	11613.74	yes	2014/11/21	-1256.14	5200.548	6456.685	yes
2014/5/23	-2402.79	9067.412	11470.2	yes	2014/11/22	-6633.58	2120	8753.584	yes
2014/5/24	-12470.3	6340	18810.31	yes	2014/11/23	-6564.1	3360	9924.096	yes
2014/5/25	-9046.8	5801.578	14848.38	yes	2014/11/24	-4805.44	3570	8375.444	yes
2014/5/26	-5874.72	14250.2	20124.93	yes	2014/11/25	-6214.84	2070	8284.838	yes
2014/5/27	-8044.22	14909.77	22953.99	yes	2014/11/26	-115.594	6634.947	6750.541	yes
2014/5/28	-4883.04	14906.35	19789.4	yes	2014/11/27	0	11831.09	11831.09	yes
2014/5/29	-7153.73	8285.533	15439.27	yes	2014/11/28	0	7590.57	7590.57	yes
2014/5/30	-9188.51	13972.5	23161.01	yes	2014/11/29	0	8647.82	8647.82	yes

2014/5/31	-9585.49	14822.96	24408.45	yes	2014/11/30	-2736.21	6439.029	9175.235	yes
2014/6/1	-7237.9	16229.96	23467.86	yes	2014/12/1	0	7278.005	7278.005	yes
2014/6/2	-9119.31	13911.93	23031.24	yes	2014/12/2	0	7416.512	7416.512	yes
2014/6/3	-5581.22	17417.69	22998.91	yes	2014/12/3	0	7137.223	7137.223	yes
2014/6/4	-5938.49	16215.59	22154.08	yes	2014/12/4	-3271.9	3605.272	6877.175	yes
2014/6/5	-6229.97	15552.26	21782.23	yes	2014/12/5	-3907.6	4135.319	8042.918	yes
2014/6/6	-7032.31	14762.28	21794.58	yes	2014/12/6	-2936.39	4736.465	7672.857	yes
2014/6/7	-6372.12	15692.87	22064.99	yes	2014/12/7	-6948.08	3190	10138.08	yes
2014/6/8	-6799.77	17712.68	24512.44	yes	2014/12/8	-1816.81	5375.105	7191.914	yes
2014/6/9	-13208.3	13322.88	26531.21	yes	2014/12/9	-5833.66	2720	8553.665	yes
2014/6/10	-6691.58	18344.29	25035.87	yes	2014/12/10	0	7343.365	7343.365	yes
2014/6/11	-2875.96	17867.35	20743.31	yes	2014/12/11	-1293.16	5560.251	6853.406	yes
2014/6/12	-8280.56	16419.61	24700.17	yes	2014/12/12	0	6951.901	6951.901	yes
2014/6/13	-7210.33	18667.41	25877.74	yes	2014/12/13	-8438.79	1940	10378.79	yes
2014/6/14	-6863.15	15541.43	22404.58	yes	2014/12/14	-1413.54	6862.643	8276.186	yes
2014/6/15	-8608.02	11411.55	20019.57	yes	2014/12/15	0	8855.406	8855.406	yes
2014/6/16	-4606.7	15432.69	20039.38	yes	2014/12/16	0	8727.719	8727.719	yes
2014/6/17	-4152.57	17198.45	21351.01	yes	2014/12/17	0	8345.927	8345.927	yes
2014/6/18	-5519.23	14098.46	19617.7	yes	2014/12/18	0	8595.2	8595.2	yes
2014/6/19	-4802.17	15556.92	20359.09	yes	2014/12/19	0	8064.447	8064.447	yes
2014/6/20	-7222.28	16661.68	23883.95	yes	2014/12/20	-7228.06	2630	9858.061	yes
2014/6/21	-5859.42	19064.33	24923.75	yes	2014/12/21	-4885.17	3199.043	8084.212	yes
2014/6/22	-5209.79	19255.63	24465.42	yes	2014/12/22	0	7460.164	7460.164	yes
2014/6/23	-8092.57	15182	23274.57	yes	2014/12/23	0	9569.959	9569.959	yes
2014/6/24	-7795.92	14827	22622.93	yes	2014/12/24	0	10769.78	10769.78	yes
2014/6/25	-6099.05	17116.21	23215.25	yes	2014/12/25	-3173.17	6930	10103.17	yes
2014/6/26	-4405.23	17105.84	21511.07	yes	2014/12/26	0	9630.359	9630.359	yes
2014/6/27	-2989.4	18090.12	21079.52	yes	2014/12/27	0	9343.874	9343.874	yes
2014/6/28	-5749.29	19324.94	25074.23	yes	2014/12/28	0	11005.29	11005.29	yes
2014/6/29	-6744.04	21284.63	28028.66	yes	2014/12/29	-804.258	10193.15	10997.41	yes
2014/6/30	-10552.1	15970.15	26522.28	yes	2014/12/30	-2063.58	7096.997	9160.574	yes
2014/7/1	-7557.44	18983.95	26541.39	yes	2014/12/31	-2589.29	8704.794	11294.08	yes
2014/7/2	-7063.16	18532.27	25595.42	yes					

3.4 Applying Charging Strategy into the System Used in the Research

To achieve a zero on-peak demand for customers using battery assisted PV system, there are 3 requirements have to be met:

- Using a proper charging strategy.
- The maximum output limit for the system has to be higher than the maximum load demand.
- The battery size has to be larger than the $D_{min.}$

The highest load demand is 8.07 kW (shown in figure 3.1), however, the highest output for the system used in this research is 6.8 kW, shown in table 3.6. This means if the load is higher than 6800W, then the grid power need to supply as a supplemental source. From the statistical analysis shown in table 3.5, the load profile used in the research requires a battery bigger than 28.075 kWh. However, the battery used in this project is only 20 kWh, this means the battery is not big enough to eliminate the peak-demand through the whole year. These are the reasons to have the peak-demand.

Table 3.6 System Output Specification

Model	Conext XW+6848 NA
Continuous Output Power	6,800 W
Surge Rating (Overload for 1 minute)	12,000 W
Surge Rating (Overload for 5 minute)	11,000 W
Surge Rating (Overload for 30 minute)	8,500 W
Surge Current	L-N: 104 A_{rms}(60 s) L-L: 52 A_{rms}(60 s)

Figure 3.7 plots the load profile higher than 6800 W. If those load fall into the on-peak time, than the demand charge is needed. Figure 3.8 shows during a certain day, when 20 kWh battery can only supply the on-peak demand part D and died, the grid has to supply

the on-peak demand part E.

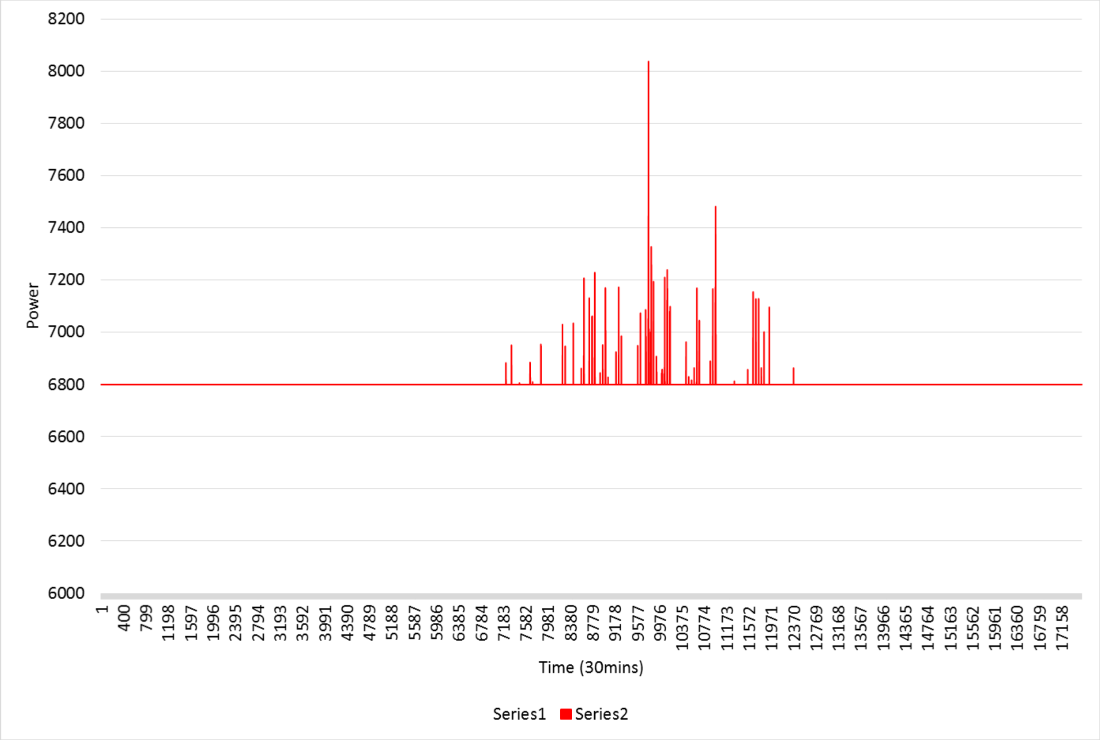


Figure 3.7 Load Profile for the Part Higher than 6800 W

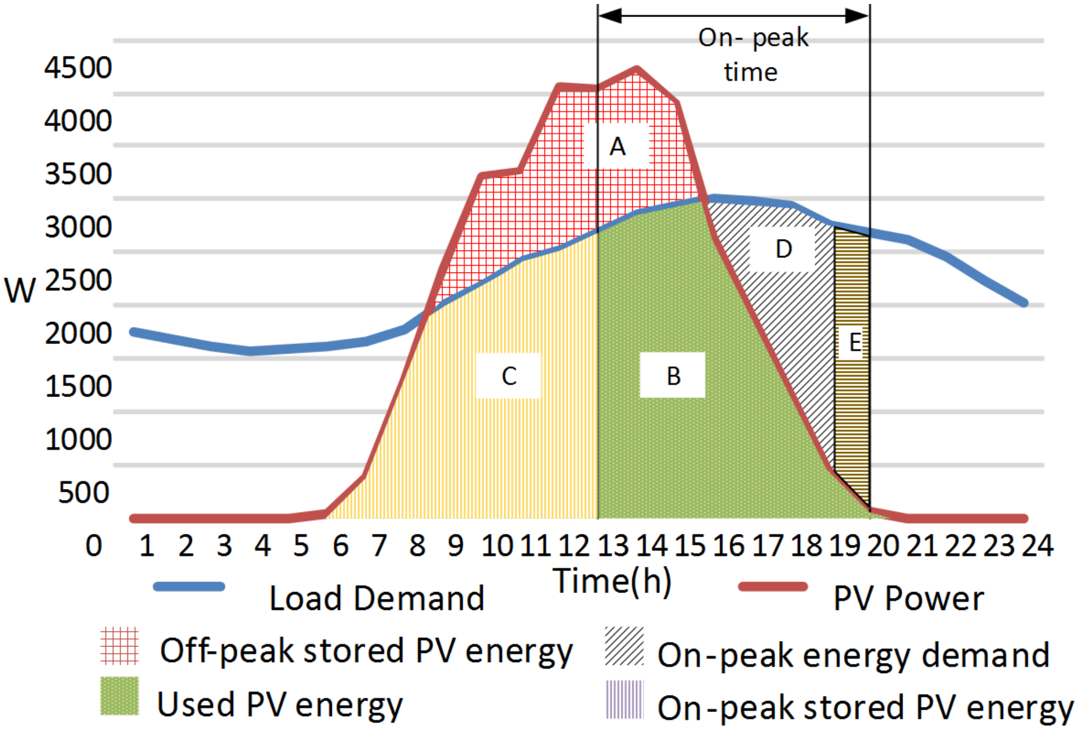


Figure 3.8 Battery Exhausted Before On-peak Time Ends

Combining the two situations shown above, a peak demand diagram throughout the whole year is plotted in figure 3.9. For example, during May.30th 2015, the average load demand from 1:30pm-2:00pm was 7400W, at this time the system's output was 6800W the maximum output limit, then the peak demand during this half hour is 7400W-6800W=600W. At the same day, the average load demand from 7:00pm-7:30pm is 5600W, from 7:30pm-8:00pm is 3800W, and by searching table 3.5, the needed battery size D for that day is found to be 23161.01Wh, which means the grid supplied 23161.01Wh-20000Wh=3161.01Wh during the on peak time. From 7:30pm-8:00pm, the grid supplied 3800W*0.5h=1900Wh, from 7:00pm-7:30pm the grid supplied 3161.01Wh-1900Wh=1261.01Wh, so the peak demand from 7:00pm-7:30pm is $\frac{1261.01Wh}{0.5h} = 2522.02W$, the peak demand from 7:30pm-8:00pm is $\frac{1900Wh}{0.5h} = 3800W$. Each day's peak demand has been calculated in the same way and plotted in figure 3.9. The resolution of the plot is 30 mins because the peak-demand is counted by the average load demand during each half hour. From figure 3.9, it can be seen that the peak demand only occurs during May-Sep which is the summer, for spring, fall and winter the system used in this research can provide a zero on-peak demand.

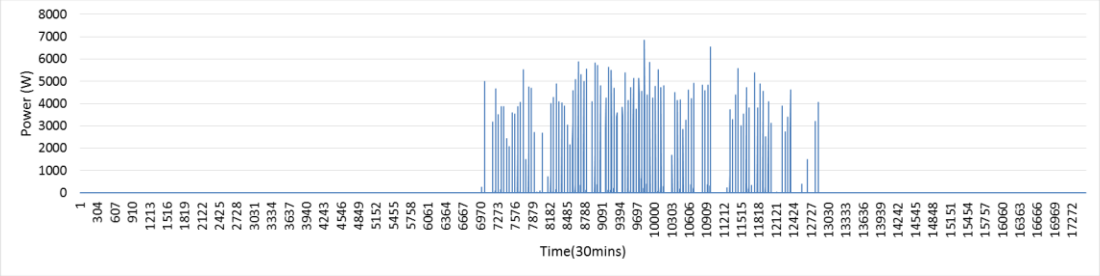


Figure 3.9 Peak Demand Diagram throughout the Year

By knowing the daily peak demand, the electricity bill can be calculated using equations 3.8-3.11, P_{grid} is the power consumption from the grid, m is the mth day, n is the nth month, u is the end of a month. For example, if a certain day's all day energy consumption is $\int_0^{24} P_{demand}(t)dt$=70 kWh, all day PV energy is $\int_0^{24} PV(t)dt$=30 kWh, E_A=7kWh and E_C=5kWh, then the PV energy been fed back to the grid in that day is PV_{waste}=14.504kWh+7kWh+5kWh-20kWh=6.504kWh, $Electricity_{on\text{-}peak}$=6kWh, then that day's off-peak grid energy consumption is $Electricity_{off\text{-}peak}$=70kWh-(30kWh-6.504kW-6kW)=52.504kWh, then that day's electricity bill can be calculated. The peak demand will be charged according to the highest peak during that month. The whole years electricity bill is calculated and the result is shown below in table 3.7. The annual electricity bill is $1283.86.

$$PV_{waste}(m) = CCL + E_A(m) + E_C(m) - 20kWh \tag{3.8}$$

$$Electricity_{on-peak}(m) = \int_{13}^{20} P_{grid}(t)dt \tag{3.9}$$

$$\begin{aligned} &Electricity_{off-peak}(m) \\ &\quad = \int_{(m-1)*24}^{m*24} P_{demand}(t) - PV(t)dt + PV_{waste}(m) \\ &\quad + Electricity_{on-peak}(m) \end{aligned} \tag{3.10}$$

$$\text{Bill(n)} = \sum_{1}^{u} (Electricity_{off-peak}(m) * Price_{off-peak}(n)$$
$$+ Electricity_{on-peak}(m) * Price_{on-peak}(n)) \quad 3.11$$
$$+ Peak_{charge}(n)$$

Table 3.7 Electricity Bill for the System with 6 kW PV and 20 kWh Battery

Month	Electricity From the Grid (kWh) On Peak/Off Peak	Electricity Charge ($)	Peak Demand (kW)/Peak Charge ($)	Service ($)	Monthly Bill ($)
Jan	0/833.24	32.50	0/0	32.44	64.94
Feb	0/556.19	21.69	0/0	32.44	54.13
Mar	0/672.22	26.22	0/0	32.44	58.66
Apr	0/707.42	26.25	0/0	32.44	58.69
May	21.46/1098.39	41.79	5/53.53	30.94	126.26
Jun	192.03/1499.77	64.97	6/67.98	30.94	163.89
Jul	296.19/1731.69	91.99	7/100.05	30.94	222.99
Aug	186.38/1583.29	78.77	7/100.05	30.94	209.76
Sep	111.55/1431.83	58.54	6/67.98	30.94	157.46
Oct	0/960.68	26.21	0/0	30.94	57.15
Nov	0/675.08	18.80	0/0	32.44	51.24
Dec	0/871.15	26.25	0/0	32.44	58.69
Total	807.62/12620.95	513.99	31/389.59	380.28	1283.86

3.5 Electricity Bill Calculation When Peak Is Eliminated

The charging strategy requires the battery size to be larger than 28.075 kWh and the maximum output limit of the system to be higher than the maximum load 8.07 kW. So assuming for the same load profile, a 30 kWh battery and an inverter with the maximum output higher than 8.07 kW is used in the research. Than there will be no on-peak demand and the electricity bill can be calculated using equation 3.12-3.14.

$$PV_{waste}(m) = CCL + E_A(m) + E_C(m) - Battery\_Capacity \tag{3.12}$$

$$Electricity_{off-peak}(m) = \int_{(m-1)*24}^{m*24} P_{demand}(t) - PV(t)dt + PV_{waste}(m) \tag{3.13}$$

$$\text{Bill(n)} = \sum_{1}^{u} Electricity_{off-peak}(m) * Price_{off-peak}(n) \tag{3.14}$$

Table 3.6 Electricity Bill for Each Month under New Charging Strategy

Month	Electricity From the Grid (kWh) On Peak/Off Peak	Electricity Bill ($)	Service ($)	Monthly Bill ($)
Jan	0/622.844	24.29	32.44	56.73
Feb	0/297.696	11.61	32.44	44.05
Mar	0/378.442	14.76	32.44	47.20
Apr	0/458.680	17.89	32.44	50.33
May	0/844.424	31.33	30.94	62.27
Jun	0/1365.852	50.67	30.94	81.61
Jul	0/1715.46	72.56	30.94	103.50
Aug	0/1433.374	60.63	30.94	91.57
Sep	0/1233.479	45.76	30.94	76.70
Oct	0/706.458	26.21	30.94	57.15
Nov	0/482.11	18.80	32.44	51.24
Dec	0/673.158	26.25	32.44	58.69

Total	0/10211.98	400.77	380.28	781.05

So when the peak demand is eliminated, the annual electricity bill will be $781.05 which is 39.16% lower compare to the bill given by the 6kW PV and 20kWh battery.

Figure 3.10 shows the electricity and bill comparison between the four scenarios, scenario A: using basic plan without PV system, scenario B: using E-27 plan with 6 kW PV without battery, scenario C: using E-27 plan with 6 kW PV with 20 kWh battery, scenario D: using E-27 plan with 6 kW battery and 30 kWh battery.

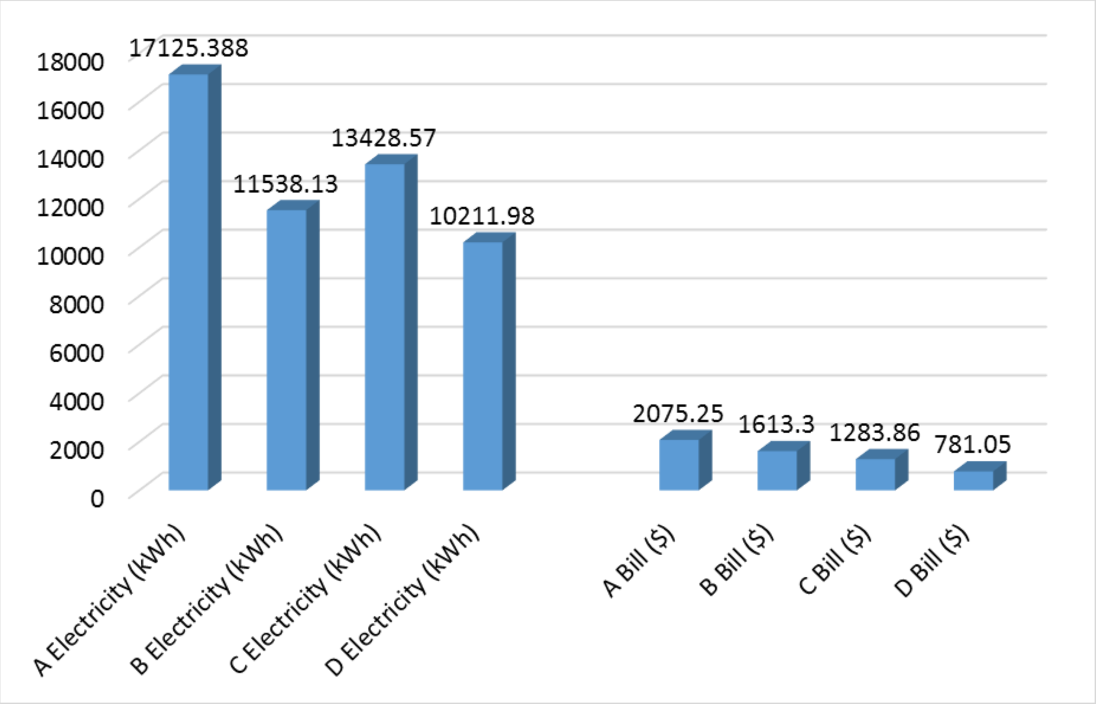


Figure 3.10. Electricity Consumption and Bill Comparison

For electricity consumption, scenario D is the lowest, because the E_A is stored into the battery and used later, and for scenario B the E_A is not been used. But scenario C's electricity consumption is higher than scenario B even a battery is used, that is because the battery pre-charging level is CCL=14.504 kWh, and the battery size is only 20 kWh, so only 5.496 kWh solar energy is stored, the amount of solar energy E_A+E_C-5.496kWh will not be used by the customer, and its usually higher than E_A.

Even the electricity consumption of scenario C is higher than scenario B, but it's bill is lower, this is because the peak demand is too high for B. Scenario D's bill is the lowest, only $781.05/yr, which is only 37.63% of A, 48.41% of B and 60.84% of C.

CHAPTER 4

ECONOMIC BENEFITS ANAYSIS AND COMPARISON BETWEEN THE REGULAR PV SYSTEM AND BATTERY ASSISTED PV SYSTEM

Because higher savings in the electricity bill can be seen by the PV customers who use battery storage, plus the PV, battery, and installation prices are declining year by year, more and more people will begin to consider this hybrid energy solution. However, the huge cost of a battery system is the biggest obstacle which stops customers to invest it. The best way to convince those potential investors to pay for the battery system is to show them how profitable the battery system can be. Pay for a battery system is like to do an investment, the cost of the whole system is the initial investment, the savings on the electricity bill is the income of this investment, and the life span of the battery system is the investment period.

4.1 Financial Model Introduction

Buying a battery system is an investment, to judge if this business is good or not, it is necessary to answer those questions: how much the battery system can save for customers, and what is the best time to do the investment. In order to answer those questions, a classic economics concept: the Net Present Value of cash flow (NPV) was introduced into this financial analysis. NPV is a calculation that compares the amount invested today to the present value of the future cash receipts from the investment [26]. A positive net present value indicates that the projected earnings generated by a project or investment (in present dollars) exceeds the anticipated costs (also in present dollars). Generally, an investment with a positive NPV will be a profitable one and one with a negative NPV will result in a net loss. This concept is the basis for the Net Present Value Rule, which dictates that the only investments that should be made are those with positive NPV values. ROI refers to the return on investment. Equations 4.1-4.4 are the mathematical models of NPV analysis of battery assisted PV system.

$$\text{Initial\_cost} = C_{\text{PV}} + C_{\text{battery}} + C_{\text{electronics}} + C_{\text{installation}} \tag{4.1}$$

$$\text{Real\_interest} = \frac{1+\text{discount\_rate}}{1+\text{inflation}} - 1 \tag{4.2}$$

$$\text{NPV} = \sum_{1}^{20} \frac{\text{Energy\_Saving}_{i} - \text{O \& M}_{i}}{(1+\text{real\_interest})^{i}} - \text{initial\_cost} \tag{4.3}$$

$$ROI = \frac{NPV}{Initial\_cost} \tag{4.4}$$

Where, C_{PV} is the cost of PV panels, $C_{battery}$ is the cost of battery, $C_{electronics}$ is the cost of electronics and $C_{installation}$ is the cost of the system installation. Here are some important data used in the calculation. For the real discount rate [27], an inflation rate of 2.25% [28] released by Bureau of Labor Statistics was considered. The yearly average discount rate of 0.75% [29] released by Federal Reserve Bank was applied. The electronics price has a 3.08% [30] decreasing rate, this data is released by Bureau of Labor Statistics, U.S. Department of Labor. The annual operations and maintenance (O&M) charge for PV system, 2016-2020 PV module price trend and 2016-2020 PV installation cost [30] are released by National Renewable Energy Laboratory (NREL), those data are plotted in figure 4.1

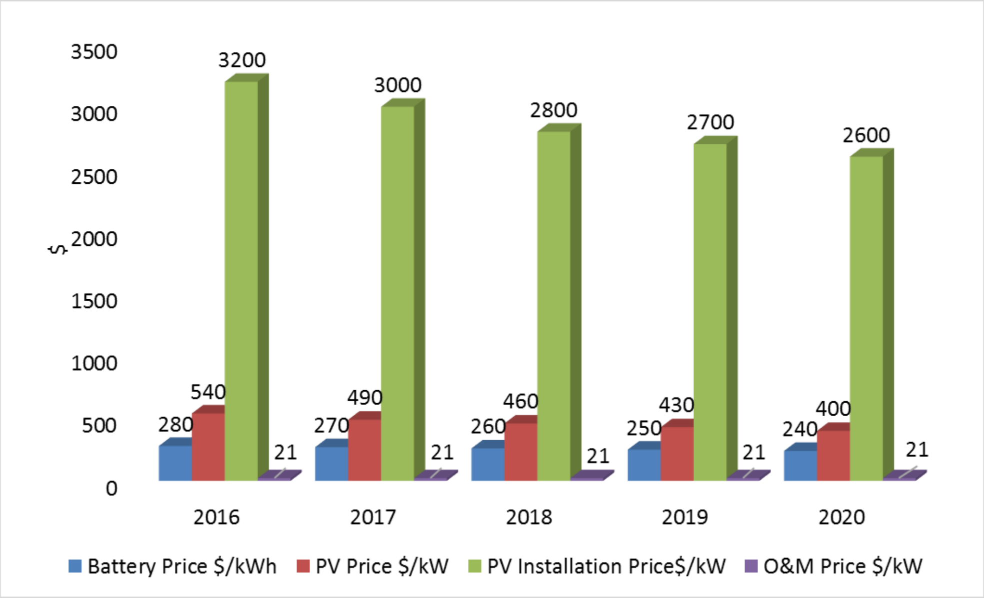


Figure 4.1 Price Trends for PV, Battery, Installation and O&M

4.2 NPV Comparison between Battery Assisted PV System and PV

By using this financing model, a 20 years NPV analysis comparison was done for the simulated house under scenarios B, C and D, However, one thing need to be addressed is most inverter manufacturer will not provide warranty for more than 10 years. In this financial analysis, the annual gaining is the savings on yearly electricity bill compare to scenario A.

Here are the data used in the analysis: the price of the string inverter used in this project is $2550/unit [33]: Schneider XW4548-120/240-60, a string inverter which has a output limit of 8.5 kW is $2300/unit [34]: ABB TRIO 8.5-TL-OUTD (S) is considered for scenario D, the charge controller is \$500/unit [34]: Schneider XW-MPPT60-150.

For scenario C, since the smart home model in this research is invested in 2016, then the $C_{battery}$= \$280/kWh * 20kWh = \$5600, C_{PV} = \$0.54/W*6 kW = \$3240, $C_{installation}$ = \$3.20/W*6kW = \$19200 and $C_{electronics}$= \$2550/unit+\$500=\$3050. Then, the Initial_cost = \$31090. The Real_discount_rate $= \frac{1+0.75\%}{1+2.25\%} - 1 = -1.47\%$, Energy_saving$_i$ = (2075.25 – 1283.86)*$(1 + 0.03)^i$, \$2075.25 is the annual electricity bill under basic plan, \$1283.86 is the annual electricity bill for scenario C, 0.03 is the electricity price yearly escalation rate [32]. For 20 years lifespan, the system's overall economic benefits NPV can be calculated using equation 4.3, the Payback Period (PBP) can be found by solving the i when NPV = 0, because NPV=0 means the present value of the future cash receipts from the investment is equal to amount of the investment. The same calculations were done on scenario B and scenario D. Table 4.1 shows the NPV comparison for this three scenarios.

Table 4.1 NPV Comparison between Scenarios B, C and D

	Scenario B	Scenario C	Scenario D
Investment Year	2016		
Initial Cost	\$26540	\$31090	\$33640
20 Year NPV	\$-12905.58	\$-7663.66	\$5681.80
Return On Investment	-47.6%	-24.65%	16.89%
Payback Period	>20	>20	17 Year

The result shows that, compare to scenario C and scenario D, scenario B's 20 year's NPV is the lowest, although scenario B's initial cost is only 85.37% and 78.89% of scenario

C and D. However, since scenario C has 6 kW PV, 20kWh battery and a smaller inverter, so it 20 year's NPV is negative. Scenario D has a positive NPV and the return on investment is 16.89%. This result clearly indicates the importance and the necessity of a battery storage for PV system.

4.3 Economic Analysis for PV System without Battery

The comparison shown in part 4.2 shows scenario B has a negative NPV which means it will make the customer have a financial loss. However, as time passes, the price of PV panel, installation is declining, so there is still a question to be answered, will the PV customer who do not have battery storage have a positive NPV in the future? So a financial analysis is done using the same load profile and rate plan E-27, the PV size ranges from 1kW-10kW, the investment year ranges from 2016-2020. The result is shown in table 4.2.

Table 4.2 NPV Analysis of 1-10 kW PV without Battery

kW	2016	2017	2018	2019	2020
1	$1832.64	$2626.49	$3411.42	$4108.60	$4819.27
2	$-522.86	$598.76	$1695.19	$2607.80	$3537.99
3	$-2857.94	$-1407.64	$1.25	$1130.30	$2281.08
4	$-5989.75	$-4246.89	$-2563.28	$-1257.27	$72.83
5	$-9381.21	$-7357.57	$-5411.55	$-3941.43	$-2445.45
6	$-12905.58	$-10691.84	$-8493.55	$-6869.93	$-5219.14
7	$-16245.42	$-13663.88	$-11196.90	$-9402.60	$-7579.06
8	$-18999.43	$-16108.21	$-13348.601	$-11358.63	$-9336.20
9	$-22201.01	$-19020.39	$-15989.38	$-13825.89	$-11627.75

10	$-25483.218	$-22016.850	$-18718.26	$-16385.25	$-14015.57

The results indicates that there will be positive NPV only when the PV capacity is lower than 4 kW. This is because the PV installation cost is highest part for a PV system, small PV panel's installation cost is low. However according to the NERL's data [30], the US average residential roof PV installation is 5.2 kW. Apparently, most residential PV customers will encounter a financial loss under this rate plan without using battery storage.

4.4 NPV Analysis for Battery Assisted PV System & Battery Size Optimization

The scenario D can produce a positive NPV and the return on investment is 16.89%, but this return rate can be higher if an optimal battery size is used. This part will demonstrate how to find the optimal battery size for PV system.

According to the charging strategy introduced in Chapter 3, the Critical Charging Level is varying based on the PV size and the load profile. Thus, for the same load profile, if the PV size is changed then the CCL will also change, the CCL is directly related to the minimum battery size (D_{min}) and the energy consumption from the grid. The battery size can be larger to decrease the wasting of solar energy or less to decrease the initial cost. In one word, each PV size and battery size combination will produce different economic benefits to the PV customer. In order to find out the optimal combination for the load profile provided by SRP, a computer code was made in Matlab, shown in APPENDIX D, figure 4.3 explains the logic of this code.

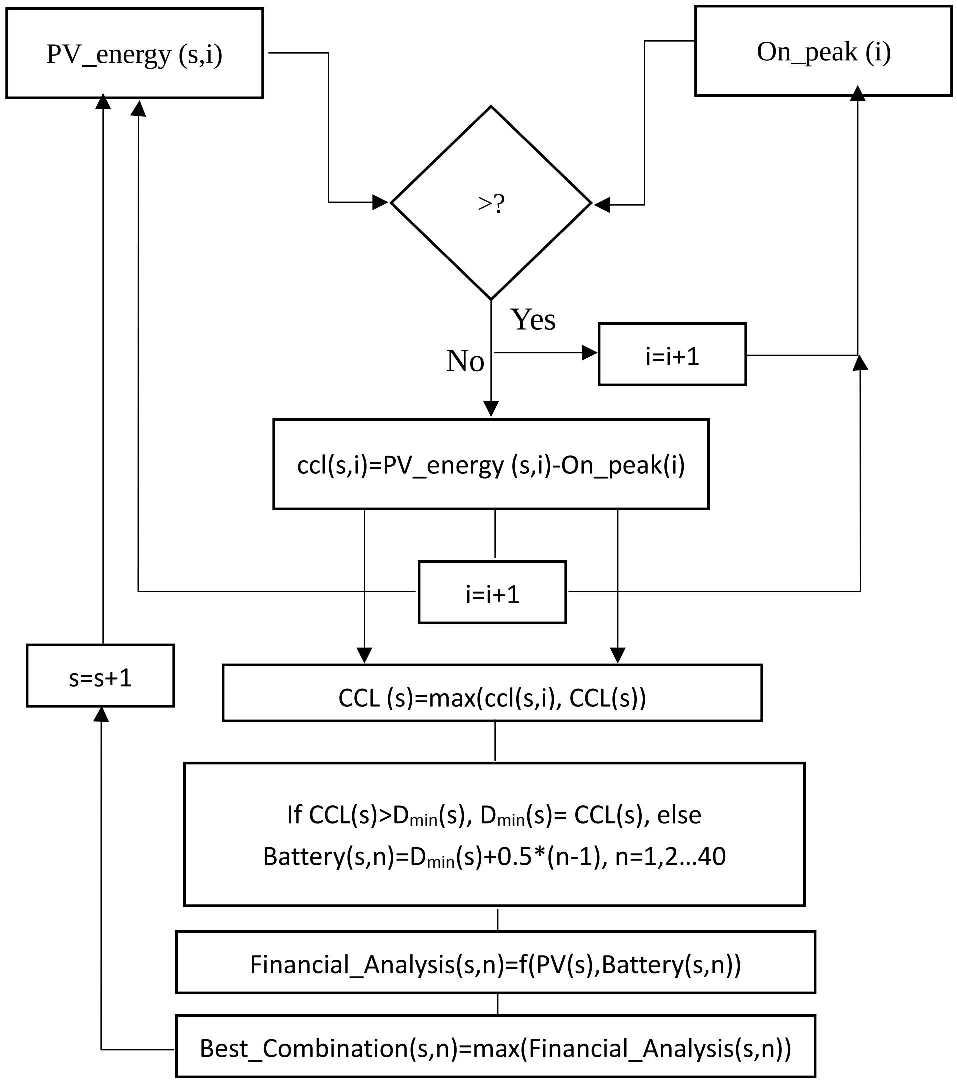


Figure 4.2 Code Logic Diagram

It considers the PV size from 1 kW- 10 kW with a step of 1 kW, under each PV size a CCL will be decided and the battery size is considered to range from D_{min} to D_{min} +19.5 kWh with step of 0.5 kWh. Financial analysis will be done on each PV and battery combinations, the best PV and Battery combination will be found at the highest return on investment. For example, with 6 kW PV the CCL is found to be 14.50 kWh and the minimum battery size is 28.075 kWh. Then, the program will do 32 times financial analysis with battery size from 28.075kWh to 44.075kWh with step of 0.5kWh, so there will be 32 financial results for those battery settings, the results including NPV value and return on investment (ROI), figure 4.3 shows the result of this analysis. The highest NPV for 6 kW PV is the battery size of D_{min}+6.5kWh=34.575kWh, the NPV is $5800 and the ROI is 16.61%. However, the highest return on investment is the battery size of D_{min}+3kWh=31.075kWh, the NPV is $5736 and the ROI is 16.90%.

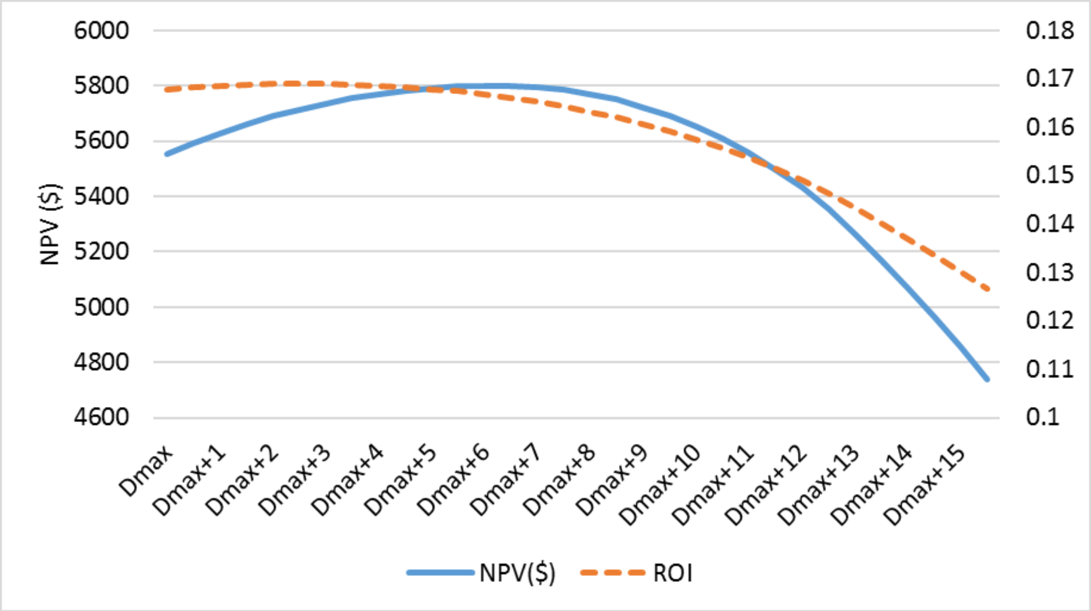


Figure 4.3 20 Years NPV and ROI for 6 kW PV with Different Battery Size

4.5 Universal Battery Optimization Model

Part 4.4 explained the battery optimization for a 6 kW PV system and the investment is done in 2016. In this part a universal model that can do battery optimization for different PV size and different investment period is built. So a battery optimization is done for PV size from 1kW-10kW and the 20 years NPV analysis for each PV and battery combination is done with investing year range from 2016-2020. In this calculation, the PV power is proportional to the PV size and the load profile is the same one used in this research. The calculation logic is in APPENDIX D. Figure 4.4 shows 20 year (from 2016) NPV for different PV sizes when battery capacity increasing from D_{min} to D_{min}+19.5 kWh with a step of 0.5 kWh. The ROI and the 20 years NPV for each battery and PV combination list in table 4.4 and table 4.5.

Table 4.4 Highest NPV for Each PV and Battery Combinations 2016-2020

PV(kW)		1	2	3	4	5	6	7	8	9	10
2016	Battery Size (kWh)	34.725	33.395	32.565	33.235	33.405	34.075	35.120	35.927	39.234	42.040
	NPV($)	18893	16751	14091	11352	8587	5800	2889	-230	-3567	-6951
	PBP	11 yr	12 yr	14 yr	15 yr	17 yr	18 yr	19 yr	20 yr	20 yr	20 yr
2017	Battery Size (kWh)	34.725	33.395	33.065	33.735	34.405	35.575	36.120	38.427	41.234	44.040
	NPV($)	21186	19350	16994	14578	12136	9674	7090	4305	1311	-1728
	PBP	10 yr	12 yr	13 yr	14 yr	15 yr	16 yr	17 yr	18 yr	19 yr	20 yr
2018	Battery Size (kWh)	34.725	33.395	33.565	34.735	35.405	37.575	37.620	39.927	43.234	46.040
	NPV($)	23528	21984	19925	17820	15691	13539	11270	8807	6143	3435
	PBP	9 yr	11 yr	12 yr	13 yr	14 yr	15 yr	16 yr	17 yr	18 yr	19 yr
2019	Battery Size (kWh)	34.725	33.395	34.065	35.235	36.405	37.075	38.620	40.927	44.234	46.540
	NPV($)	25845	24495	22647	20759	18846	16914	14869	12637	10212	7736
	PBP	9 yr	10 yr	11 yr	12 yr	13 yr	14 yr	15 yr	16 yr	17 yr	18 yr
2020	Battery Size (kWh)	34.725	33.395	34.065	35.235	36.405	37.075	38.620	40.927	44.234	46.540
	NPV($)	27545	26419	24776	23092	21381	19650	17802	15759	13516	1.1219
	PBP	8 yr	10 yr	11 yr	12 yr	13 yr	13 yr	14 yr	15 yr	16 yr	17 yr

Table 4.5 Highest ROI for Each PV and Battery Combinations 2016-2020

PV(kW)		1	2	3	4	5	6	7	8	9	10
2016	Battery (kWh)	34.725	33.395	32.065	30.735	29.405	30.075	33.120	36.427	41.234	40.040
	ROI	1.1617	0.8533	0.6125	0.4286	0.2842	0.1690	0.0748	-0.0054	-0.0747	-0.1325
	PBP	11 yr	12 yr	14 yr	15 yr	17 yr	18 yr	19 yr	20 yr	20 yr	20 yr
2017	Battery (kWh)	34.725	33.395	32.065	30.735	29.405	30.075	34.620	36.427	41.234	40.040
	ROI	1.3598	1.0342	0.7770	0.5791	0.4229	0.2974	0.1939	0.1056	0.0291	-0.0348
	PBP	10 yr	12 yr	13 yr	14 yr	15 yr	16 yr	17 yr	18 yr	19 yr	20 yr
2018	Battery (kWh)	34.725	33.395	32.065	30.735	29.405	29.575	31.620	35.427	39.734	43.540
	ROI	1.5771	1.2328	0.9577	0.7447	0.5758	0.4391	0.3256	0.2282	0.1437	0.0731
	PBP	9 yr	11 yr	12 yr	13 yr	14 yr	15 yr	16 yr	17 yr	18 yr	19 yr
2019	Battery (kWh)	34.725	33.395	32.065	30.735	29.405	29.075	31.620	35.427	39.734	44.040
	ROI	1.7997	1.4276	1.1300	0.8993	0.7163	0.5681	0.4450	0.3392	0.2474	0.1708
	PBP	9 yr	10 yr	11 yr	12 yr	13 yr	14 yr	15 yr	16 yr	17 yr	18 yr
2020	Battery (kWh)	34.725	33.395	32.065	30.735	29.405	28.075	30.020	33.427	37.734	42.540
	ROI	1.8997	1.5402	1.2455	1.0139	0.8283	0.6763	0.5464	0.4339	0.3356	0.2538
	PBP	8 yr	10 yr	11 yr	12 yr	13 yr	13 yr	14 yr	15 yr	16 yr	17 yr

Here is the explanation for the results in table 4.4, for the same load profile used in this research, if a 7 kW PV panels are installed in 2018, then the battery size with the highest 20-year NPV is 37.620 kWh, the 20-year NPV is $11270. However, the battery size of 31.620 kWh can produce the highest ROI, which is 32.56%. So the results shown in table 4.4 and table 4.5 can be a reference for the customer to decide what size of PV and battery they need and when to do the investment.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 General Conclusion

Driven by the increasing desire for green energy, the rising electricity price and the reducing cost of the semiconductor manufacturing due to the improved technology, the solar market is continuously expanding. However, because of the time distribution characters of solar energy, large penetration of solar system creates a very low load factor, which leads to a financial loss to utility companies. In order to let PV customers share the cost, a special price plan is designed for them, this plan usually contains energy charge, demand charge and service charge. The demand charge is charged by per kW during the on peak time, and this part is a major part that makes the PV customers electricity bill almost the same as regular customers, as it is analyzed in Chapter 3. To help PV customer reduce their electricity bill and help utility companies reduce their loss, an idea of combining battery storage system with PV system is came up. This thesis presented the work of system testing, battery charging strategy development and financial analysis.

In the first step, the selection of equipment used in this project is present, including the specifications of battery, inverter and charge controller. The design of load bank used to simulate a residential load profile is also explained in detail. The whole system is capable of simulating a residential house, the energy source for this house is from both the grid and the PV panel. The load profiles used in the experiment are provide by SRP.

For the second step, a series of performance tests were completed to verify the system’s ability to continuously provide energy supply to the house. Those tests include PV energy smooth operation test, frequency regulation ability test, AC starting test, battery round trip efficiency analysis. The result of those test shows the system can smooth the intermittent solar energy, handle power surge, start an AC and maintain the battery round trip efficiency at a high level. Those test proofed the feasibility of this setup so further research can be conducted upon this system.

The third part of this research explained the electricity rate structure for PV customer and regular customer. The electricity bills for each customer are calculated and compared, the result shows that the PV customer only saved $461.95 per year, this saving is too less even it’s 20 years gaining cannot compensate the initial cost on the PV system. According to the PV customer’s rate structure, the reason for this contradiction was found, that the demand charge took a large part in their electricity bill, to solve this problem the demand charge has to be eliminated.

Step four of this research introduce how battery assisted PV system can help PV customer eliminate the demand charge and help utility companies on peak shaving. A sophisticated charging strategy for this battery assisted PV system has been developed based on historical data analysis, those data includes one year PV energy data collected from our PV modules and one year 15-mins resolution residential house load data provided by SRP. By applying this charging strategy, the PV customer’s electricity bill has dropped

51.6% compare to the PV customer without battery storage. This charge strategy also created great financial gain to the PV customer, even the initial cost is higher.

In step five, a computer program has been developed to optimize PV customer’s battery size, this battery size will provide customer the most financial gain within the lifespan of the whole system. The result shows a small PV module combine with a big battery storage system will create the most profit and this system’s economic benefits will become larger and larger as time passes due to the reducing cost and the increasing electricity price. This program not only can provide reference to customer who does not have a PV system but also provide reference to PV customer who does not have a battery storage system. This program is suitable to any location and any home once the historical PV data and load data are known.

5.2 Future Work

For the battery round trip efficiency test, the battery used in this research was put in a place which is exposed to the direct sunlight, this will cause the battery temperature go above the rated operation temperature. A more accurate round trip efficiency analysis need to be done by putting the battery in the shed to avoid the direct sunlight.

In this thesis, the charging strategy’s critical charging level is a fixed level, which is based on the yearly biggest difference between PV energy and on-peak load demand. In this case, the whole year’s peak demand is eliminated. However, it requires customer to have a huge battery, but for those customers with small batteries this method cannot work well. Only if the system output can do independent adjustment to achieve the minimum peak demand for the customers, the customer can get the maximum benefits. For example if the battery storage in certain day is 4 kWh and the on peak demand is 5 kWh in total, then the system output power will have a threshold to make sure the 1 kWh grid energy distributes during on-peak hour at the lowest peak value. This adjustment should base on a machine-learning program which can estimated certain day’s on-peak demand based on previous few days’ load. By comparing the battery energy storage in that day with the load estimation, this output limit can be found and automatically apply to the inverter.

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APPENDIX A

ELECTRICITY BILL ANALYSIS UNDER SRP BASIC PLAN

```
clc;
data = find(srp_hourly>(-1), 1, 'last' );
day=data/24;
for m=1:12
    elec(m)=0;
end
for m=1:day
  day_elec(m)=0;
end
for m=1:day
for i=((m-1)*24+1):(m*24)
    day_elec(m)=day_elec(m)+srp_hourly(i);
end
end
for m=1:31
    elec(1)=elec(1)+day_elec(m);
end
for m=32:59
    elec(2)=elec(2)+day_elec(m);
end
for m=60:90
    elec(3)=elec(3)+day_elec(m);
end
for m=91:120
    elec(4)=elec(4)+day_elec(m);
end
for m=121:151
    elec(5)=elec(5)+day_elec(m);
end
for m=152:181
    elec(6)=elec(6)+day_elec(m);
end
for m=182:212
    elec(7)=elec(7)+day_elec(m);
end
for m=213:243
    elec(8)=elec(8)+day_elec(m);
end
for m=244:273
    elec(9)=elec(9)+day_elec(m);
```

```
end
for m=274:304
   elec(10)=elec(10)+day_elec(m);
end
for m=305:334
   elec(11)=elec(11)+day_elec(m);
end
for m=335:365
   elec(12)=elec(12)+day_elec(m);
end
for m=1:12
   if elec(m)<700000
      a(m)=elec(m);   else
      a(m)=700000
   end
   if elec(m)>700000
      b(m)=elec(m)-700000;
   else
      b(m)=0;   end
   if elec(m)>2000000
      c(m)=elec(m)-2000000
   else
      c(m)=0;
   end
end
for m=1:12
   if (m>10) || (m<5)
      elec_bill(m)=0.0803*((a(m)+b(m)+c(m))/1000)+20;
   else
      if (m==7) || (m==8)
         elec_bill(m)=(0.1168*a(m)+0.1180*b(m)+0.1331*c(m))/1000+18.5;
      else
         elec_bill(m)=(a(m)*0.1102+b(m)*0.1121+c(m)*0.1226)/1000+18.5;
      end
   end
end
```

APPENIDX B

ELECTRICITY BILL ANALYSIS WITH 6 kW PV

```
clc;
data = find(srp_hourly>(-1), 1, 'last' );
day=data/24;

for m=1:data
   h_pv(m)=h_pv(m)/6*9;
   if h_pv(m)>srp_hourly(m)
       h_pv(m)=srp_hourly(m);
   else
       h_pv(m)=h_pv(m);
   end
   load_pv(m)=srp_hourly(m)-h_pv(m);
end

for m=1:data
   x=rem(m,24);
  if x > 13 && x <21
       elec_on_peak(m)=load_pv(m);
       elec_off_peak(m)=0;
  else
       elec_on_peak(m)=0;
       elec_off_peak(m)=load_pv(m);
  end

end

for m=1:12
   elec_on(m)=0;
   elec_off(m)=0;
end
for m=1:day
  day_on_elec(m)=0;
  day_off_elec(m)=0;
end


for m=1:day
for i=((m-1)*24+1):(m*24)
   day_on_elec(m)=day_on_elec(m)+elec_on_peak(i);
   day_off_elec(m)=day_off_elec(m)+elec_off_peak(i);
```

```
end
end

for m=1:day
   peak_day=[elec_on_peak((m-1)*24+1) elec_on_peak((m-1)*24+2)
elec_on_peak((m-1)*24+3) elec_on_peak((m-1)*24+4) elec_on_peak((m-
1)*24+5) elec_on_peak((m-1)*24+6) elec_on_peak((m-1)*24+7)
elec_on_peak((m-1)*24+8) elec_on_peak((m-1)*24+9) elec_on_peak((m-
1)*24+10) elec_on_peak((m-1)*24+11) elec_on_peak((m-1)*24+12)
elec_on_peak((m-1)*24+13) elec_on_peak((m-1)*24+14) elec_on_peak((m-
1)*24+15) elec_on_peak((m-1)*24+16) elec_on_peak((m-1)*24+17)
elec_on_peak((m-1)*24+18) elec_on_peak((m-1)*24+19) elec_on_peak((m-
1)*24+20) elec_on_peak((m-1)*24+21) elec_on_peak((m-1)*24+22)
elec_on_peak((m-1)*24+23) elec_on_peak((m-1)*24+24)];
   peak_24(m)=max(peak_day);
end



for m=1:31
   elec_on(1)=elec_on(1)+day_on_elec(m);
   elec_off(1)=elec_off(1)+day_off_elec(m);
end

for m=32:59
   elec_on(2)=elec_on(2)+day_on_elec(m);
   elec_off(2)=elec_off(2)+day_off_elec(m);
end
for m=60:90
   elec_on(3)=elec_on(3)+day_on_elec(m);
   elec_off(3)=elec_off(3)+day_off_elec(m);
end
for m=91:120
   elec_on(4)=elec_on(4)+day_on_elec(m);
   elec_off(4)=elec_off(4)+day_off_elec(m);
end
for m=121:151
   elec_on(5)=elec_on(5)+day_on_elec(m);
   elec_off(5)=elec_off(5)+day_off_elec(m);
end
```

```
for m=152:181
    elec_on(6)=elec_on(6)+day_on_elec(m);
    elec_off(6)=elec_off(6)+day_off_elec(m);
end
for m=182:212
    elec_on(7)=elec_on(7)+day_on_elec(m);
    elec_off(7)=elec_off(7)+day_off_elec(m);
end
for m=213:243
    elec_on(8)=elec_on(8)+day_on_elec(m);
    elec_off(8)=elec_off(8)+day_off_elec(m);
end
for m=244:273
    elec_on(9)=elec_on(9)+day_on_elec(m);
    elec_off(9)=elec_off(9)+day_off_elec(m);
end
for m=274:304
    elec_on(10)=elec_on(10)+day_on_elec(m);
    elec_off(10)=elec_off(10)+day_off_elec(m);
end
for m=305:334
    elec_on(11)=elec_on(11)+day_on_elec(m);
    elec_off(11)=elec_off(11)+day_off_elec(m);
end
for m=335:365
    elec_on(12)=elec_on(12)+day_on_elec(m);
    elec_off(12)=elec_off(12)+day_off_elec(m);
end

peak=[peak_24(1) peak_24(2) peak_24(3) peak_24(4) peak_24(5) peak_24(6)
peak_24(7) peak_24(8) peak_24(9) peak_24(10) peak_24(11) peak_24(12)
peak_24(13) peak_24(14) peak_24(15) peak_24(16) peak_24(17) peak_24(18)
peak_24(19) peak_24(20) peak_24(21) peak_24(22) peak_24(23) peak_24(24)
peak_24(25) peak_24(26) peak_24(27) peak_24(28) peak_24(29) peak_24(30)
peak_24(31); peak_24(32) peak_24(33) peak_24(34) peak_24(35)
peak_24(36) peak_24(37) peak_24(38) peak_24(39) peak_24(40) peak_24(41)
peak_24(42) peak_24(43) peak_24(44) peak_24(45) peak_24(46) peak_24(47)
peak_24(48) peak_24(49) peak_24(50) peak_24(51) peak_24(52) peak_24(53)
peak_24(54) peak_24(55) peak_24(56) peak_24(57) peak_24(58) peak_24(59)
0 0 0;peak_24(60) peak_24(61) peak_24(62) peak_24(63) peak_24(64)
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peak_24(65) peak_24(66) peak_24(67) peak_24(68) peak_24(69) peak_24(70)
peak_24(71) peak_24(72) peak_24(73) peak_24(74) peak_24(75) peak_24(76)
peak_24(77) peak_24(78) peak_24(79) peak_24(80) peak_24(81) peak_24(82)
peak_24(83) peak_24(84) peak_24(85) peak_24(86) peak_24(87) peak_24(88)
peak_24(89) peak_24(90);peak_24(91) peak_24(92) peak_24(93) peak_24(94)
peak_24(95) peak_24(96) peak_24(97) peak_24(98) peak_24(99)
peak_24(100) peak_24(101) peak_24(102) peak_24(103) peak_24(104)
peak_24(105) peak_24(106) peak_24(107) peak_24(108) peak_24(109)
peak_24(110) peak_24(111) peak_24(112) peak_24(113) peak_24(114)
peak_24(115) peak_24(116) peak_24(117) peak_24(118) peak_24(119)
peak_24(120) 0; peak_24(121) peak_24(122) peak_24(123) peak_24(124)
peak_24(125) peak_24(126) peak_24(127) peak_24(128) peak_24(129)
peak_24(130) peak_24(131) peak_24(132) peak_24(133) peak_24(134)
peak_24(135) peak_24(136) peak_24(137) peak_24(138) peak_24(139)
peak_24(140) peak_24(141) peak_24(142) peak_24(143) peak_24(144)
peak_24(145) peak_24(146) peak_24(147) peak_24(148) peak_24(149)
peak_24(150) peak_24(151);peak_24(152) peak_24(153) peak_24(154)
peak_24(155) peak_24(156) peak_24(157) peak_24(158) peak_24(159)
peak_24(160) peak_24(161) peak_24(162) peak_24(163) peak_24(164)
peak_24(165) peak_24(166) peak_24(167) peak_24(168) peak_24(169)
peak_24(170) peak_24(171) peak_24(172) peak_24(173) peak_24(174)
peak_24(175) peak_24(176) peak_24(177) peak_24(178) peak_24(179)
peak_24(180) peak_24(181) 0; peak_24(182) peak_24(183) peak_24(184)
peak_24(185) peak_24(186) peak_24(187) peak_24(188) peak_24(189)
peak_24(190) peak_24(191) peak_24(192) peak_24(193) peak_24(194)
peak_24(195) peak_24(196) peak_24(197) peak_24(198) peak_24(199)
peak_24(200) peak_24(201) peak_24(202) peak_24(203) peak_24(204)
peak_24(205) peak_24(206) peak_24(207) peak_24(208) peak_24(209)
peak_24(210) peak_24(211) peak_24(212);peak_24(213) peak_24(214)
peak_24(215) peak_24(216) peak_24(217) peak_24(218) peak_24(219)
peak_24(220) peak_24(221) peak_24(222) peak_24(223) peak_24(224)
peak_24(225) peak_24(226) peak_24(227) peak_24(228) peak_24(229)
peak_24(230) peak_24(231) peak_24(232) peak_24(233) peak_24(234)
peak_24(235) peak_24(236) peak_24(237) peak_24(238) peak_24(239)
peak_24(240) peak_24(241) peak_24(242) peak_24(243);peak_24(244)
peak_24(245) peak_24(246) peak_24(247) peak_24(248) peak_24(249)
peak_24(250) peak_24(251) peak_24(252) peak_24(253) peak_24(254)
peak_24(255) peak_24(256) peak_24(257) peak_24(258) peak_24(259)
peak_24(260) peak_24(261) peak_24(262) peak_24(263) peak_24(264)
peak_24(265) peak_24(266) peak_24(267) peak_24(268) peak_24(269)
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peak_24(270) peak_24(271) peak_24(272) peak_24(273) 0;peak_24(274)
peak_24(275) peak_24(276) peak_24(277) peak_24(278) peak_24(279)
peak_24(280) peak_24(281) peak_24(282) peak_24(283) peak_24(284)
peak_24(285) peak_24(286) peak_24(287) peak_24(288) peak_24(289)
peak_24(290) peak_24(291) peak_24(292) peak_24(293) peak_24(294)
peak_24(295) peak_24(296) peak_24(297) peak_24(298) peak_24(299)
peak_24(300) peak_24(301) peak_24(302) peak_24(303)
peak_24(304);peak_24(305) peak_24(306) peak_24(307) peak_24(308)
peak_24(309) peak_24(310) peak_24(311) peak_24(312) peak_24(313)
peak_24(314) peak_24(315) peak_24(316) peak_24(317) peak_24(318)
peak_24(319) peak_24(320) peak_24(321) peak_24(322) peak_24(323)
peak_24(324) peak_24(325) peak_24(326) peak_24(327) peak_24(328)
peak_24(329) peak_24(330) peak_24(331) peak_24(332) peak_24(333)
peak_24(334) 0;peak_24(335) peak_24(336) peak_24(337) peak_24(338)
peak_24(339) peak_24(340) peak_24(341) peak_24(342) peak_24(343)
peak_24(344) peak_24(345) peak_24(346) peak_24(347) peak_24(348)
peak_24(349) peak_24(350) peak_24(351) peak_24(352) peak_24(353)
peak_24(354) peak_24(355) peak_24(356) peak_24(357) peak_24(358)
peak_24(359) peak_24(360) peak_24(361) peak_24(362) peak_24(363)
peak_24(364) peak_24(365)];
AMax = max(peak')';

for i=1:12
    peak_demand(i)=1.5*AMax(i)/1000;
end

for m=1:12

    if (m>10) || (m<5)
        elec_bill(m)=elec_on(m)/1000*0.0430+elec_off(m)/1000*0.0390;
        if peak_demand(m)<=3
          peak_charge(m)=3.55*ceil(peak_demand(m));
        else
            if 3<peak_demand(m)<=10
                peak_charge(m)=(3*3.55+(ceil(peak_demand(m))-3)*5.68);
            end
            if peak_demand(m)>10
                peak_charge(m)=(3.55*3+5.68*7+(ceil(peak_demand(m))-
10)*9.74);
            end
```

```
        end
    else
        if (m==7) || (m==8)
            elec_bill(m)=elec_on(m)/1000*0.0633+elec_off(m)/1000*0.0423;
        if peak_demand(m)<=3
          peak_charge(m)=9.59*ceil(peak_demand(m));
        else
            if 3<peak_demand(m)<=10
                peak_charge(m)=(3*9.59+(ceil(peak_demand(m))-3)*17.82);
            end
            if peak_demand(m)>10
                peak_charge(m)=(9.59*3+17.82*7+(ceil(peak_demand(m))-
10)*34.19);
            end
        end
        else
            elec_bill(m)=elec_on(m)/1000*0.0486+elec_off(m)/1000*0.0371;
        if peak_demand(m)<=3
          peak_charge(m)=8.03*ceil(peak_demand(m));
        else
            if 3<peak_demand(m)<=10
                peak_charge(m)=(3*8.03+(ceil(peak_demand(m))-3)*14.63);
            end
            if peak_demand(m)>10
                peak_charge(m)=(8.03*3+14.63*7+(ceil(peak_demand(m))-
10)*27.77);
            end
        end
        end
    end
end
for i=1:12
    if (i>10) || (i<5)
    total_elec_bill(i)=elec_bill(i)+peak_charge(i)+32.44;
    else
        total_elec_bill(i)=elec_bill(i)+peak_charge(i)+30.94;
    end
end
```

APPENDIX C

ELECTRICITY BILL ANALYSIS WHEN BATTERY ASSISTED PV SYSTEM IS USED

```
clc;
data = find(srp_hourly>(-1), 1, 'last' );
day=data/24;

for i=1:data
    if srp_hourly(i)<=6000;
        SRP(i)=srp_hourly(i);
        power_over_rating(i)=0;
    else
        SRP(i)=6000;
        power_over_rating(i)=SRP_orignal(i)-6000;
    end
end

for m=1:day
    PV(m)=0;
    for i=((m-1)*24+1):(m*24)
    PV(m)=PV(m)+h_pv(i);
    end
end

for m=1:day
    pvsumbeforeonpeak(m)=0;
    for i=((m-1)*24+1):(m*24)
      x=rem(i,24);
      if x > 0 && x <14
      pvsumbeforeonpeak(m)=pvsumbeforeonpeak(m)+h_pv(i);
      else
      pvsumbeforeonpeak(m)=pvsumbeforeonpeak(m)+0;
      end
    end
end

for m=1:day
    for i=((m-1)*24+1):(m*24)
      x=rem(i,24);
      if x > 0 && x <14
          pv_stored(i)=h_pv(i);
      else
          pv_stored(i)=h_pv(i)-SRP(i);
```

```
          if pv_stored(i)>0
             pv_stored(i)=pv_stored(i);
          else
             pv_stored(i)=0;
          end
      end

    end
end

for m=1:day
    battery(m)=0;
    for i=((m-1)*24+1):(m*24)
      battery(m)=battery(m)+pv_stored(i);
    end
end

for m=1:day
    srp_on_peak(m)=0;
    for i=((m-1)*24+1):(m*24)
      x=rem(i,24);
      if x > 13 && x <21
      srp_on_peak(m)=srp_on_peak(m)+SRP(i);
      else
      srp_on_peak(m)=srp_on_peak(m)+0;
      end
    end
    CCL(m)=PV(m)-srp_on_peak(m);

end


ccl=min(CCL')';

for i=1:day
    battery_min(i)=0;
end


for m=1:day
```

```
    for i=((m-1)*24+1):(m*24)
      x=rem(i,24);
      if x > 13 && x <21
          shortage(i)= SRP(i)-h_pv(i);
          if shortage(i)>0
              battery_min(m)=battery_min(m)+shortage(i);
          else
              battery_min(m)=battery_min(m)+0;
          end
      end

    end
end

Battery=max(battery_min')';
for m=1:day
    pv_waste(m)=-ccl+battery(m)-28705;
    if pv_waste(m)>0
        pv_waste(m)=pv_waste(m);
    else
        pv_waste(m)=0;
    end
end

for m=1:day
    dayily_off(m)=0;
    for i=((m-1)*24+1):(m*24)
    dayily_off(m)=dayily_off(m)+SRP(i);
    end
    dayily_off(m)=dayily_off(m)-PV(m)+pv_waste(m);
end

for m=1:12
    elec(m)=0;
end
for m=1:31
    elec(1)=elec(1)+dayily_off(m);
end

for m=32:59
```

```
   elec(2)=elec(2)+dayily_off(m);
end
for m=60:90
   elec(3)=elec(3)+dayily_off(m);
end
for m=91:120
   elec(4)=elec(4)+dayily_off(m);
end
for m=121:151
   elec(5)=elec(5)+dayily_off(m);
end
for m=152:181
   elec(6)=elec(6)+dayily_off(m);
end
for m=182:212
   elec(7)=elec(7)+dayily_off(m);
end
for m=213:243
   elec(8)=elec(8)+dayily_off(m);
end
for m=244:273
   elec(9)=elec(9)+dayily_off(m);
end
for m=274:304
   elec(10)=elec(10)+dayily_off(m);
end
for m=305:334
   elec(11)=elec(11)+dayily_off(m);
end
for m=335:365
   elec(12)=elec(12)+dayily_off(m);
end
 for m=1:12
   if (m>10) || (m<5)
      elec_bill(m)=0.0390*elec(m)/1000;
   else
      if (m==7) || (m==8)
         elec_bill(m)=0.0423*elec(m)/1000;
      else
         elec_bill(m)=0.0371*elec(m)/1000;
```

```
        end
    end
end
annual_bill=0;
for m=1:12
    annual_bill=annual_bill+elec_bill(m);
end
total_bill=annual_bill+380.28;
```

APPENDIX D

BATTERY SIZE OPTIMIZATION AND ECONOMIC ANALYSIS

```
clc;
data = find(srp_hourly>(-1), 1, 'last' );
day=data/24;
pv_waste=zeros(10,40,365);
dayily_off=zeros(10,40,365);
elec=zeros(10,40,12);
elec_bill=zeros(10,40,12);
for s=1:10

for i=1:data
    if srp_hourly(i)<=6000;
        SRP(i)=srp_hourly(i);
        power_over_rating(i)=0;
    else
        SRP(i)=6000;
        power_over_rating(i)=SRP_orignal(i)-6000;
    end
end

for m=1:day
    PV(s,m)=0;
    for i=((m-1)*24+1):(m*24)
    h_pv_m(s,i)=h_pv(i)/6*s;
    PV(s,m)=PV(s,m)+h_pv_m(s,i);
    end
end

for m=1:day
    pvsumbeforeonpeak(s,m)=0;
    for i=((m-1)*24+1):(m*24)
      x=rem(i,24);
      if x > 0 && x <14
      pvsumbeforeonpeak(s,m)=pvsumbeforeonpeak(s,m)+h_pv_m(s,i);
      else
      pvsumbeforeonpeak(s,m)=pvsumbeforeonpeak(s,m)+0;
      end
    end
end

for m=1:day
```

```
   for i=((m-1)*24+1):(m*24)
     x=rem(i,24);
     if x > 0 && x <14
        pv_stored(s,i)=h_pv_m(s,i);
     else
        pv_stored(s,i)=h_pv_m(s,i)-SRP(i);
        if pv_stored(s,i)>0
            pv_stored(s,i)=pv_stored(s,i);
        else
            pv_stored(s,i)=0;
        end
     end

   end
end

for m=1:day
   battery(s,m)=0;
   for i=((m-1)*24+1):(m*24)
     battery(s,m)=battery(s,m)+pv_stored(s,i);
   end
end

for m=1:day
   srp_on_peak(s,m)=0;
   for i=((m-1)*24+1):(m*24)
     x=rem(i,24);
     if x > 13 && x <21
     srp_on_peak(s,m)=srp_on_peak(s,m)+SRP(i);
     else
     srp_on_peak(s,m)=srp_on_peak(s,m)+0;
     end
   end
   CCL(s,m)=PV(s,m)-srp_on_peak(s,m);

end

CCLMin = min(CCL')';
ccl(s)=CCLMin(s);
```

```
for i=1:day
    battery_min(s,i)=0;
end



for m=1:day
    for i=((m-1)*24+1):(m*24)
      x=rem(i,24);
      if x > 13 && x <21
          shortage(s,i)= SRP(i)-h_pv_m(s,i);
          if shortage(s,i)>0
              battery_min(s,m)=battery_min(s,m)+shortage(s,i);
          else
              battery_min(s,m)=battery_min(s,m)+0;
          end
      end

    end
end

Battery=max(battery_min')';

for p=1:40

for m=1:day


    pv_waste(s,p,m)=-ccl(s)+battery(s,m)-(Battery(s)+500*(p-1));
    if pv_waste(s,p,m)>0
        pv_waste(s,p,m)=pv_waste(s,p,m);
    else
        pv_waste(s,p,m)=0;
    end
end

for m=1:day
    for i=((m-1)*24+1):(m*24)
    dayily_off(s,p,m)=dayily_off(s,p,m)+SRP(i);
    end
    dayily_off(s,p,m)=dayily_off(s,p,m)-PV(s,m)+pv_waste(s,p,m);
end
```

```
for m=1:12
   elec(s,p,m)=0;
end

for m=1:31
   elec(s,p,1)=elec(s,p,1)+dayily_off(s,p,m);
end

for m=32:59
   elec(s,p,2)=elec(s,p,2)+dayily_off(s,p,m);
end
for m=60:90
   elec(s,p,3)=elec(s,p,3)+dayily_off(s,p,m);
end
for m=91:120
   elec(s,p,4)=elec(s,p,4)+dayily_off(s,p,m);
end
for m=121:151
   elec(s,p,5)=elec(s,p,5)+dayily_off(s,p,m);
end
for m=152:181
   elec(s,p,6)=elec(s,p,6)+dayily_off(s,p,m);
end
for m=182:212
   elec(s,p,7)=elec(s,p,7)+dayily_off(s,p,m);
end
for m=213:243
   elec(s,p,8)=elec(s,p,8)+dayily_off(s,p,m);
end
for m=244:273
   elec(s,p,9)=elec(s,p,9)+dayily_off(s,p,m);
end
for m=274:304
   elec(s,p,10)=elec(s,p,10)+dayily_off(s,p,m);
end
for m=305:334
   elec(s,p,11)=elec(s,p,11)+dayily_off(s,p,m);
end
for m=335:365
```

```
    elec(s,p,12)=elec(s,p,12)+dayily_off(s,p,m);
end

for m=1:12

    if (m>10) || (m<5)
        elec_bill(s,p,m)=0.0390*elec(s,p,m)/1000;
    else
        if (m==7) || (m==8)
            elec_bill(s,p,m)=0.0423*elec(s,p,m)/1000;
        else
            elec_bill(s,p,m)=0.0371*elec(s,p,m)/1000;
        end
    end
end

annual_bill=0;
for m=1:12
    annual_bill=annual_bill+elec_bill(s,p,m);
end
total_bill(s,p)=annual_bill+380.28;
end

OM=21;
PV_cp(s)=6000/6*s;
discount_rate=0.0075;
inflation=0.0225;
Converter=2550;
controller=500;
real_discount=(1+discount_rate)/(1+inflation)-1;
for i=1:5
PVC(s,i)=PV_cp(s)*PV_price(i);
INSC(s,i)=PV_cp(s)*INS_price(i);
initial_c(s,i)=PVC(s,i)+INSC(s,i)+(Converter+controller)*0.95^i;
end

for k=1:40
for m=1:5
    NPV(s,k,m)=0;
    B_c(s,k,m)=(Battery(s)+(k-1)*500)/1000*B_price(m);
```

```
   initial_cost(s,k,m)=initial_c(s,m)+B_c(s,k,m);
   for i=1:20
       Energy_saving(s,k,i)=(2075.25-total_bill(s,k))*(1+0.03)^(m+i-1);
       npv(s,k,i)=(Energy_saving(s,k,i)-
OM*PV_cp(s)/1000)/((1+real_discount)^(m+i-1));
       NPV(s,k,m)=NPV(s,k,m)+npv(s,k,i);
       if NPV(s,k,m)-initial_cost(s,k,m)<0
          PBP(s,k,m)=i;
       end
   end
    real_NPV(s,k,m)=NPV(s,k,m)-initial_cost(s,k,m);
end
end
end
```