PERFORMANCE COMPARISON OF SELF-CONSUMPTION FOR A PHOTOVOLTAIC SYSTEM WITH BATTERY STORAGE AND LOAD MANAGEMENT

A Thesis
by
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Abstract

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As the energy consumption in the U.S. continuous to rise, there is a need to install more power plants to supply the energy demand. However, installing more fossil fuel power plants is very harmful to the environment. The rapid growth in photovoltaic (PV) system does contribute in reducing the amount of new power plants, but since its performance relies on weather conditions, this system may not be very reliable on its own. The non-dispatchable nature of PV limits the amount of PV on the current grid. In order to improve this system's reliability, it is possible to add energy storage and charge it during off peak demand or when there is excess in energy PV generation. Therefore, whenever there is a peak demand, PV power can be combined with battery power to supply the demand. In addition, load management is another technique that can potentially allow PV to satisfy more loads

In this study, performance of a residential PV system with and without storage was studied in order to compare the improvements in self-consumption, meaning a decrease in grid imports/exports. Two different load management schemes were compared.

Dedication

To my family, for supporting me every single day even from thousands of miles away from me. They have always believed that I can do more and learn more each day.

Acknowledgments

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Thanks to all three members of my thesis committee: Brian Raichle, Jeffrey Ramsdell and Jeffrey Tiller. They all have put in many hours of reading, editing, discussing and problem solving. Dr. Raichle made himself available the majority of the time to help me collect and analyze the data.

A special thank you to my good friend Zach Sprau who installed the PV system at the Solar Lab. Without his help, I would not be able to accomplish my goals.

Thanks to Adara Power for helping commissioning and configuring the energy storage unit.

Thanks to the Nagy family for being my second family here in the United States. They helped me a lot in the transition from Brazil to the U.S. and also made sure that I was always loved from the beginning.

Thanks for all the friends that I have made here in Boone. They made sure that I would never feel lonely or unhappy. Especially when I missed my family the most.

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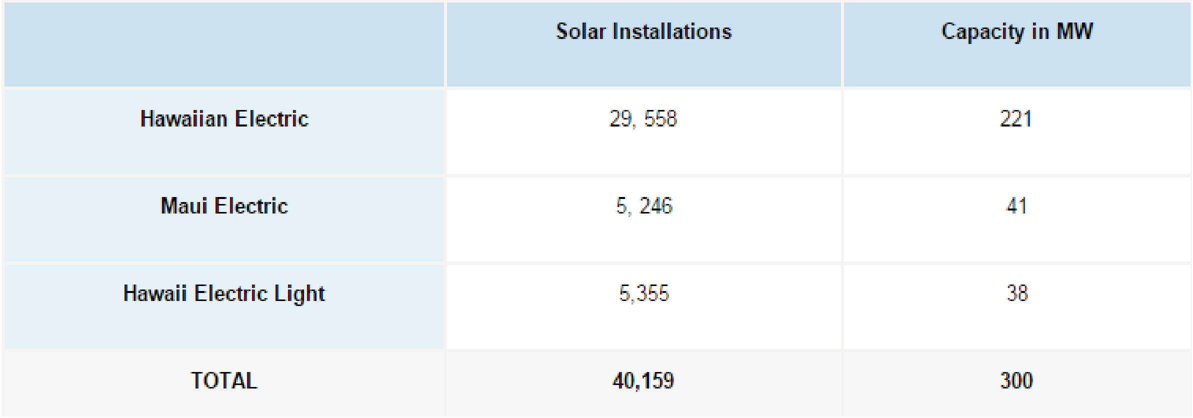
CHAPTER 1: INTRODUCTION

Introduction

With a decrease in the cost investment required, along with federal and state tax incentives (where applicable), photovoltaic (PV) systems have been more economically attractive in the past few years. For example, in 2013, the Hawaiian utility companies Hawaiian Electric, Maui Electric, and Hawai'i Electric Light, had a total of 17,609 solar installations with more than 129 MW of capacity. This represents a 39% increase in PV installations in that state compared to 2012. The total number of PV systems installed in Hawaii by December 31, 2013 was 40,159, with a total capacity of 300 MW, with 96% of those systems taking advantage of net metering, whereby a PV system is connected to and exports excess electricity to the grid (Rosegg, 2014). Table 1 shows the numbers of installations and capacity.

Table 1. *Solar Installations and Capacity by Utility as of December 31, 2013 (Rosegg, 2014)*



	Solar Installations	Capacity in MW
Hawaiian Electric	29, 558	221
Maui Electric	5, 246	41
Hawaii Electric Light	5,355	38
TOTAL	**40,159**	**300**

However, this rapid growth resulted in some neighborhood circuits reaching extremely high levels of PV generation. As a result, these distribution circuits sometimes exceeded 100% of the daytime minimum load, meaning that generation would need to be curtailed and lose revenue. Hence, interconnection studies and possible implementation of safety measures or upgrades has to be done before installing more PV systems (Rosegg, 2014). In addition to approvals for each installation, Hawaiian Electric company, Inc. (HECO) started charging $500 for solar permits (Francescato, 2014).

Although Hawaii, with very high electric rates, currently represents an extreme case, this situation could be repeated in other states across the United States, meaning that further research should be done to address the issues posed by increased numbers of grid-connected PV systems.

Another relevant issue regards the relationship between energy generation and load demand. The demand for electricity has a time varying nature that is influenced by residential and business behavior as well as weather conditions. Traditional generation is dispatchable, meaning that power plants can be turned on and off to meet demand. Figure 1 illustrates a typical daily load curve. The shape of the load profile determines the schedule for the operation of power plants. The lower part of the demand is supplied by power plants with low variable operating costs (costs that vary with changes in output), such as coal and nuclear power plants. Those types of energy generation, called base load, have high investment costs and lower fuel costs. Because it takes many hours to turn these plants on or off, they run throughout the entire year (Kaplan, 2008).

The intermediate part of the graph is supplied by “load-following” units. These units are able to more quickly respond to the load variation by changing their outputs. Combined cycle units can be used for this purpose. These units, called intermediate load plants, usually are efficient but use expensive natural gas or fuel oil as fuel (Kaplan, 2008).

The high peaks in the load profile are supplied with peaking units. These units have a fast startup and shutdown time to meet those brief peaks. However, they usually have the most expensive operating cost and only run for few hundreds of hours a year (Kaplan, 2008).

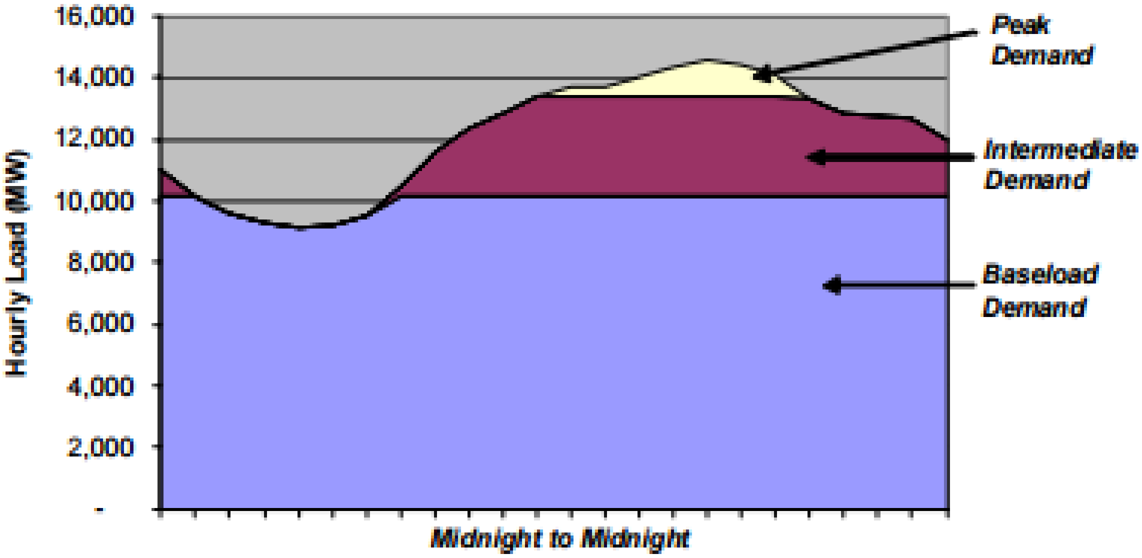


Figure 1. Example of a daily load profile (Kaplan, 2008, p. 3).

As mentioned before, the peak demand only happens during a small period of time in a year, meaning that very expensive power plants designed to supply those peaks will be running sporadically throughout a year. In order to better understand the situation, it is possible to obtain real data in the PJM Interconnection’s website.

The company “PJM Interconnections” is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and District of Columbia” (PJM, 1999-2016). This company provides a large amount of information related to energy generation of a year for the area previously cited. Figure 2 is a graph plotted with the power demand in Gigawatts

(GW) for the year 2013. In order to better visualize the magnitude of the peaks throughout the year, the graph was plotted starting from the highest hourly power to the lowest one. The graph does not show information about the time of peak demand, but highlights the magnitude and occurrence of peaks.

The data for the chart in Figure 2 shows that for the 35 first hours there was a difference of 10 Gigawatts (GW) between the highest power demand to the lowest power demand (within those 35 hours). A typical power rate for a coal power plant is 1 GW. Hence, in less than 2 days, the equivalent of 10 large power plants operating at full power would be needed to supply the demand. It is important to understand that these generating assets would only be on during 35 hours out of 8,760 hours in an entire year, representing a very inefficient and expensive business.

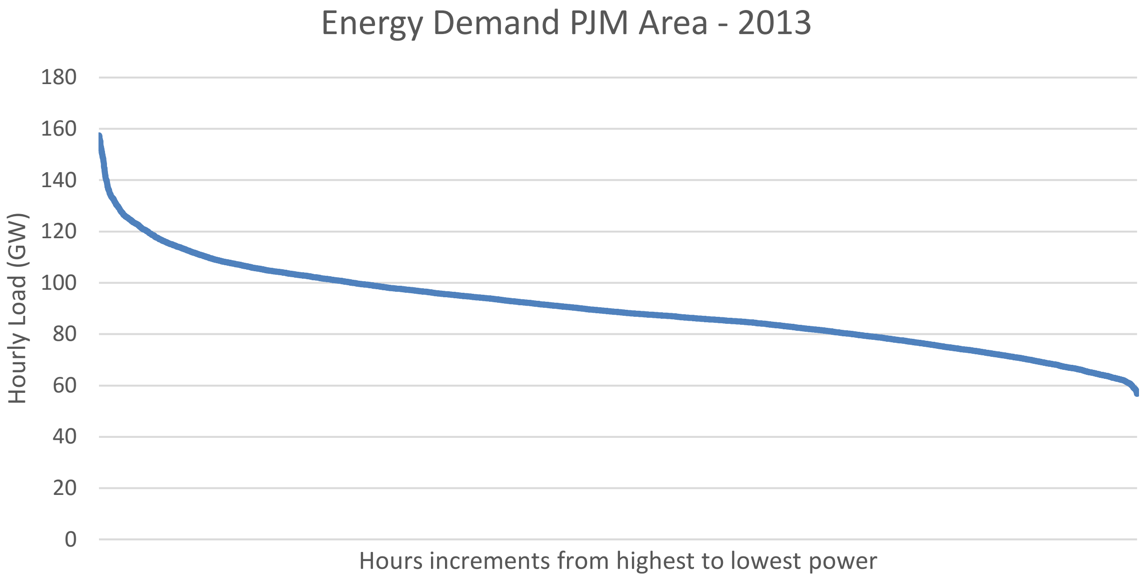


Figure 2. PJM Energy Demand 2013 (PJM, 1999-2016).

Renewable energy systems such as PV are very important for today’s energy generation because it uses non-polluting resources. However, PV is affected by weather conditions, and it may not be very effective during those high peak demands presented on

Figure 2. In the first case, for example, the highest peak demand happens at 5 pm when there will not be as much PV generation as it could have around noon. Therefore, there would still be a need for building new dispatchable power plants to supply power during peak demand or during adverse weather conditions. For the second case, assuming a large amount of PV penetration in the country, a PV system usually has the highest power generation around noon, a time of a day which is off the peak demand for most seasons. Therefore, a high PV generation off the peak demand would require either the PV system or a baseload power plant to be turned off. Ideally, one would not want to turn the PV system off since it uses renewable resources and has a very low variable operating cost. However, not having reliable energy generation can lead to a brownout when the weather suddenly changes its condition and the baseload power plant does not have enough time to ramp up and supply the power demand.

A possible solution for two issues related to reliability of PV – variable rates of solar resource and non-coincidence of solar electrical production and electric utility peak loads - would be to add electrical storage, such as battery banks, to the electrical system. Batteries can instantaneously deliver power when needed and are reliable when properly used. In addition, lithium-ion batteries have been increasing their energy density and decreasing their costs over the years. Battery banks can either be used with or without PV. Without PV, the battery banks can be charged during off peak and discharged during peak demand. With PV, excess energy generated during periods of high solar electric production can charge the batteries and be used to supply the peak demand as needed.

Since 2009, self-consumption systems (where residents seek to meet a maximum amount of their electricity demand via their own PV arrays and on-site battery storage) have become a trend in Europe (European Photovoltaic Industry Association, 2013). This type of system prioritizes energy consumption on site via direct PV use and battery storage over energy exports to the grid. Combining self-consumption with a load management system makes the results even greater.

This study will examine the performance of a self-consumption system with load management by analyzing the energy imported and exported to the grid. The data collection will be done in Boone, North Carolina. More details about the experiment will be further presented in this thesis.

Statement of the Problem

The rapid growth of PV installations can result in some problems for the utility grid if the solar electric products exceeds the voltage or current limits of the distribution or transmission lines, power electronics equipment, etc. Although a grid-tied PV system exports only the excess power to the grid, depending on the amount of PV installed in a neighborhood, extra safety measures and grid upgrades will have to be implemented. A well-designed self-consumption system can decrease considerably the impact on grid, providing benefits for both utility companies and for customers. Although this type of system has become common in Europe, it has not been used within the United States, and questions remain about its applicability in locations across the US.

Purpose of the Study

This research tests a self-consumption system combined with a load management system in the United States in order to verify its applicability and its effectiveness in this geographic location.

The goal of this project is to compare the performance of a self-consumption system located in Boone, North Carolina by using the methods of integrated storage and load management. Data shall be collected for a grid connected PV system with different setups regarding energy storage and load management. This will be carried out under experimental conditions at a solar research facility located on the campus of Appalachian State University.

Research Questions

The research questions for this study are the following:

- To what extent can a PV self-consumption system with battery storage installed in Boone, North Carolina reduce grid imports/exports compared to a PV system without storage?
- How much would load management added to the same PV system with storage contribute to reduce grid imports/exports?
- To what extent do the irradiance levels and profile affect the grid imports/exports?

Limitations of the Study

There are three limitations for this study. The first one is regarding the time for data collection, the second is related to the lack of side-by-side systems and the third is regard to the hourly average loads.

Due to some delays on acquiring the components for the research, the time frame for the data collection was shortened, changing all the plans for each system setup simulated. As there are no side-by-side systems, the comparisons will need to be done under similar, but not identical, meteorological conditions. As the data used to recreate the load profile had a timestamp of 1 hour, there was not a way to simulate any short term demands, which limits the capability of recreating more realistic loads.

Significance of the Study

This study is intended to quantify the performance of a self-consumption system in the United States. This type of system has been in use in Europe since 2009 and it has achieved positive results from both the utility grid and from consumers (European Photovoltaic Industry Association, 2013). The goal is to help further research in self-consumption systems here at Appalachian State University and provide the bases for a financial analysis for the customer side. The findings of this research are intended to help promote further consideration of self-consumption systems across the United States.

CHAPTER 2: REVIEW OF LITERATURE

PV system design varies by topologies, technologies, objectives and economics, as well as municipal and utility policy.

Residential PV System Topologies

Off Grid

Off-grid topology is a PV system that has no connection to the grid. It can be either a PV system that only powers some specific loads or a stand-alone system that would take a residence completely off grid.

If the residence is still connected to the grid but has an off-grid PV system, the system usually powers critical loads such as refrigerator and lights, and has a back-up battery bank in case the grid goes down.

A stand-alone system is more elaborated since the residence is completely off grid. The PV system is sized to exceed the daily loads and also has a battery bank the stores the excess energy generated to supply power during the night or when PV cannot supply the load by itself. In order to make sure that the residence will not have a lack of power, it is very common to combine a generator with the system.

Grid Connected

Traditionally, the grid-connected PV system is simply a PV system that is connected to the grid through an inverter. Depending on the agreement done with the utility, the PV system can supply power to the loads and export the excess in exchange of credits or sell all the power to the grid as will be discussed in the next section.

Currently, battery banks are being introduced to grid-connected PV systems for Time-of-Use (TOU) and peak-shaving purposes. Basically, the batteries would be charged either with PV excess power or by the grid during off peak and discharged during the peak demand since for some regions there is a difference in energy rates during the peak demand. In addition, some utilities include a peak demand charge. By doing that, it also helps to cut the peaks off, meaning that the grid will not be supplying a considerable amount of energy during peak demand.

Self-Consumption

A self-consumption system is a hybrid of both off-grid and grid-connected system that prioritizes self-consumption. In order to do that, PV first supplies the battery bank so it can supply the loads when needed. If PV generation is higher than the power used to charge the batteries, the excess is used to power the loads. Any other excess power is exported to the grid.

The excess power exported is sold at a certain percentage of the retail price, according to the country and its regulations, instead of exchanging it for credits throughout the year. Self-consumption systems have been used in Europe since 2009, and the conditions vary for each country. For instance, in Germany, the remuneration has been higher for consumers who achieve a rate of self-consumption over 30% (EPIA, 2013). The schemes of self-consumption vary depending on the power capacity of the system, as can be seen in Figure 3.

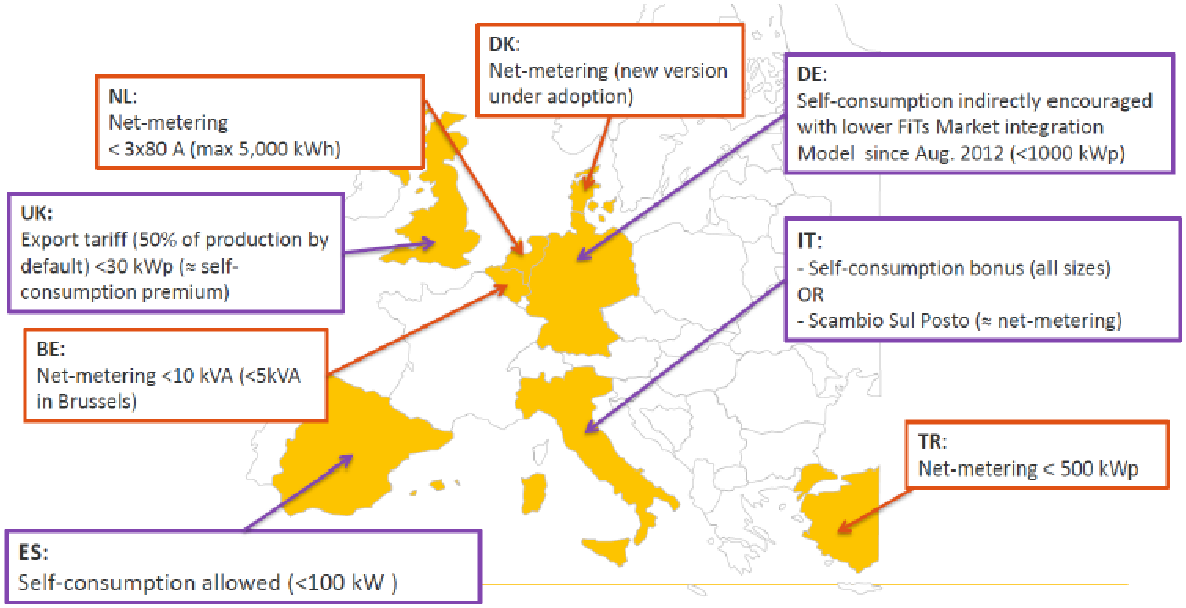


Figure 3. Overview of main net-metering and self-consumption schemes in Europe (EPIA, 2013, p. 4).

Residential Interconnection Agreements

Net Metering

Net Metering is a service that allows a customer to connect their renewable energy systems, such as PV and wind, to the power grid. A bidirectional meter is installed in order to measure the grid import and export so the customer will only pay for the “net” energy consumed. If there was more energy generated than consumed, the customer can qualify for credits, depending on the state or utility company. In effect, the customer is compensated for their energy at the retail rate. The idea behind the Net Metering is to provide the customer a reliable source of energy when the generators (PV panels or wind turbine for instance) are not producing enough energy. By doing that, the grid can be seen as a storage system for the customer.

Buy-All Sell-All

Buy-all sell-all systems allow the customer to connect their renewable energy system to the grid. However, it works differently than the net metering. The energy generated is not used at any moment to supply the owner’s load. All the energy generated is exported to grid and the owner receives a payment based on the energy generated at the agreed upon rate, typically the avoided cost. Some utilities and municipalities offer a premium for renewable generated electricity, such as for North Carolina’s NC GreenPower program and feed-in tariffs, which have been common in Europe. The customer purchases at the retail rate all of their consumed electricity.

Self-Consumption Systems

Since the focus of this project is a self-consumption system, it is important to understand all the aspects and components of this type of system as well as discussing other similar systems

Battery Technologies

There are different ways to store electricity by converting it into another form such as kinetic or potential energy. The most common way to store energy in a small-scale renewable energy system is through chemical potential energy. Within this category, there are several types of battery chemistries available in the market, including lead-acid, nickel cadmium (NiCd), nickel metal hydride (NiMH), and several types of lithium ion (Li-ion) chemistry (Nair, 2011).

The oldest technology available in this market is the lead-acid batteries, which represented about 79% of the battery market in 2008. The ideal lead-acid battery for a small-scale renewable energy system is known as a deep-cycle battery. These batteries can be discharged multiple times by as much as 80% of their capacity without damaging their chemical properties. They offer low investment cost, lowest self-discharge rate among all rechargeable batteries, and are relatively easy to maintain. In general, they represent a cost-competitive solution in the energy storage industry. However, they have diminished performance under low and high ambient temperatures, and they are not environmentally friendly (Nair, 2011; Baker, 2008).

NiCd batteries are proven to be an alternative solution for a battery bank system. They are robust, and, compared to a lead-acid battery, have a longer life cycle, higher energy density, and lower maintenance requirements. They offer many advantages in PV applications, such as reliability, long life, and cycling ability. However, they are large, contain toxic heavy metals, and present a severe self-discharge process (Nair, 2011; Baker, 2008).

Based on their higher energy density compared to the NiCd batteries (25-30%) and the lack of toxic substances such as heavy metals (lead or mercury), NiMH batteries are a feasible alternative solution for energy storage. Although they are superior to lead-acid and NiCd in terms of specific energy, they are largely inferior to Li-ion batteries (Ruetschi, 1995). One of the drawbacks for NiMH technology is that they suffer from severe self-discharge, meaning that they are inefficient for long-term energy storage (Nair, 2010).

Li-ion batteries are commonly used in portable electronics but their usage in electric vehicles and renewable energy systems is becoming more common. Compared to the other three battery technologies, Li-ion batteries have a higher energy density and they can achieve a storage efficiency close to 100%. The only drawbacks for this technology are the high investment cost and the complicated charge management for the system. However, based on the wide range of applications, much of the research and development work has been done to reduce the capital cost for this technology (Nair, 2011; Baker, 2008).

Due to the high energy density level combined with the decrease in cost the Li-ion batteries are the number one choice to develop a self-consumption system.

Grid Services Provided by Battery Banks

The Rocky Mountain Institute (RMI) developed a report about “The economics of the battery energy storage”. The report evaluates the services that a battery storage unit can provide to ISOs/RTOs, utilities and customers, and estimates the value that they can provide. Figure 4 presents all those services and the stakeholders that each one can benefit. Tables A.1, A.2, and A.3 in appendix A describe all 13 services.

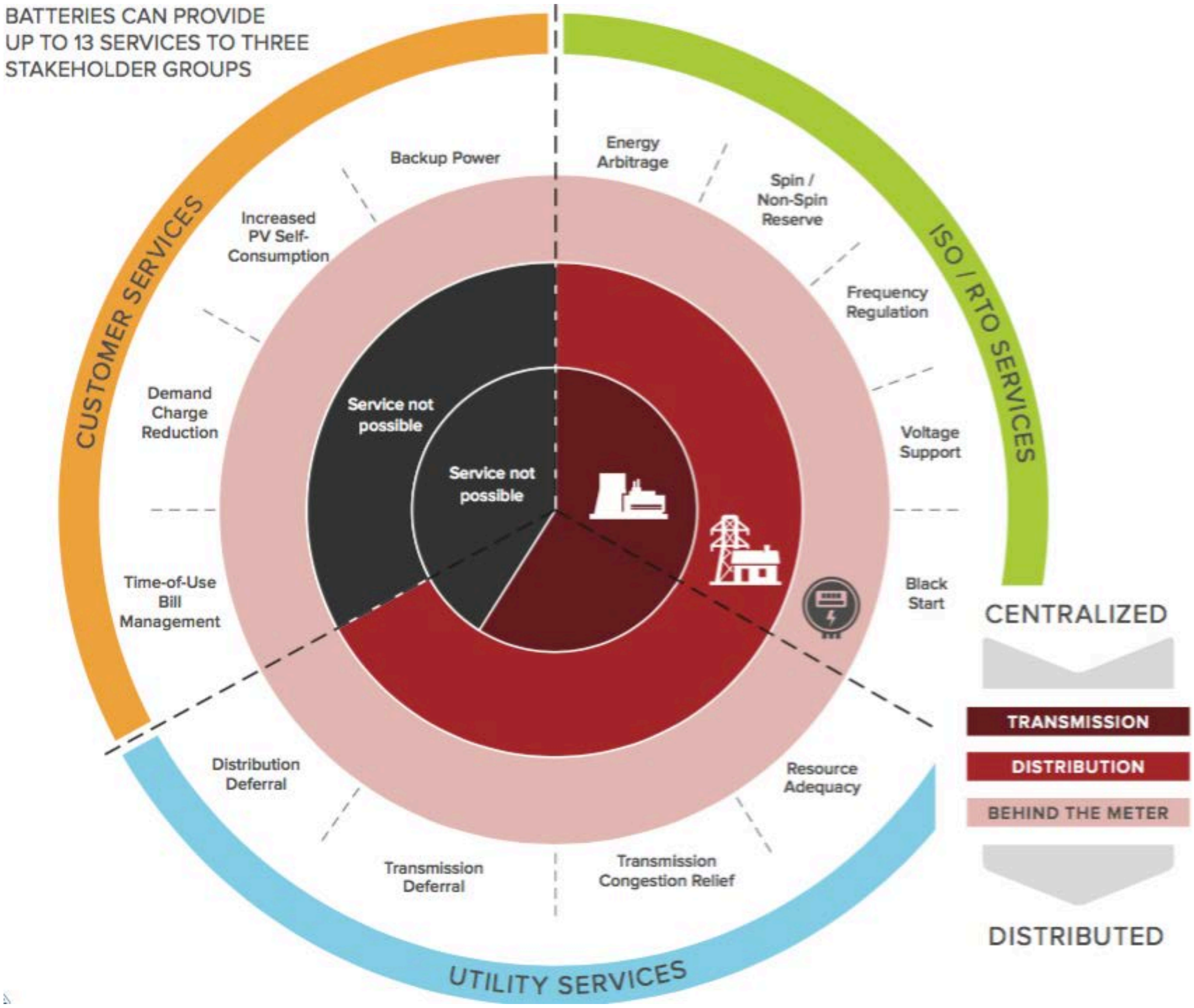


Figure 4. Batteries can provide up to 13 services to the stakeholders (Rocky Mountain Institute, 2015, p. 6).

Depending on which service that battery is primarily intended to provide, multiple stacked usage can be realized to create the most value for the system. For example, according to the RMI report, demand charge reduction represents a 5-50% utilization rate, leaving an open space for applying a different application for the battery bank. By integrating a PV system with a battery bank, the self-consumption feature will increase, since the excess power can be used to charge the batteries, creating less dependency on the grid.

Although the RMI report cannot fully answer the question of where should the battery storage be deployed to maximize the net value on the system, the study showed that “behind-the-meter energy-storage business models that deliver a stack of services to both customers and other electricity system stakeholders can already provide positive net value to the electricity system under prevailing energy storage cost structures” (Rocky Mountain Institute, 2015, p. 40). This statement justifies an investment in research of battery storage in a residential system.

Battery Manufacturers

There are some companies in the U.S. that develop Li-ion battery banks to provide the services previously discussed. Although it is not the focus of this research, it is important to know that there are companies that manufactures battery banks in utility scale, one of the solutions that could alleviate the need to install new massive power plants that run for few hours of a year to supply the peak demand.

Alevo is a Swiss-based group founded in 2009 that manufactures 2 MW/1 MWh utility scale battery banks. The product GridBank was designed to reduce the greenhouse gas emissions, increase the integration with the renewable energy systems and provide a range of services such as frequency regulation, transmission and distribution deferral, voltage support, etc, in order to improve the efficiency of the electric grid. According to Alevo, the GridBank can be used to smooth out peaks by storing excess generation during low demand times and discharging it during peak demands (Alevo Group S.A., 2016). Figure 5 is an illustrative picture of the GridBank.

Figure 5. Alevo container sized GridBank (Alevo Group S.A., 2016).

Tesla has been making great advances on the Li-ion technology in the past few years and recently they developed the product called Tesla Powerwall. The Powerwall is a 3.3 kW/ 6.4 kWh Li-ion battery bank that was developed to work as a power back-up system combined with a PV system. The Powerwall can be stacked up to 9 total and each bank has its own battery protection system (BPS) and charge controller. Figure 6 shows a representation of the Tesla Powerwall.

Figure 6. Tesla Powerwall (Tesla Motors, 2016).

Another residential/small commercial scale company in this market is the Adara Power. They offer the juiceBox Energy, a 5.5 kW/ 8.6 kWh Li-ion battery bank. As all Li-ion batteries, it has its own BPS in order to protect the bank (Adara Power, 2016). The interesting feature of the Juicebox Energy is that it communicates with the company and the Schneider inverter XW+. The company takes over the inverter in order to provide constant assistance to the customer, offering a safe environment and higher efficiency. This product was designed to deliver peak-shifting, back-up power, energy efficiency and time-of-use bill management. Due to the easy access to this technology, I will be using this battery bank to develop this research. Figure 7 displays the JuiceBox Energy.

Figure 7. The JuiceBox energy (Adara Power, 2016).

Self-Consumption Inverter

One of the most important components of a self-consumption system is the inverter Companies such as SMA and Schneider both develop this technology. However, I will only focus on the Schneider inverter since this is the one used in this research.

Schneider offers two different products with almost the same capabilities, but one exports power to the grid (Conext XW+) and the other does not (Conext SW). The main feature of this inverter is PriorityPower, which makes the inverter prioritizes self-consumption rather than exporting/importing to/from the grid. With the ParallelPower feature, the inverter can be programmed to offset utility peaks, meaning that it can schedule the use of the battery bank when the price for electricity is high (during peak demand). The inverter also provides a reliable backup system when combined with a battery bank.

As mentioned before, the Schneider inverter works great with the JuiceBox energy, making it the perfect solution for this research.

Load Management

Another way to improve self-consumption within a system is through load management. In order to develop an efficient load management system, it is important to understand some concepts regarding demand response and how to analyze the residential load profile.

According to the *National Action Plan on Demand Response*, demand response can be defined by "the ability of customers to respond to either a reliability trigger or a price trigger from their utility system operator, load-serving entity, regional transmission organization/independent system operator (RTO/ISO), or other demand response provider by lowering their power consumption" (The Federal Energy Regulatory Commission Staff, 2010, p. 3).

The terms deferrable and non-deferrable can be applied to describe the temporal nature of loads.

A deferrable demand is one that can be shifted in time according to planned changes previously authorized by the customer. In other words, it means that loads such as air conditioning and water heating can be deferred along the day (Castillo, 2011), intentionally avoiding the peak demand.

A non-deferrable demand is one that cannot be shifted in time. For instance, lights, TVs, and refrigerators are loads that represent instantaneous or continuous consumption (Castillo, 2011), meaning that a change on use cannot be rescheduled.

When analyzing a residential load profile, it is important to not only graph the total load used throughout the day but also to point out which specific loads have been used in a certain time interval. By doing that, it is possible to categorize the deferrable and non-deferrable loads in order to facilitate the load management process.

According to Guido Benetti, there are three techniques that can be used to increase the efficiency of a load system. The techniques are: Demand-side management (DSM), demand response (DR) and electric load management (ELM) (Benetti, 2015).

DSM refers to methods or activities on the demand side that will change the utility’s load profile. This can include, for example, exchanging the lighting system from incandescent bulbs to LEDs or installing an up-to-date dynamic load management system (Benetti, 2015).

DR is based on techniques that will induce the customer to reduce their power consumption and it can vary from incentive-based to time-based. Incentive-based is when the utilities or operators get access to manage a customer’s load. Time-based evaluates schedules of energy pricing in different programs: Time-of-use rates, critical peak pricing and real-time pricing (RTP). TOU rates refers to a static price schedule. Critical peak pricing bases on a less predetermined variant of TOU. RTP is a highly dynamic pricing scheme whereby wholesale market prices are forwarded directly to end customers (Benetti, 2015).

ELM is a more general technique that refers to any policy devised to manage a set of loads to achieve a goal, such as energy usage optimization or peak shaving (Benetti, 2015).

The load management in this research will be basically a ELM. However, since the loads that will be used are created to simulate a load profile, the microcontroller will only shift the deferrable load that will be defined later in this research to either shave a peak and/or take advantages of the excess solar energy available.

Previous Research

Previous research has shown some experiments with self-consumption systems, such as studies done by M. Castillos-Cagigal (2011) and Joern Hoppmann (2014), but using different approaches.

In the first study, a self-consumption system was developed in a prototype self-sufficient house called the “Magic Box.” This system contained a battery bank system and “Active Demand-Side Management” (ADSM) to control the deferrable loads. The study presented promising results, such as a self-consumption rate of 77%. Although the author presented a list of loads and their energy consumption, he did not provide any information regarding which loads were shifted nor which technology was used to do the load management. Furthermore, the data presented corresponded to either a day or a week for each scenario, and no cloudy day was analyzed. Analyzing the performance of a self-consumption system during a cloudy day is important in order to verify the efficiency of the system. Figure 3 below shows the system’s schematic. Note that the system is AC coupled.

The second research adopted the same topology as showed in Figure 3 but with no load management. The author simulated loads for a typical residential load profile in Germany, scaled to an annual consumption of 3,908 kWh for eight different scenarios based on different energy costs. The model created for this experiment simulated the PV power from 0.4 kW_p to 14 kW_p with steps of 0.4 kW_p. The battery storage was sized from 0 kW_h

(i.e., no storage) to 20 kWh, increasing in intervals of 0.5 kWh. The results presented show the optimal size for a self-consumption system based on the economic aspects modeled. According to the author, an optimal system has a PV capacity of 7 kW_p for some scenarios and a storage capacity varying from 3 to 5 kWh depending on the scenario studied.

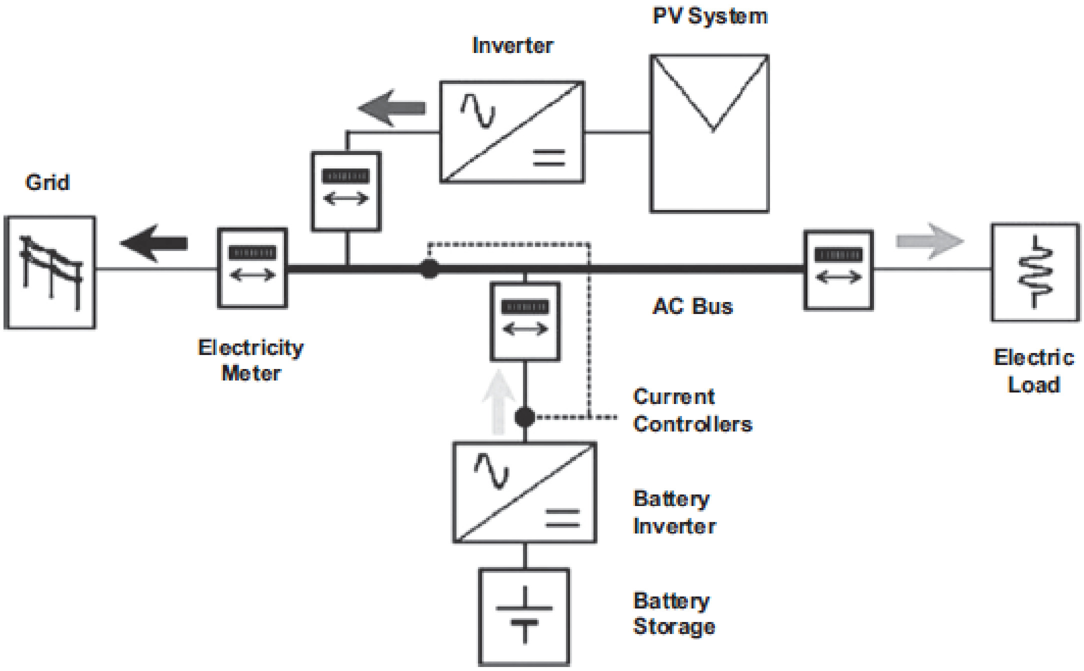


Figure 8. Self-consumption topology (Castillo, 2011, p. 2340).

CHAPTER 3: METHODOLOGY

The PV self-consumption system was installed in the Solar Lab from Appalachian State University located at State Farm Road, Boone, North Carolina. The facility holds weather measurement devices and includes a PV system owned by the Renewable Energy Initiative (REI), a renewable energy fund sponsored by students at Appalachian State. Solar thermal research used to be performed at the same lab.

Load Characterization

Load Selection

As the research is taking place in Boone, North Carolina, the load profile used for the simulation came from Dr. Brian Raichle’s residence, also in Boone. He kept record of the energy usage of his residence from 2012 to 2014. However, the data collected for 2012 and 2014 had some missing months. Therefore, the year 2013 was the only one analyzed to recreate a continuous load profile. The process to create a load profile followed 3 steps:

1. The data was divided into the four seasons
    - Winter: January to March
    - Spring: April to June
    - Summer: July to September
    - Fall: October to December

2. As the data presented the power consumption for each hour in a day, the hourly average was taken for each season
3. With one-hour timestamp hourly average data, it was possible to recreate a single load profile to represent each season

As the data collection was set during spring, the load profile obtained is represented by the graph in Figure 9. The total energy consumption is 23.61 kWh.

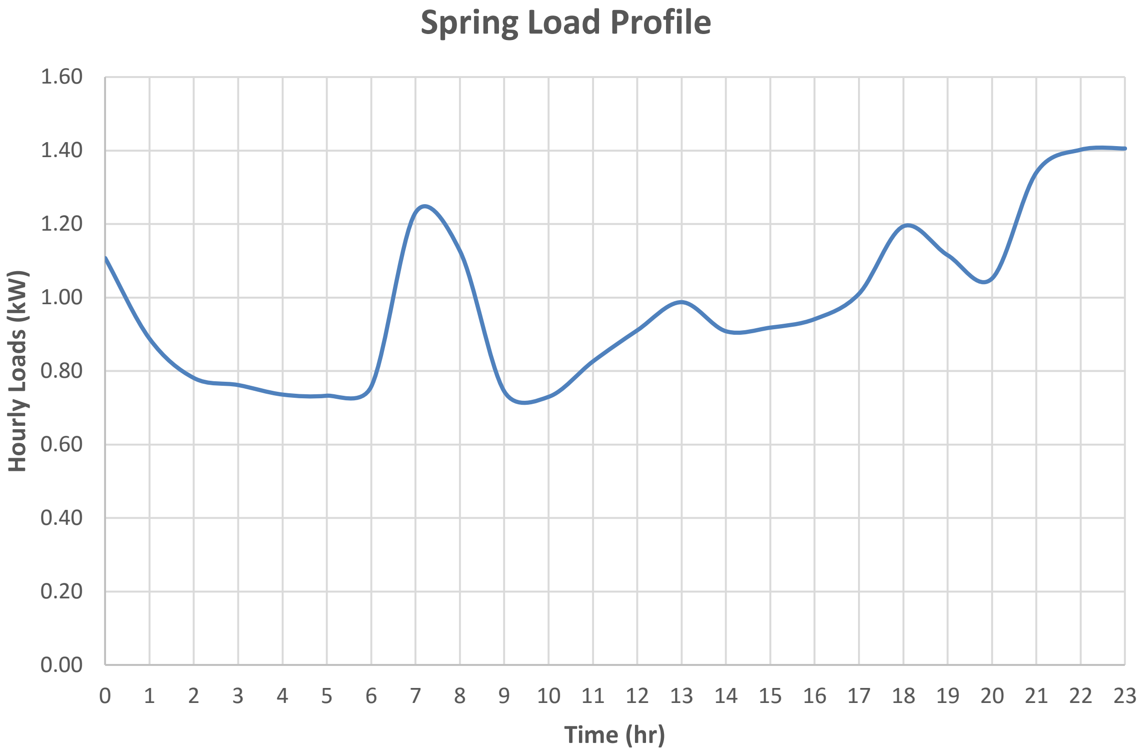


Figure 9. Hourly average spring load profile.

Building the Load Profile

Since the data collected did not distinguish which loads were being used for each hour of the day, the approach used to recreate the load profile was to define 6 loads with different power ratings that, when added up in a certain pattern, would match the hourly power consumption. Due to low costs, the loads were composed by incandescent light bulbs and resistive space heaters, and the respective hourly average power ratings can be seen in Table 2.

Table 2. *Loads' Power Rating*

Load	Composition	Power (W)
1	Space heater	400
2	Space heater	760
3	4x70W light bulbs	280
4	3x70W light bulbs	210
5	2x70W light bulbs	140
6	4x60W and 1x55 light bulbs	295

A sketch for the microcontroller Arduino was developed to create the pattern that simulates the load profile. The loads were connected to solid-state relays that would turn them on/off according to the time of day. The pattern created for the load profile with and without load management can be seen in Table 3. The simulated load profile presented an increase of only 0.345 kWh over the model load profile, which represents approximately 1.5% of the total energy. The Arduino sketch can be found in appendix B.

Loads 1, 3, 4, 5 and 6 were used to simulate the base load throughout the day while load 7 was mainly used to achieve the peaks of power as it can be seen on Figure 9. Load 7 was also chosen to represent the deferrable load for the load management. A good example of a deferrable load is an electric water heater. A good insulated water tank has minor heat losses, allowing small variations in temperature throughout the day. Therefore, a portion of the water heating process can be shifted along a day. For instance, according to the heat transfer equation, a 50-gallon water tank would need 7.91 kWh to increase the water temperature from 55 °F to 120 °F. The calculation can be seen on the equation below,

$$Q = mc\Delta T \tag{1}$$

where Q is the heat transfer in BTU, c is the water specific heat (1 BTU/lb/F), ΔT is the difference in temperature (65 °F) and m is the mass, defined by,

$$m = \rho v \tag{2}$$

where ρ is the water density (8.3 lb/gallon) and v is the volume (50 gallons). Therefore,

$$Q = 50\ gallons * 8.3 \frac{lb}{gallon} 1 \frac{BTU}{\frac{lb}{F}} * 65F = 26975\ BTU \tag{3}$$

Converting for kWh,

$$\frac{26975}{3412} \frac{BTU}{\frac{BTU}{kWh}} = 7.91\ kWh \tag{4}$$

It can be seen in Table 3 that load 2 is turned on 10 hours/day, meaning that its total energy consumption per day is 7.6 kWh. Therefore, load 2 is representing the magnitude of an electric water heater for a 50-gallon tank since it consumes approximately 96% of the total energy previously calculated. Two loads management schemes were created that shift a fraction of this energy.

For this research, the 3-hours load management was developed by shifting load 2 during the 3 hours starting at 9-11 PM to the 3 hours starting at 9-11 AM, so the power generated by the PV can be used to power this load instead of power from the grid. Around 1/3 of the load 2 draw was shifted in time. The 5-hours load management shifted power drawn during the 3 hours from the previous profile plus shifted power drawn during the 2 hours starting at 6 and 7 PM to 12 and 1 PM. Around ½ of the load 2 draw was shifted in time.

Although the light bulbs and space heaters might vary the power output along the time that they are on, the hourly average power was very close to the expected as it can be seen in Figures 10 to 12. The total daily energy measured for every data collected was off by less than 1.5% of the total expected energy.

Table 3. *Load Profile Pattern with the Respective Expected hourly Power Consumption and Daily Energy Consumption*

Hour	Load profile without load management	Power (kW)	Load profile with 3h load management	Power (kW)	Load profile with 5h load management	Power (kW)
0	Load 2+4+5	1.110	Load 2+4+5	1.110	Load 2+4+5	1.110
1	Load 2+5	0.900	Load 2+5	0.900	Load 2+5	0.900
2	Load 3+4+6	0.785	Load 3+4+6	0.785	Load 3+4+6	0.785
3	Load 2	0.760	Load 2	0.760	Load 2	0.760
4	Load 1+4+5	0.750	Load 1+4+5	0.750	Load 1+4+5	0.750
5	Load 1+4+5	0.750	Load 1+4+5	0.750	Load 1+4+5	0.750
6	Load 2	0.760	Load 2	0.760	Load 2	0.760
7	Load 2+4+6	1.265	Load 2+4+6	1.265	Load 2+4+6	1.265
8	Load 1+3+4+6	1.185	Load 1+3+4+6	1.185	Load 1+3+4+6	1.185
9	Load 1+4+5	0.750	Load 1+2+4+5	1.510	Load 1+2+4+5	1.510
10	Load 3+5+6	0.715	Load 2+3+5+6	1.475	Load 2+3+5+6	1.475
11	Load 1+3+5	0.820	Load 1+2+3+5	1.580	Load 1+2+3+5	1.580
12	Load 3+4+5+6	0.925	Load 3+4+5+6	0.925	Load 2+3+4+5+6	1.685
13	Load 1+3+6	0.975	Load 1+3+6	0.975	Load 1+2+3+6	1.735
14	Load 3+4+5+6	0.925	Load 3+4+5+6	0.925	Load 3+4+5+6	0.925
15	Load 3+4+5+6	0.925	Load 3+4+5+6	0.925	Load 3+4+5+6	0.925
16	Load 3+4+5+6	0.925	Load 3+4+5+6	0.925	Load 3+4+5+6	0.925
17	Load 1+3+4+5	1.030	Load 1+3+4+5	1.030	Load 1+3+4+5	1.030
18	Load 2+5+6	1.195	Load 2+5+6	1.195	Load 5+6	0.435
19	Load 2+5+6	1.195	Load 2+5+6	1.195	Load 5+6	0.435
20	Load 1+3+4+5	1.030	Load 1+3+4+5	1.030	Load 1+3+4+5	1.030
21	Load 1+2+4	1.370	Load 1+4	0.610	Load 1+4	0.610
22	Load 1+2+6	1.455	Load 1+6	0.695	Load 1+6	0.695
23	Load 1+2+6	1.455	Load 1+6	0.695	Load 1+6	0.695
	Total Daily Energy (kWh)	23.955				

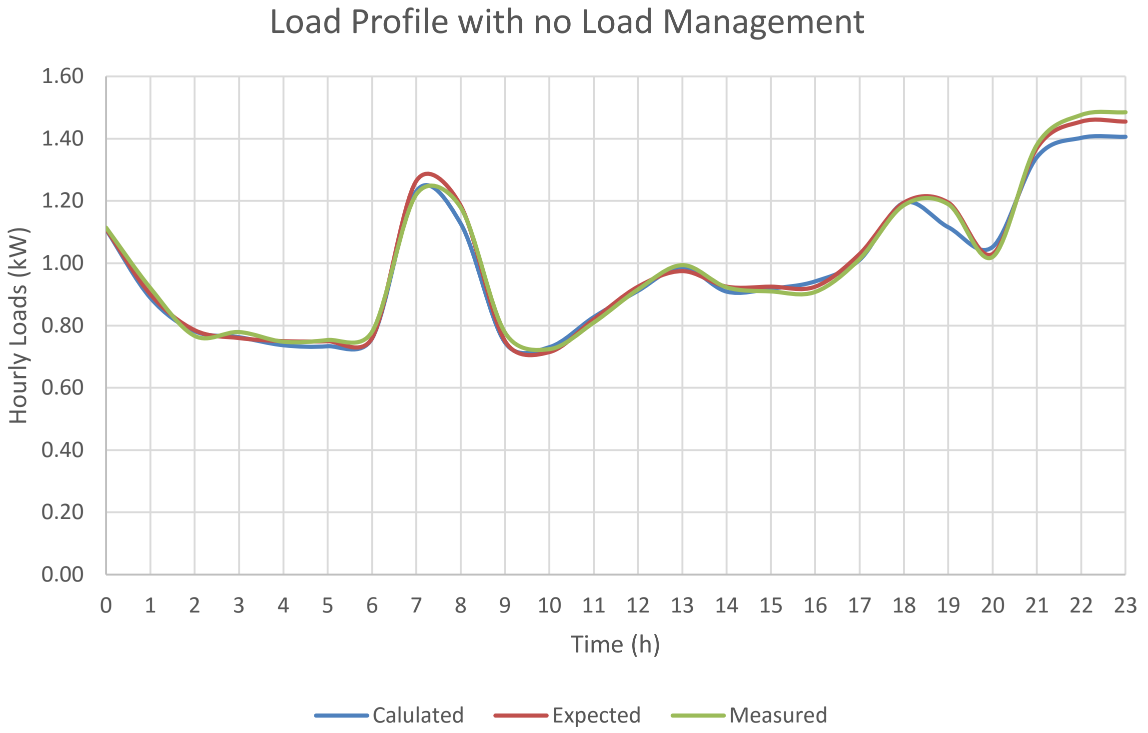


Figure 10. Comparison between calculated, expected and measured load profile with no load management.

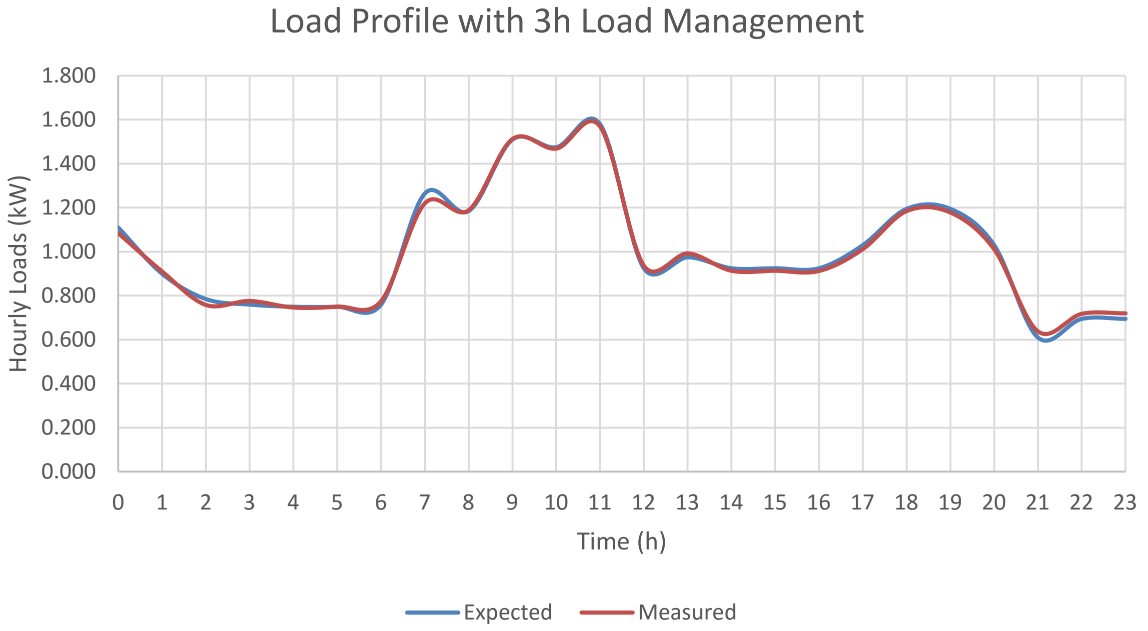


Figure 11. Comparison between expected and measured load profile with 3h load management.

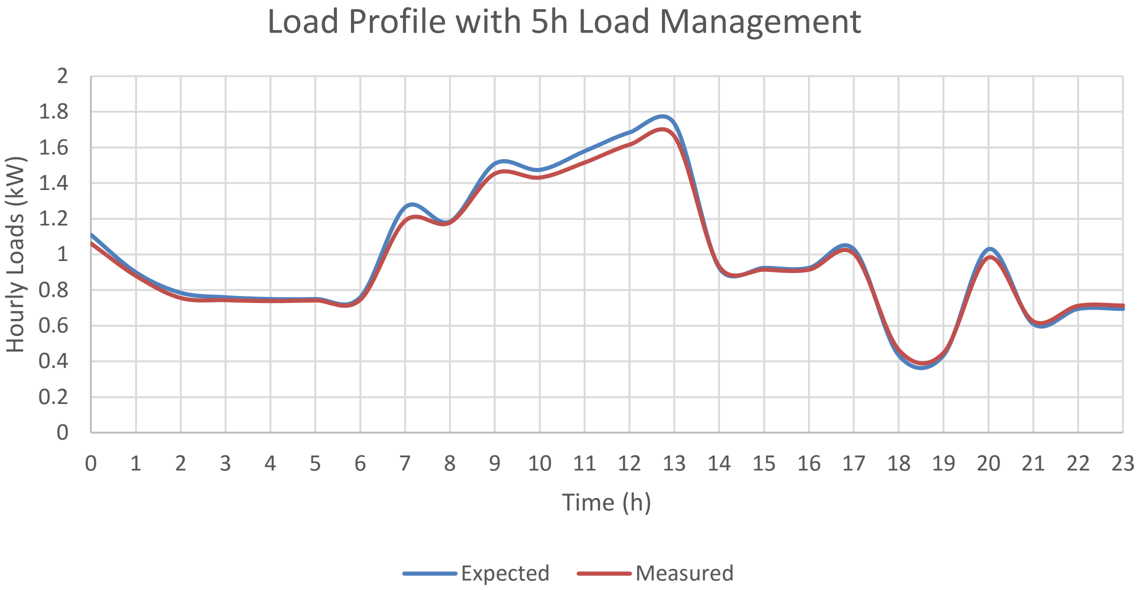


Figure 12. Comparison between expected and measured load profile with 5h load management.

System Overview

As mentioned before, the PV system is located at State Farm, Boone, North Carolina. The system's major components are: SolarWorld PV modules, Midnite Solar charge controller, Adara Power lithium-ion battery and Schneider inverter.

There PV array is composed by 12 SOW280W280M4 modules arranged in 3 strings of 4 modules. Each module is rated at 280 W, with an open circuit voltage of 39.5 V, maximum power point voltage of 31.2 V, short circuit current of 9.71 A and maximum power point current of 9.07 under the Standard Test Conditions (STC). The total PV peak power is 3.36 kW. Figure 13 presents the PV array at the Solar Lab.

Figure 13. 3.36 kW PV array.

The charge controller used for this research was a Midnite Solar Classic 200. There were not many parameters to be configured for this charge controller. The most important parameters set for this charge controller were the battery type and the battery charging voltage. The charge controller prioritizes battery charge, meaning that the energy generated by the PV system will first charge the battery and then supply the loads.

As mentioned before, the battery bank is an 8.6 kWh lithium-ion system developed to work specifically with a Schneider inverter. The battery bank communicates with the inverter via XanBus, which also allows Adara Power to monitor the system to prevent any damage to the system.

The inverter is a Schneider Conext XW+ 5548. The inverter was developed to prioritize self-consumption over grid export. The inverter configuration can be seen in the Appendix C. However, it is important to mention a few things related to the inverter set up that defines most of its behavior. The current system is not exporting power to the grid (GridSell off), meaning that there is no excess PV generation. The inverter's Grid Support mode is enabled, which limits the power drawn from the grid for battery charge. If the battery state of charge (SOC) is close to 30%, the grid will be used to charge the battery as long as there is not enough PV power. Grid charging did not happen during data collection. Figure 14 presents the system configuration.

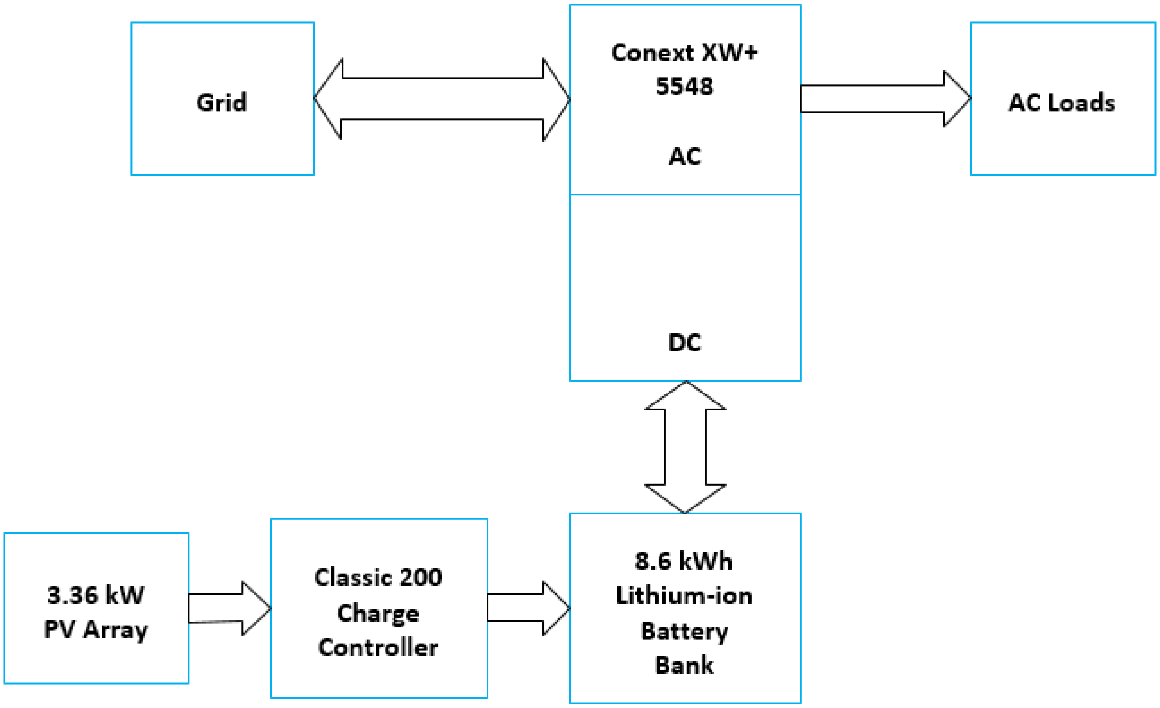


Figure 14. System schematic.

Figure 15. System installed at State Farm.

Figure 15 presents the system installed at State farm and the numbers represent the following devices.

1. Schneider inverter
2. Midnite Solar charge controller
3. JuiceBox Battery / Adara Battery
4. Solid state relays
5. Loads (light bulbs)

System's Conditions

The experiment was developed and analyzed in several different conditions in order to verify improvements on self-consumption. The system's conditions are listed below.

1. Loads without load management + grid
2. Loads without load management + grid + PV (Net metering)
3. Loads without load management + grid + PV + storage

4. Loads with load management (3h and 5h) + grid
5. Loads with load management (3h and 5h) + grid + PV (Net metering)
6. Loads with load management (3h and 5h) + grid + storage

Data Collection

This research has two different systems for data collection: one developed with a Campbell Scientific data logger and one developed by the company Adara Power. All data collected had the same setup including PV power and storage, except for the difference in the load profile.

The Campbell Scientific includes the following measurements:

- Grid power
- Loads power
- Battery voltage
- PV current (Charge Controller output)
- Irradiance

The power data acquisitions were made with CR Magnetics power transducers with a basic accuracy of 0.5% installed on grid line 1, grid line 2, load line 1 and load line 2. The battery voltage was measured with a CR Magnetics voltage transducer with a basic accuracy of 1.0% installed in the E-panel. The PV current was measured at first with a 50 A CR Magnetics current transducer and then with a 75 A current transducer, both with a basic accuracy of 1.0%, installed at the output of the charge controller. The reason that the 50 A transducer was replaced with a 75 A model was that a small amount of data collected was stored as NAN (not a number). The replacement of the transducer fixed that issue. All transducers used were from the company CR Magnetics. The irradiance was measured with a

LiCorr 200 horizontal mounted pyranometer. The measured daily irradiance was used to calculated the total amount of sun hours for each day, which defines how many hours of a day that particular area received 1000 W/m^2 of irradiance. All sensor outputs were sent to the Campbell Scientific data logger and the data was collected every 10 seconds with 1 minute averages recorded.

The Adara power website includes the following measurements:

- Battery SOC
- Battery Voltage
- Battery Current
- Battery Temperature

As this data acquisition was made by Adara Power, the data was provided through the company's website with a timestamp of a minute. The data can also be visualized as a chart with different time different timestamps.

Figure 16 presents a representative chart with 10-minute timestamp data of May 24th with total grid, total load, PV power and battery power measurements. Figure 17 presents a PV power vs Irradiance scatter chart for the same sample day.

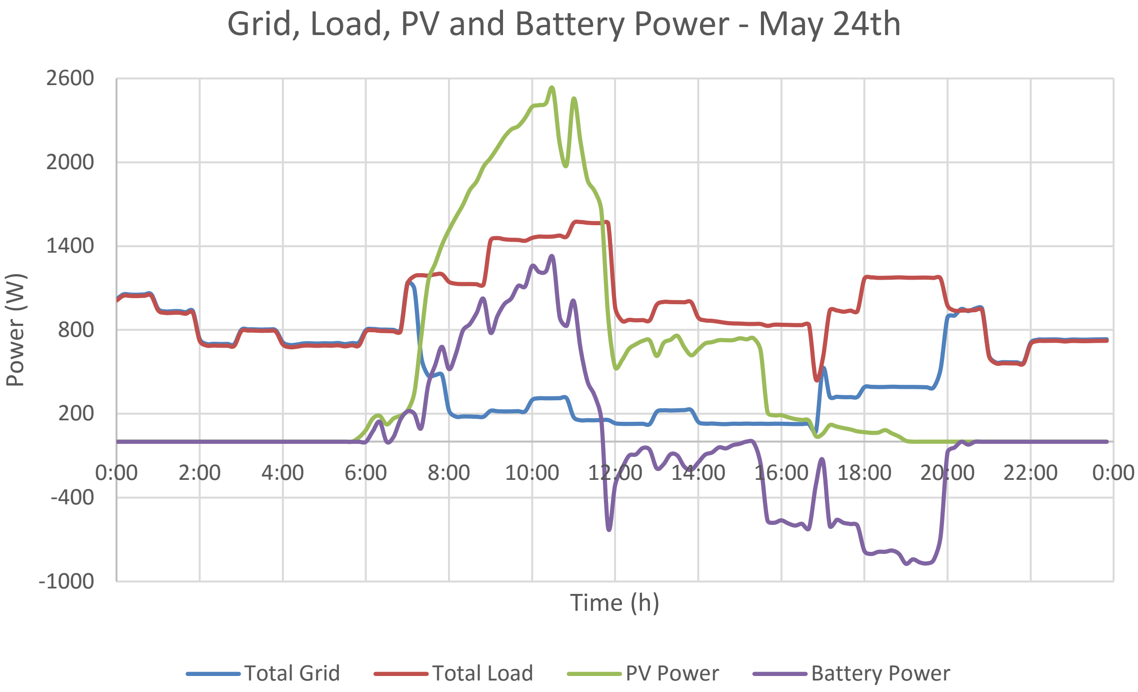


Figure 16. Grid, load, PV and battery power for May 24th.

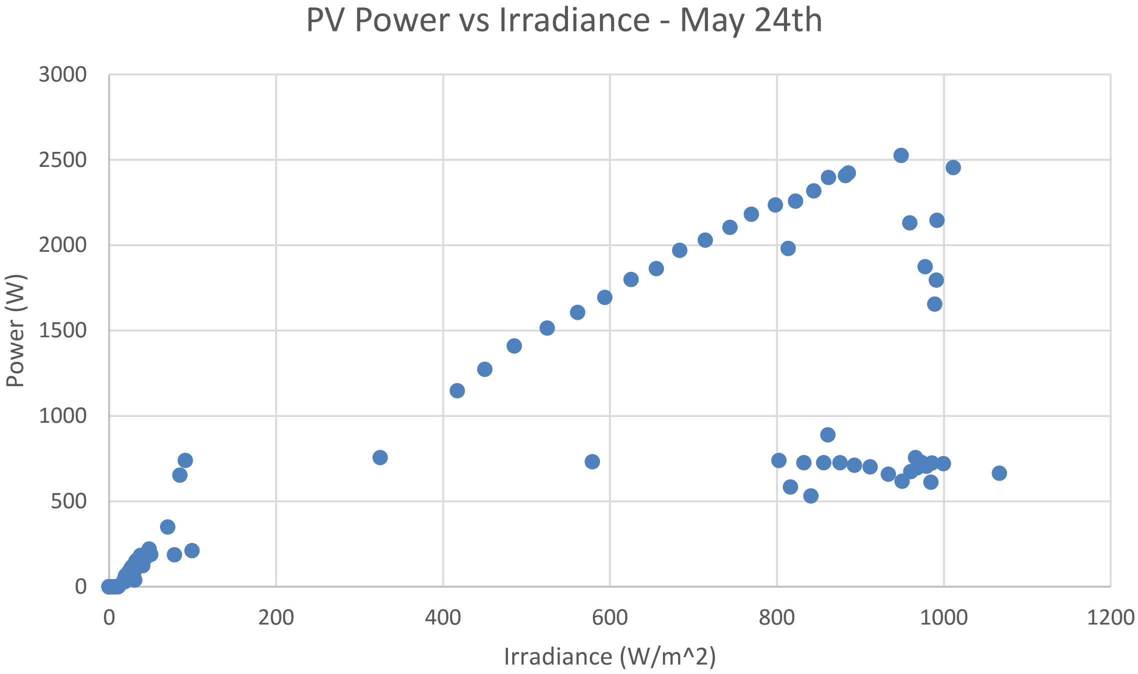


Figure 17. PV power vs Irradiance - May 24th.

As it can be seen in Figure 17, there are some data points with a high irradiance level and with a low PV power generated. It happens when the battery is almost at 100% SOC. When the battery is getting to that point, the charge controller changes the charging state from absorb to float. Therefore, the PV power will be curtailed in order to decrease the charge current maintaining the battery voltage at the same level. Also, as the charge controller and the inverter were not developed by the same company, they do not communicate with each other, which prevents the charge controller from knowing if any loads need to be supplied when the battery reaches 100% SOC.

For this research, data was collected for an amount of 23 days from April to June under different experimental conditions as it can be seen in Table 4.

Table 4. *Days of Data Collection*

Month	Day	Load Profile	Current Transducer
April	29	without load management	50 A
	30	without load management	50 A
May	19	with 3h load management	75 A
	20	with 3h load management	75 A
	24	with 3h load management	75 A
	25	with 3h load management	75 A
	26	with 3h load management	75 A
	27	with 3h load management	75 A
	28	without load management	75 A
	29	without load management	75 A
	30	without load management	75 A
	31	without load management	75 A
June	1	without load management	75 A
	2	without load management	75 A
	3	with 3h load management	75 A
	4	with 3h load management	75 A
	5	with 3h load management	75 A
	6	with 5h load management	75 A
	7	with 5h load management	75 A
	8	with 5h load management	75 A
	9	with 5h load management	75 A
	10	with 5h load management	75 A
	11	with 5h load management	75 A

CHAPTER 4: DATA ANALYSIS AND RESULTS

Although a self-consumption PV system is typically defined as a residential topology, the term self-consumption can be used for all of the other PV system topologies. The difference between the topologies would be how the energy generating source and storage (if applicable) blend changes with each self-consumption factor. The self-consumption factor is defined by the amount of energy generated which is delivered to the loads divided by the total amount of energy consumed by the loads. Therefore, applying appropriate energy storage and load management to a PV system would affect the self-consumption factor, possibly reducing the amount of grid imports/exports.

This chapter will be analyzing the changes in the self-consumption factor for a grid tied net metering system and a self-consumption system with and without load management, based on irradiance levels.

Data Validation

Before analyzing the data regarding the self-consumption factor, it is important to validate the data measured. The data validation can be done based on a power flow equation derived from the conservation of energy. For this particular system, the power flow is defined by the load power (P_{Load}) minus the grid power (P_{Grid}), minus the PV power generated (P_{PV}) minus the battery power (P_{batt}) multiplied by the inverting efficiency (ε = 95.7%) is equal to 0, as it can be seen on equation 5. $\mathrm{P_{batt}}$ is positive if battery is being charged or negative if battery is being discharged.

$$P_{load} - P_{grid} - (P_{PV} - P_{batt}) * \varepsilon = 0 \tag{5}$$

Another way to analyze the energy balance is to calculate power from the grid based on load, PV and battery power and compare it to the grid measurement. Equation 6 shows how to calculate the expected grid power.

$$P_{grid} = P_{load} - (P_{PV} - P_{batt}) * \varepsilon \qquad (6)$$

In order to visualize the comparison between measured grid power and calculated grid power based on the rest of the measured data, Figure 18 shows the data collected on May 25th that had a load profile with load management and a total sun hours of 5.28 h.

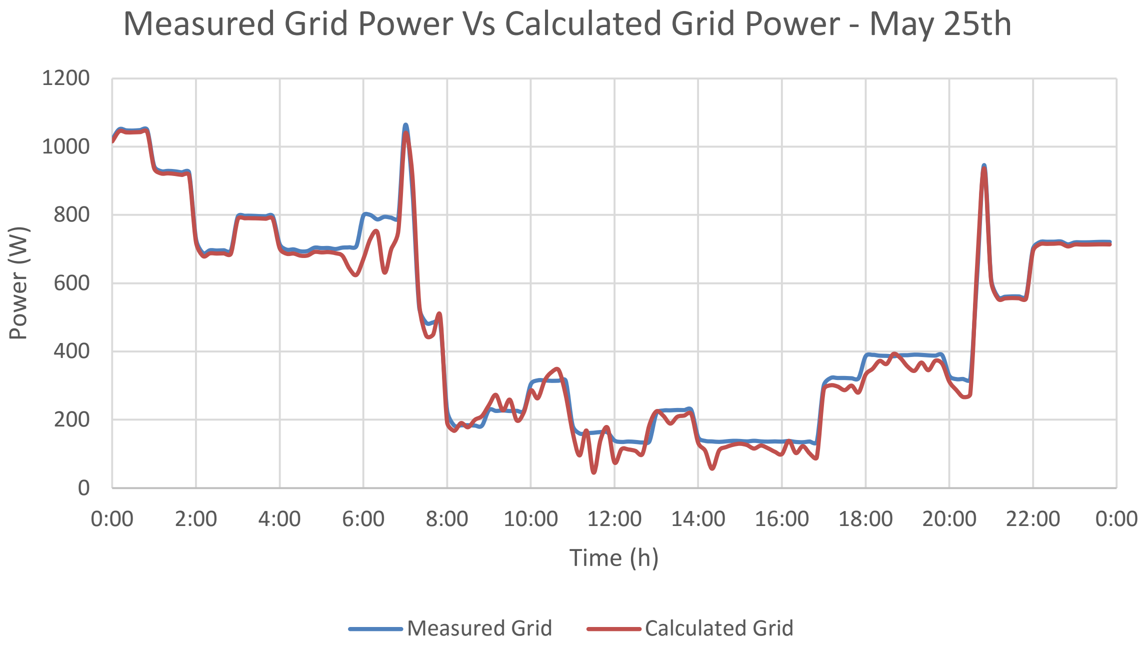


Figure 18. Comparison between measured grid and calculated grid on May 25th.

The total grid energy (*E_{Grid}*) measured for May 25th was 11.57 kWh while the calculated grid energy was 11.13 kWh, representing an error of 3.8%. Agreement between measured and calculated power is very good before 5 AM and after 9 PM, suggesting that the disagreement is due to measured PV power. Figure 19 shows a histogram for the power flow difference measured grid – calculated grid for May 25th. As it can be seen, the higher amount of occurrences happens in range between -50 W and zero, with a peak difference of around 10 W, validating the data collected and suggesting that the calculated grid power is undervalued.

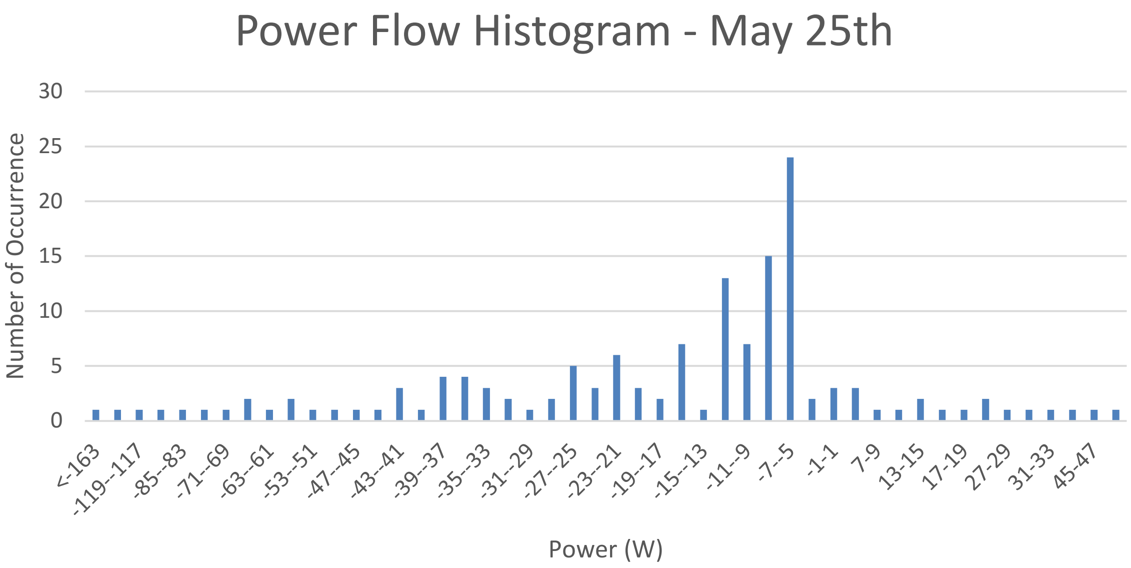


Figure 19. Energy balance histogram for May 25th.

Another sample day used for data validation was May 28th that had a load profile without load management and with a total sun hours of 6.46 h. Figures 20 and 21 show the comparison between the measured grid power and calculated grid power, and the power flow difference histogram, respectively. The total grid energy measured for May 28th was 13.19 kWh while the calculated grid energy was 12.77 kWh, which represents an error of 3.2%. Very similar trends are seen during these 23 days.

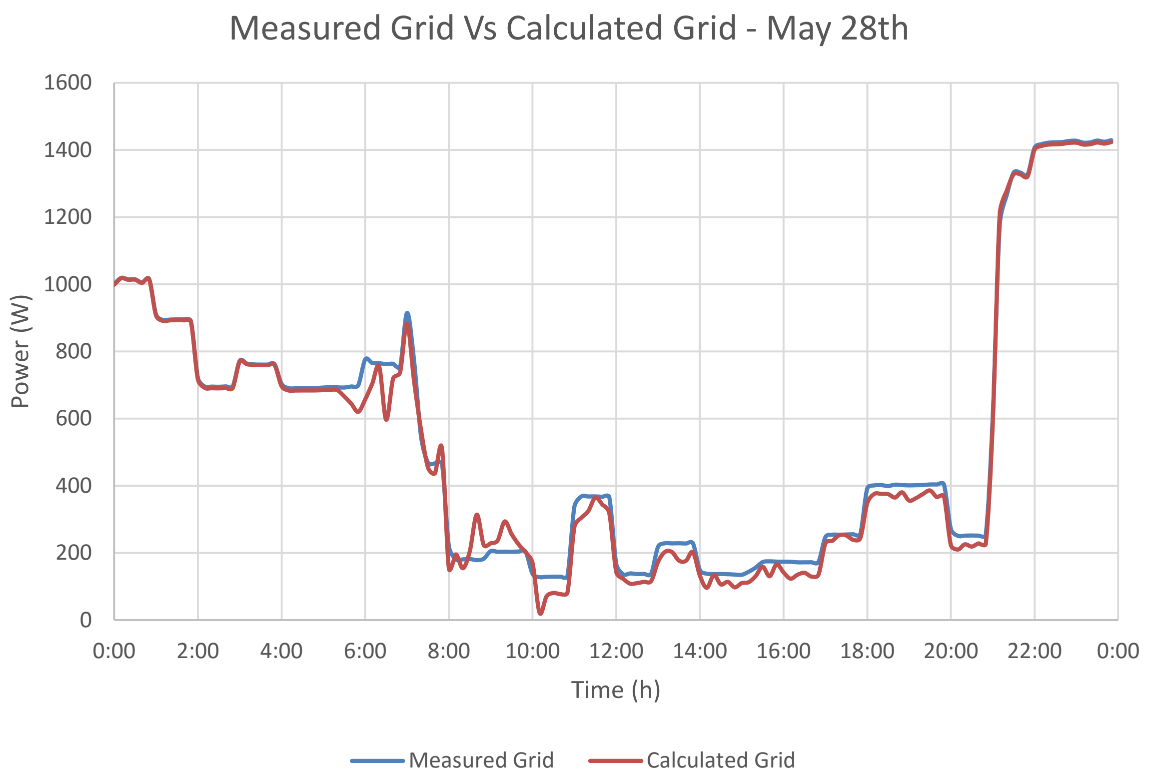


Figure 20. Comparison between measured grid and calculated grid on May 28th.

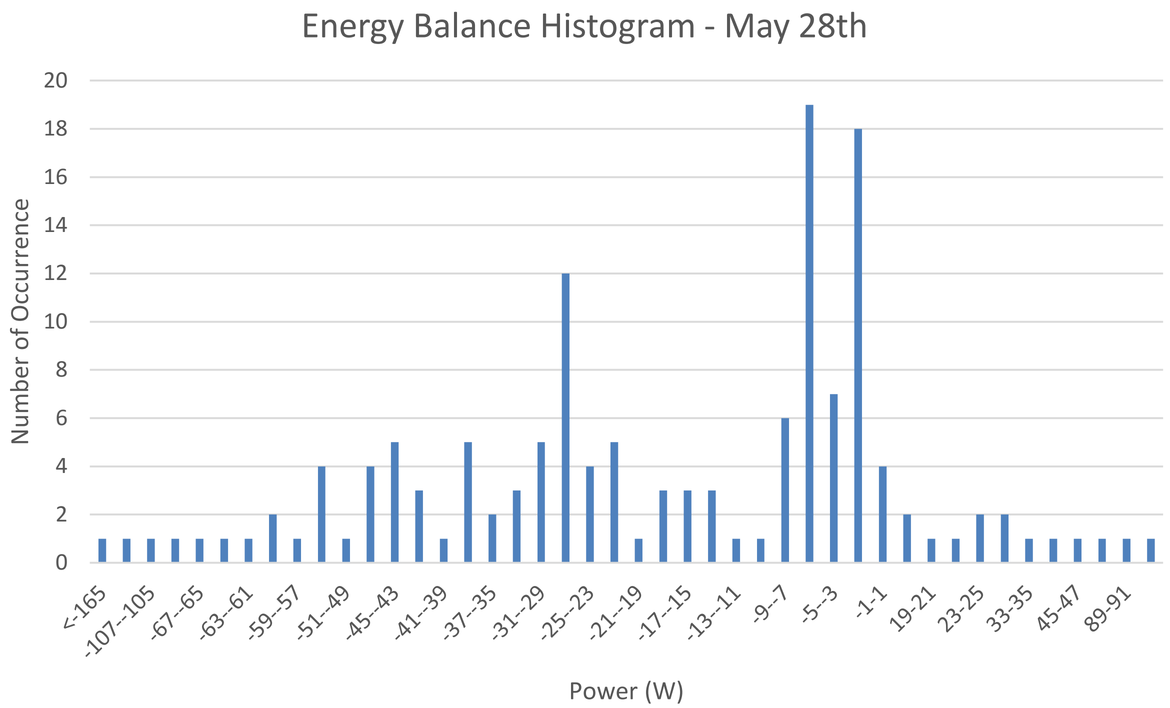


Figure 21. Energy balance histogram for May 25th.

Data Analysis

Grid Tied Net Metering System

The data collected includes energy storage, and as mention before, when the battery SOC gets above 80% the charge controller begins to curtail PV power. Therefore, in order to analyze self-consumption for a net metering system it is necessary to calculate PV power based on the measured irradiance. April 30th was used as a sample day to analyze the relation between irradiance and the battery SOC. The irradiance was analyzed during the period that the battery bank was being charged by the array and had a SOC less than 80%. Figure 22 shows power vs irradiance with a trend line defining the linear equation for the calculated PV power.

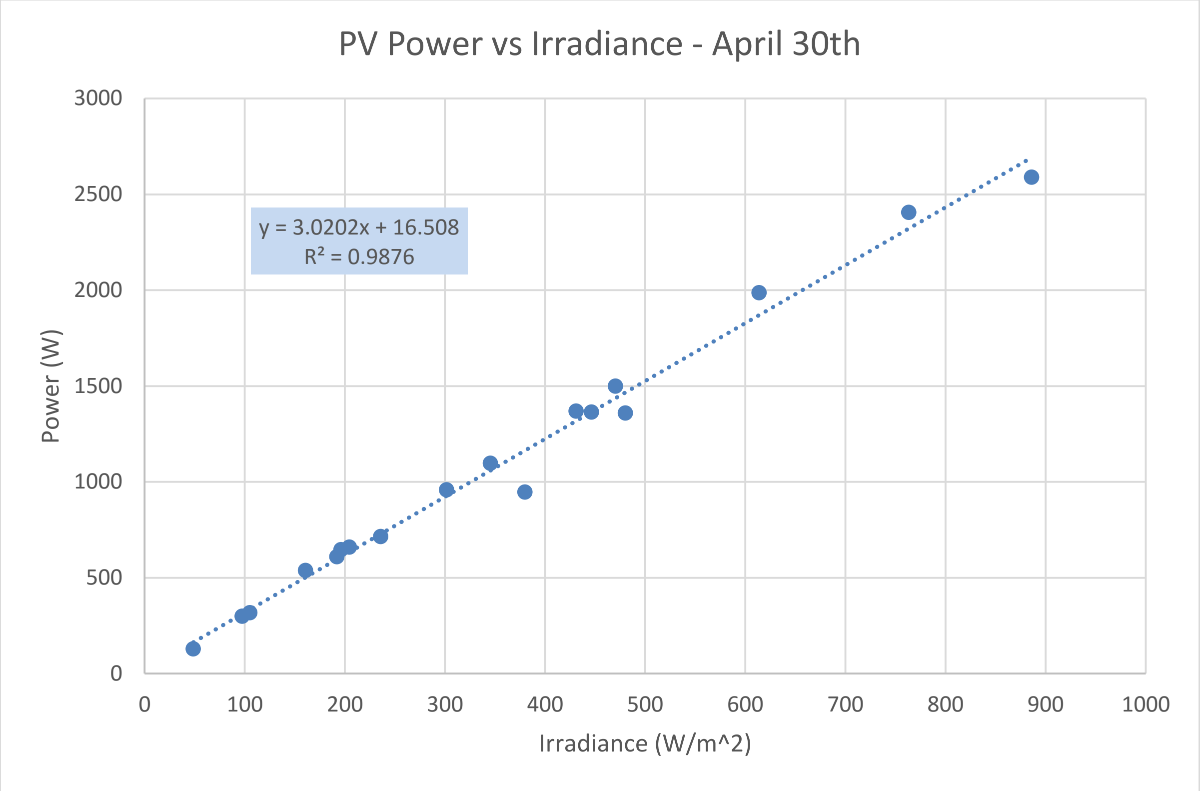


Figure 22. PV Power vs Irradiance - April 30th.

Based on the trend line, the calculated PV power is:

$$P_{PV,Calc} = 3.0202 * Irrad + 16.508 \tag{7}$$

where $P_{PV,Calc}$ is the PV power calculated and *Irrad* is the irradiance.

Using the calculated PV power and not including the battery energy into the equation, it is possible to evaluate self-consumption of the system as a grid tied net metering system. As mentioned before, the self-consumption factor is defined by the amount of energy generated that was sent to the loads divided by the total energy consumed by the loads. For a PV system without storage, the energy provided to the loads comes solely from PV ($E_{PV,Load}$). Although the energy provided by the grid does not fully affect the self-consumption factor, it is important to understand its behavior. For that, the 2 following sets of equations will calculate the power sent to the loads from grid (equation 8) and PV (equation 9). The text after // are comments explaining each equation.

```
// net metering; calculate power sent to loads from the grid                ( 8 )
$If\ ((P_{Load} - P_{PV} * \varepsilon) < 0)$  // PV fully satisfies loads; no grid needed
    $P_{Grid,Load} = 0$
$If\ ((P_{Load} - P_{PV} * \varepsilon) > 0)$  // PV partially satisfies loads; difference from grid
    $P_{Grid,Load} = P_{Load} - P_{PV} * \varepsilon$
```

```
// net metering; calculate power sent to loads from PV                      ( 9 )
$If\ ((P_{Load} - P_{PV} * \varepsilon) < 0)$  // PV fully satisfies loads; PV = loads
    $P_{PV,Load} = P_{Load}$
$If\ ((P_{Load} - P_{PV} * \varepsilon) > 0)$  // PV partially satisfies loads; all PV goes to loads
    $P_{PV,Load} = P_{PV} * \varepsilon$
```

P_{Load} is the power consumed by the loads, P_{PV} is the power generated by the PV array, $P_{Grid,Load}$ is the power provided from the grid to the loads, $P_{PV,Load}$ is the power provided from the PV array to the loads and ε is the inverting efficiency.

Based on the total power calculated for each grid and PV supplied to the load, it is possible to calculate the energy in kWh for a 10-minutes timestamp by the following equation:

$$E = \frac{P}{6*1000} \qquad (10)$$

The self-consumption factor (ξ) is taken from Castillos' research (Castillo, 2011, p. 2343) and for this particular system is defined by equation 11.

$$\xi = \frac{E_{PV,Load}}{E_{Load}} \qquad (11)$$

Note that this definition of self-consumption does not value excess PV energy that would be exported to the grid.

In order to visualize the behavior of the PV and grid when suppling the loads, Figures 23 to 27 will show the charts with P_{Load}, $P_{PV,Load}$ and $P_{Grid,Load}$ for some sample days. In this analysis $P_{Grid,Load}$ satisfies any load not satisfied by $P_{PV,Load}$.

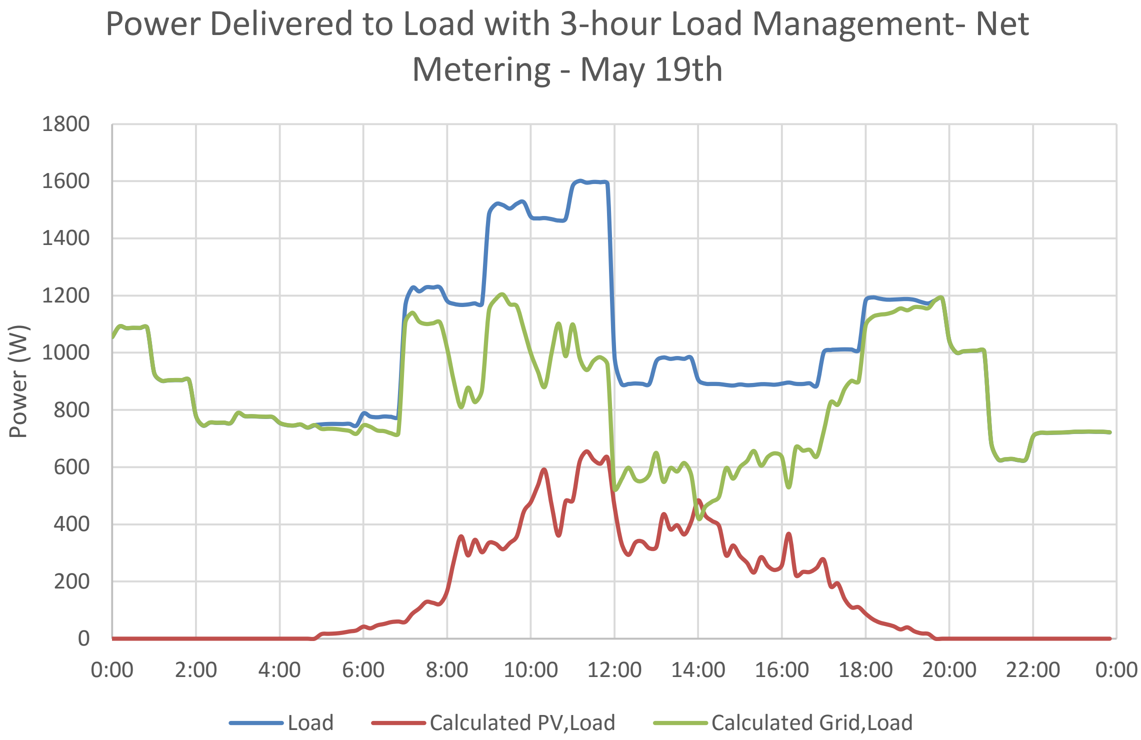


Figure 23. Power delivered to loads with 3-hour load management – net metering - May 19th

The net metering self-consumption factor for May 19th is 15.9% with an amount of 1.23 sun hours.

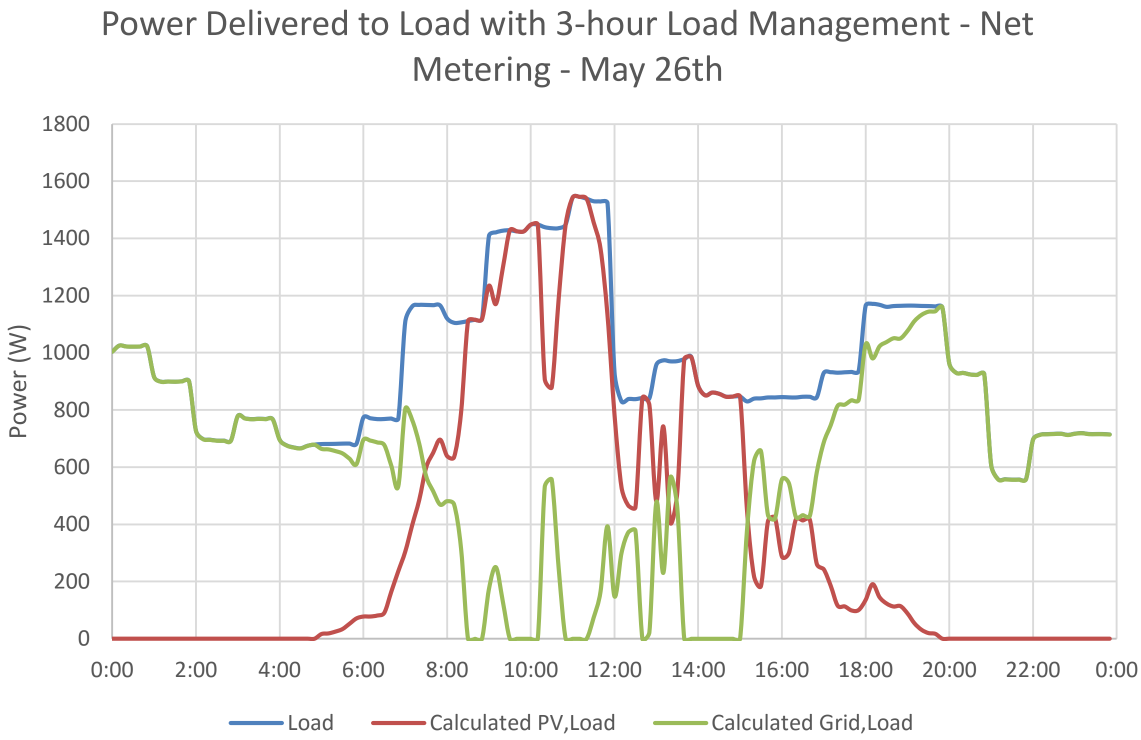


Figure 24. Power delivered to loads with 3-hour load management – net metering - May 26th.

The net metering self-consumption factor for May 26th is 38.9% with 3.95 sun hours.

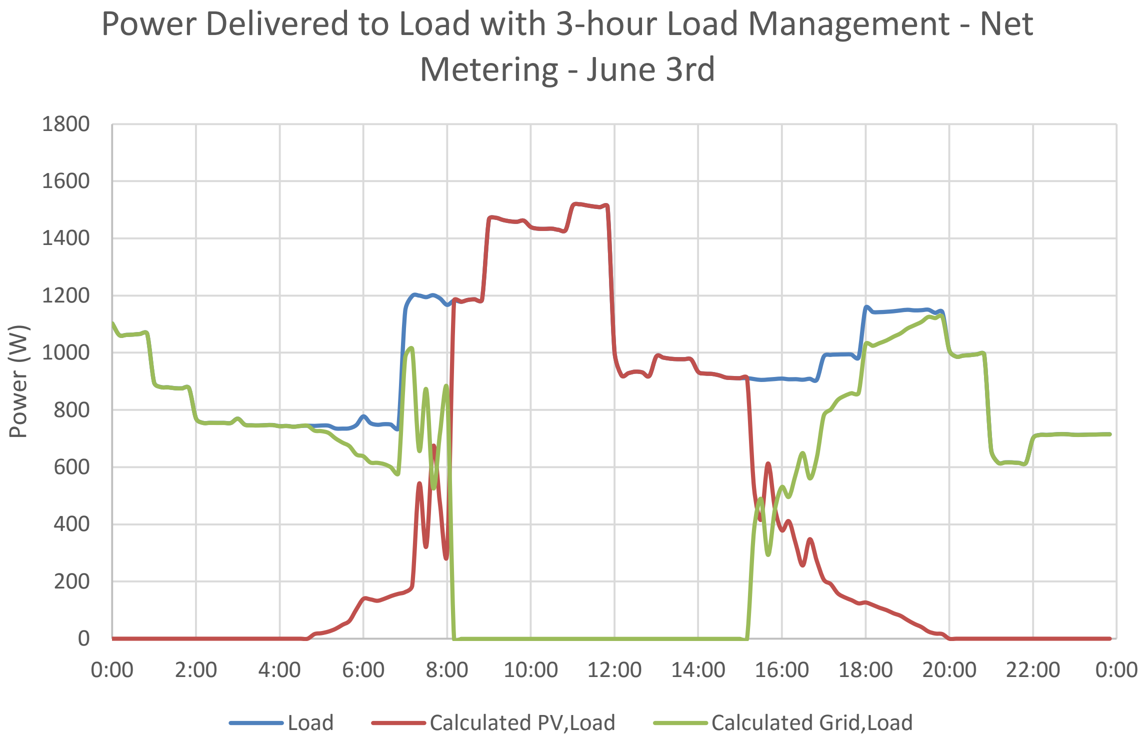


Figure 25. Power delivered to loads with 3-hour load management – net metering - June 3rd.

The net metering self-consumption factor for June 3rd is 43.3% with 6.26 sun hours.

In order to compare the effects of adding load management, it is important to analyze 2 days with a comparable amount of irradiance. May 28th had 6.46 sun hours and there was no load management applied to the loads while June 3rd had a 3-hour load management applied to it. May 28th presented a self-consumption factor 39.8%. As can be seen, even with a smaller amount of irradiance, load management can considerably increase self-consumption for a net metering system. The increase from one day to the other was about 8%. With the same approach, June 8th was a sample day that had a 5-hour load management and an amount of 6.46 sun hours. The self-consumption was 49.3%, representing an increase in self-consumption of 24% compared to May 28th and 13% compared to June 3rd. The behavior of the system for May 28th and June 8th can be seen in Figures 26 and 27, respectively.

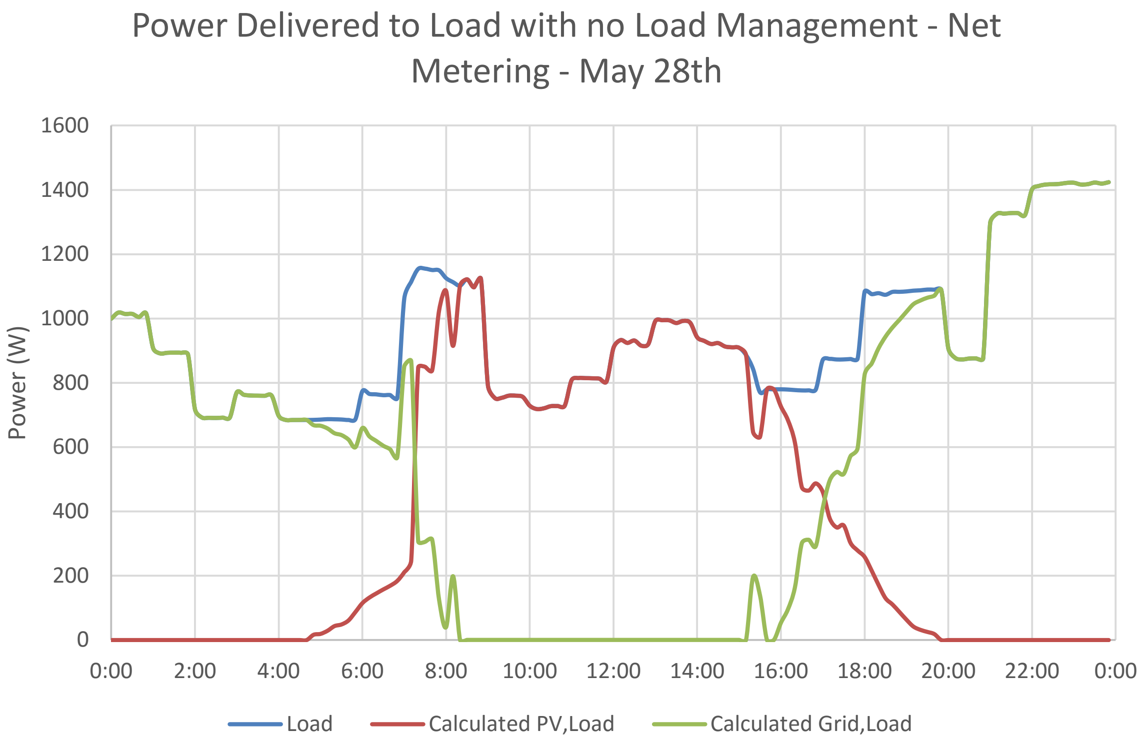


Figure 26. Power delivered to loads with no load management – net metering - May 28th.

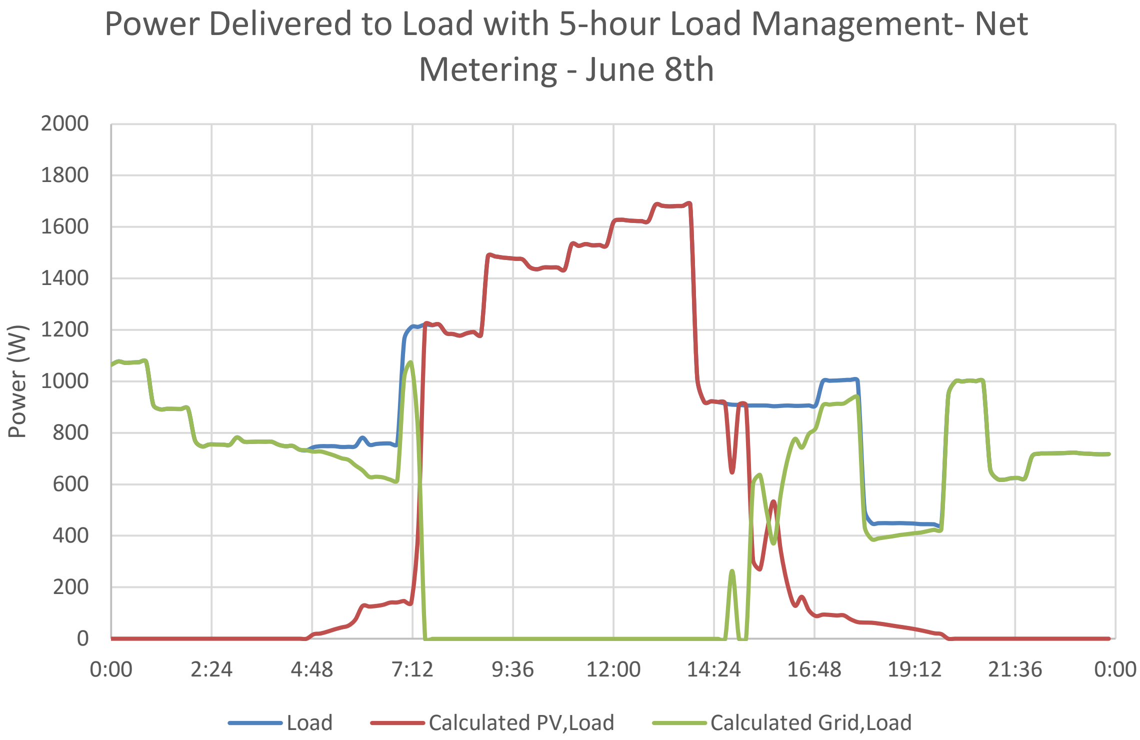


Figure 27. Power delivered to loads with 5-hour load management– net metering - June 8th.

Self-consumption System

As storage is added to the PV system, now the PV power is not only used to supply the loads. As a matter of fact, for this system with this particular charge controller, the PV power is first used to charge the battery and its excess goes to the loads. As the battery SOC gets close to 100%, the PV power is curtailed. Therefore, all data used for the self-consumption system was measured as mentioned in the methodology.

A similar set of equations were used to calculate the power sent from the grid, PV and battery bank to the loads, respectively. The equations are arranged as it was written in the programming language C to facilitate understanding the system's behavior. The // are comments explaining each equation. The priority of power flow is for battery charges and discharges.

```
// self-consumption; calculate power sent to loads from the grid                    (12)
$If\ ((P_{Load} - P_{PV} * \varepsilon) < 0)$          // PV fully satisfies loads; no grid needed
    $P_{Grid,Load} = 0$
$Else$
    $If\ ((P_{Load} - P_{Batt} * \varepsilon) < 0)$     // batteries are charging; no excess PV
        $P_{Grid,Load} = P_{Load}$
    $Else$   // batteries discharging and partially satisfying loads; difference from grid
        $P_{Grid,Load} = P_{Load} - (P_{PV} - P_{Batt}) * \varepsilon$
```

```
// self-consumption; calculate power sent to loads from PV                          (13)
$If\ (P_{Batt} \geq 0)$                                 // batteries are charging
    $If\ ((P_{Load} - P_{PV} * \varepsilon) < 0)$      // PV fully satisfies loads; PV = loads
        $P_{PV,Load} = P_{Load}$
    $Else$
        $If\ ((P_{PV} - P_{Batt}) > 0)$                 // PV charging batteries; excess to loads
            $P_{PV,Load} = (P_{PV} - P_{Batt}) * \varepsilon$
        $Else$                                          // PV used to charge batteries; none sent to loads
            $P_{PV,Load} = 0$
$Else$                                                  // batteries are discharging
    $If\ ((P_{Load} - P_{PV} * \varepsilon) > 0)$      // PV partially satisfies loads; PV satisfies loads
        $P_{PV,Load} = P_{PV} * \varepsilon$
    $Else$                                              // PV and battery satisfy the loads
        $P_{PV,Load} = (P_{PV} + P_{Batt}) * \varepsilon$        // (battery discharge is negative)
```

```
// self-consumption; calculate power sent to loads from battery
$P_{Batt,Load} = P_{batt} * \varepsilon$  // Battery discharge                        ( 8)
```

P_{Load} is the power consumed by the loads, P_{PV} is the power generated by the PV array, P_{Batt} is either power for charging or discharging the batteries, $P_{Grid,Load}$ is the power provided from the grid to the loads, $P_{PV,Load}$ is the power provided from the PV array to the loads, $P_{Batt,Load}$ is the power from the batteries to the load and ε is the inverting efficiency.

In order to calculate the self-consumption factor for this particular system, the battery discharges are added to the equation 11, as it can be seen on equation 15.

$$\xi = \frac{E_{PV,Load} + E_{Batt,Load}}{E_{Load}} \qquad (9)$$

In order to visualize the behavior of the PV and grid when suppling the loads, Figures 28 to 31 will show the charts with P_{Load}, $P_{PV,Load}$, $P_{Batt,Load}$ and $P_{Grid,Load}$ for the sample days.

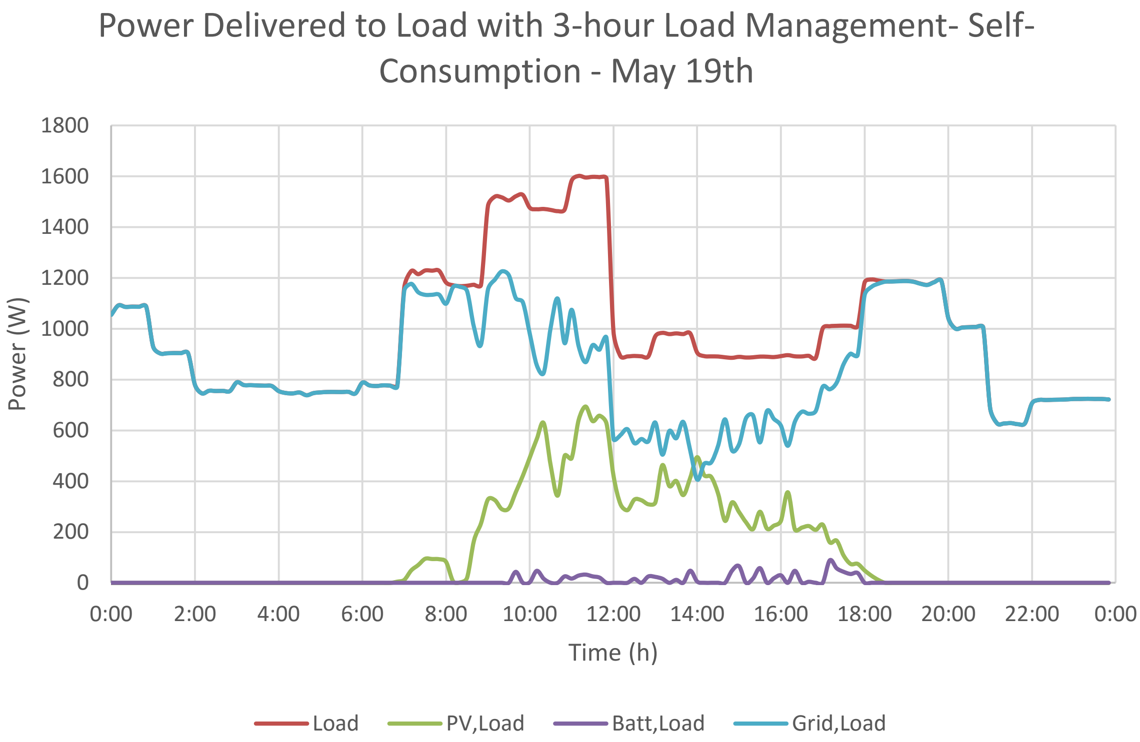


Figure 28. Power delivered to loads with 2-hour load management - self-consumption - May 19th.

The system’s self-consumption factor for May 19th is 14.7% with an amount of 1.23 sun hours.

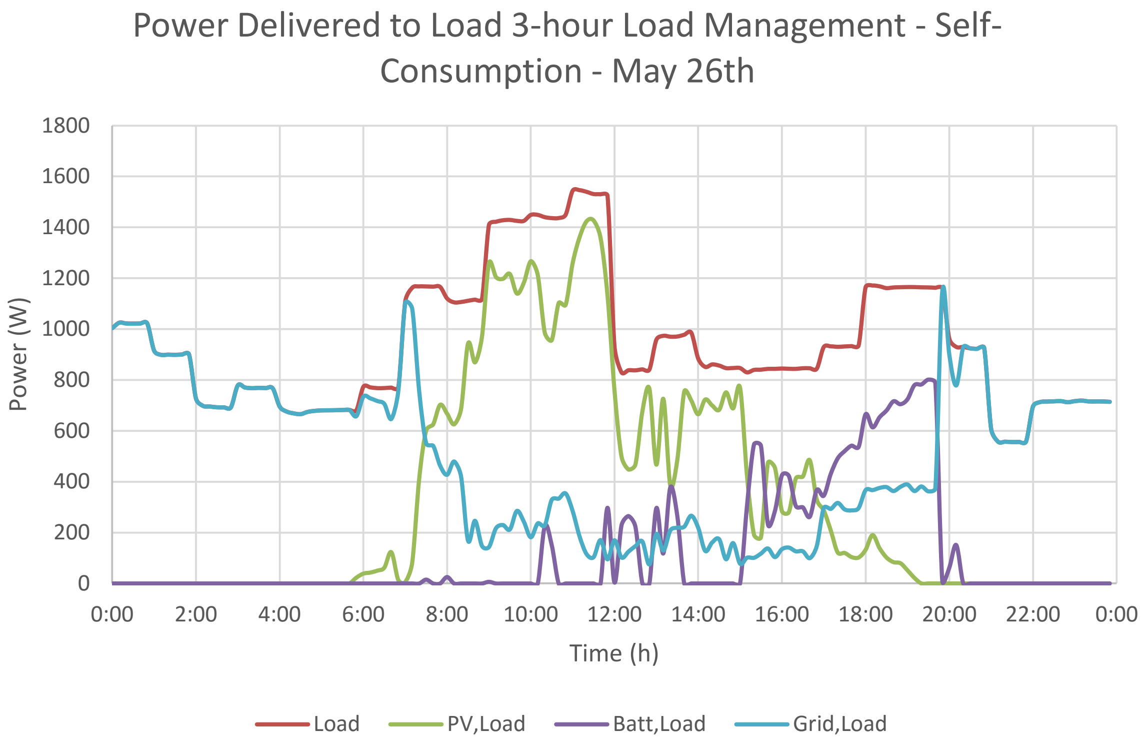


Figure 29. Power delivered to loads with 3-hour load management- self-consumption - May 26th.

The system's self-consumption factor for May 26th is 47.4% with an amount of 3.95 sun hours.

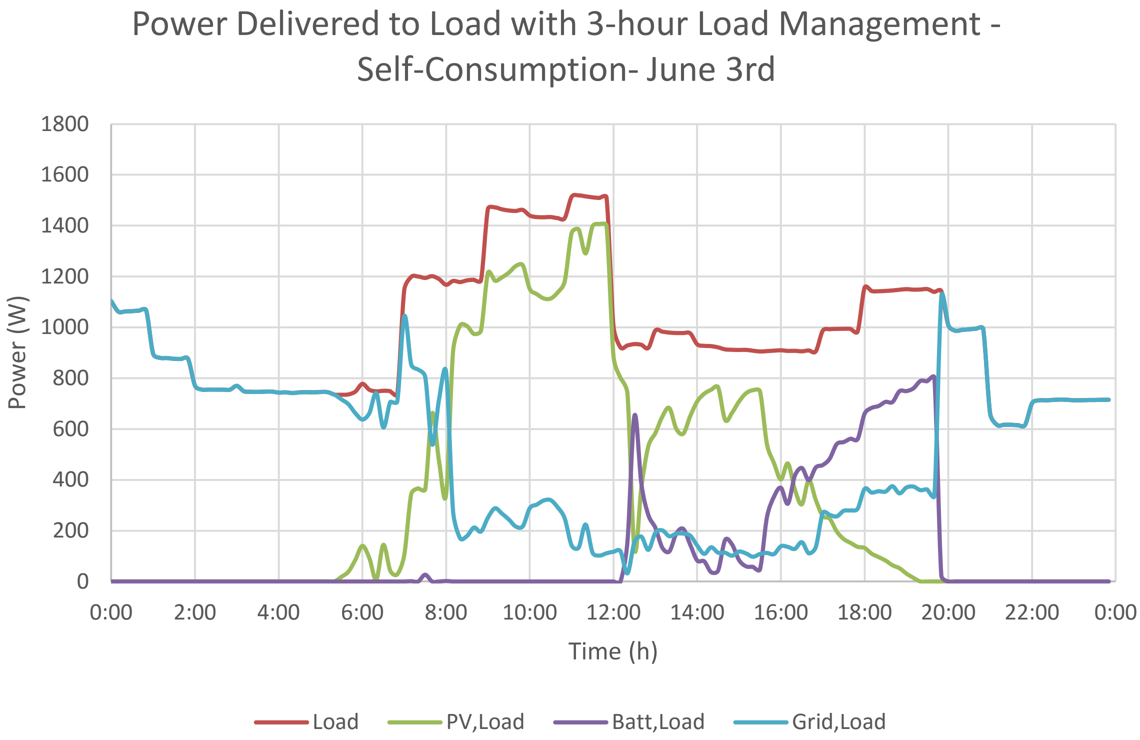


Figure 30. Power delivered to loads with 3-hour load management - self-consumption - June 3rd.

The system's self-consumption factor for June 3rd is 47.9% with an amount of 6.26 sun hours.

The same analysis done for the net metering system was made for the self-consumption system. Three days with equivalent amount of sun hours but with different load profiles were compared. May 28th had no load management and presented a self-consumption factor of 43.4% with 6.46 sun hours while June 8th had a self-consumption factor of 53.3% with the same amount of sun hours as May 28th. Therefore, there was an improvement of 10% from June 3rd to May 28th, 23% from June 8th to May 28th, and 11% from June 8th to June 3rd. Figures 31 and 32 show the system's behavior for May 28th and June 8th, respectively.

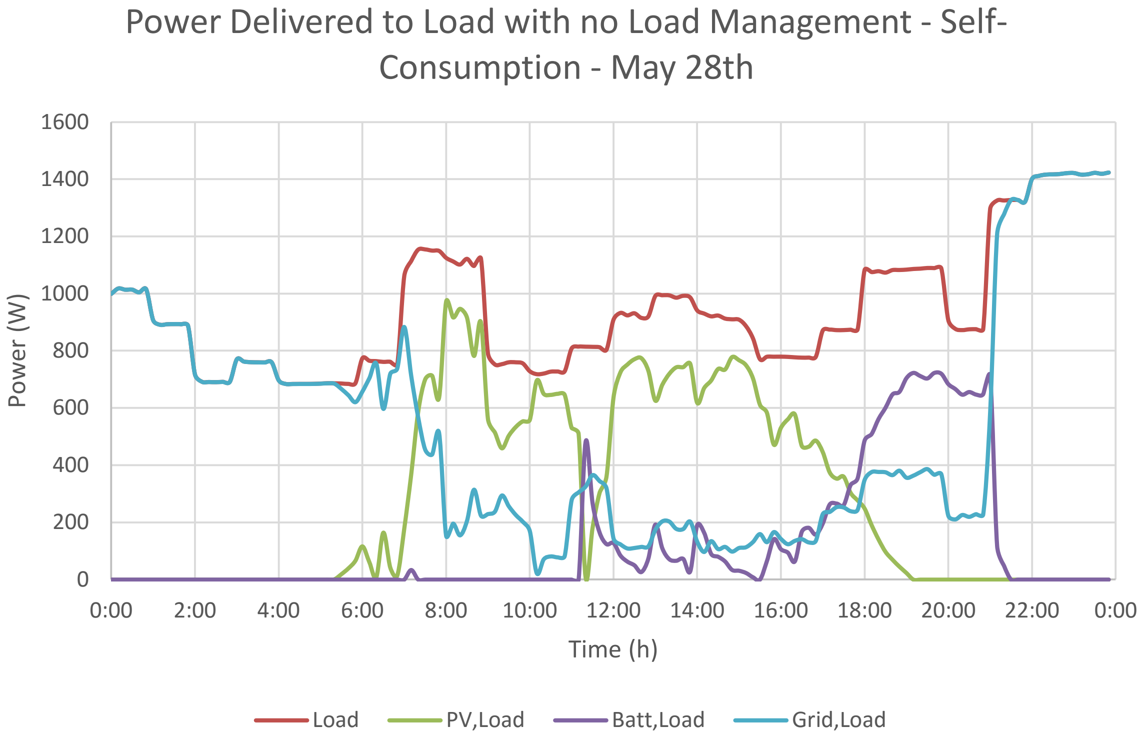


Figure 31. Power delivered to loads with no load management - self-consumption - May 28th.

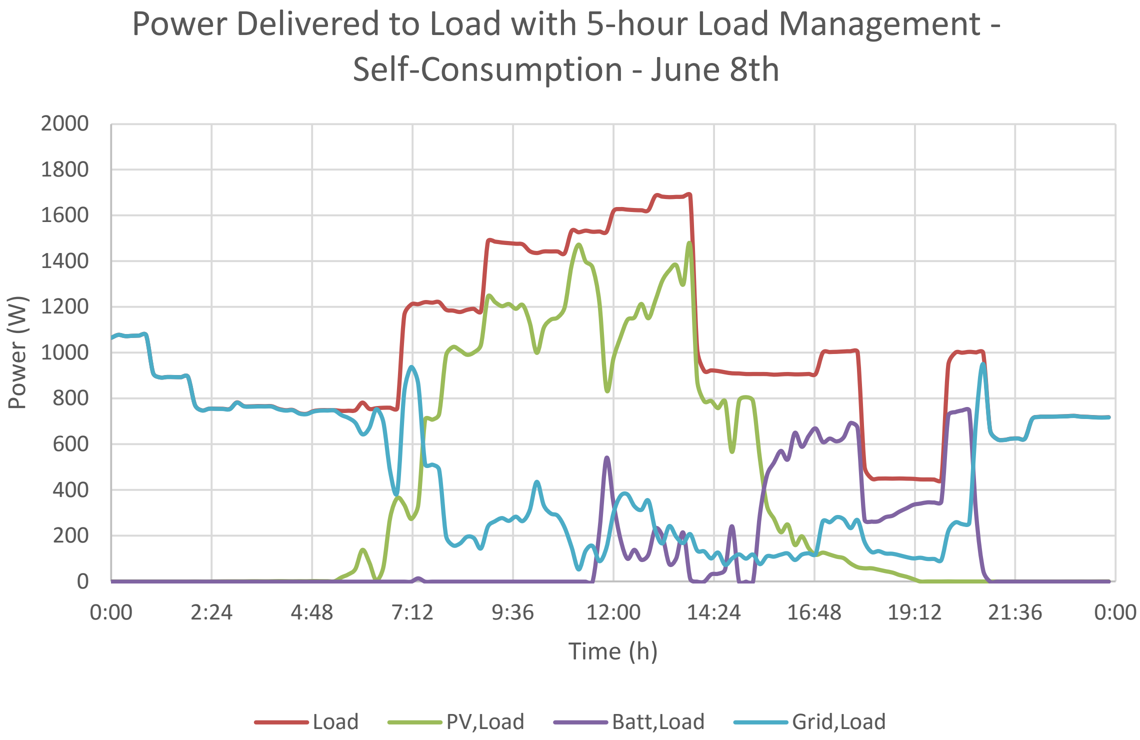


Figure 32. Power delivered to loads with 5-hour load management - self-consumption - June 8th.

Table 5 contains a summary of the findings for the 23 sample days, listed from the lowest to the highest amount of sun hours. The table includes the self-consumption factor for a net metering and a self-consumption system, the total daily energy delivered from PV to loads ($E_{PVsc,Load}$) for the self-consumption system, the total daily energy calculated ($E_{PVnet,Load}$) for the net metering system, the total daily energy delivered from the batteries to the load ($E_{Batt,Load}$) and the total daily energy consumed by the loads (E_{Loads}).

Table 5. *Summary of Findings*

Month	Day	Sun Hours	Load Profile	ξ Net Metering	ξ Self Consumption	$E_{PVsc,Load}$ (kWh)	$E_{PVnet,Load}$ (kWh)	E_{Batt} (kWh)	E_{Load} (kWh)
May	20	0.98	with 3h LM	12.9%	11.5%	2.47	3.07	0.27	23.84
April	30	1.92	without LM	19.5%	22.2%	3.81	4.65	1.47	23.81
May	19	1.93	with 3h LM	15.9%	14.7%	3.34	3.79	0.16	23.80
May	29	2.18	without LM	27.9%	30.4%	5.34	6.05	1.26	21.73
June	5	3.09	with 3h LM	34.4%	39.4%	7.62	8.01	1.56	23.30
June	2	3.43	without LM	31.0%	38.5%	5.95	7.27	3.1	23.46
June	1	3.44	without LM	27.4%	39.4%	5.5	6.44	3.75	23.47
May	31	3.88	without LM	31.2%	39.4%	6.04	7.2	3.03	23.03
May	26	3.95	with 3h LM	38.9%	47.4%	7.86	8.84	2.91	22.74
June	6	4.17	with 5h LM	46.5%	50.0%	9.61	10.9	2.11	23.43
May	30	4.44	without LM	34.9%	41.9%	6.02	7.63	3.14	21.86
June	4	4.71	with 3h LM	39.8%	47.1%	7.65	9.32	3.39	23.45
May	25	5.28	with 3h LM	46.1%	51.4%	8.61	10.56	3.18	22.92
May	27	5.48	with 3h LM	41.5%	49.0%	7.77	9.42	3.36	22.73
June	10	6.1	with 5h LM	50.9%	52.8%	9.46	11.94	2.93	23.45
June	7	6.2	with 5h LM	46.3%	50.3%	8.92	10.87	2.89	23.47
June	3	6.26	with 3h LM	43.3%	47.9%	8.32	10.15	2.92	23.46
April	29	6.27	without LM	36.8%	41.5%	6.77	8.77	3.12	23.83
May	28	6.46	without LM	39.8%	43.4%	6.8	8.97	2.99	22.56
June	8	6.46	with 5h LM	49.3%	53.3%	9.46	11.63	3.13	23.61
June	11	6.65	with 5h LM	48.7%	49.7%	8.59	11.18	2.81	22.95
May	24	6.77	with 3h LM	44.1%	48.2%	7.84	10.12	3.23	22.96
June	9	6.92	with 5h LM	49.1%	52.4%	9.24	11.59	3.14	23.62

Irradiance Analysis

By observing Table 5, it can be seen that there are some sample days that have the same system and similar amount of sun hours but with a significant difference in the self-consumption factor. For instance, if you compare May 25th (5.28 sun hours) with May 27th (5.48 sun hours), it is possible to see that even though the 25th had a lower amount of sun hours, it presented a higher net metering self-consumption factor. The reason behind it is that there was a larger amount of irradiance for the hours with more power consumption on the 25th than on the 27th. Figure 33 shows the irradiance profile for both days and, since both load profiles were very similar, just the May 27th load profile was plotted on the chart. As it can be seen, from 8 to 11am, time of the day that there is a larger power consumption, the irradiance for May 25th is greater than on May 27th, meaning that more PV power was used to supply the loads. It gets a lot more evident when $P_{Grid,Load}$ are plotted on the same graph as it can be seen in Figure 34. It is clear that there was less power draw from the grid for May 25th than for May 27th. Another way to notice this difference based on the irradiance profile is to check the calculated $E_{PV,Load}$. The highest self-consumption factor had the highest $E_{PV,Load}$, 10.56 kWh for May 25th and 9.42 kWh for May 27th.

The same observation can be seen on the self-consumption system. However, since the battery discharges are included on the calculation for the self-consumption factor, the final results might not be as different as it can be for the net metering system.

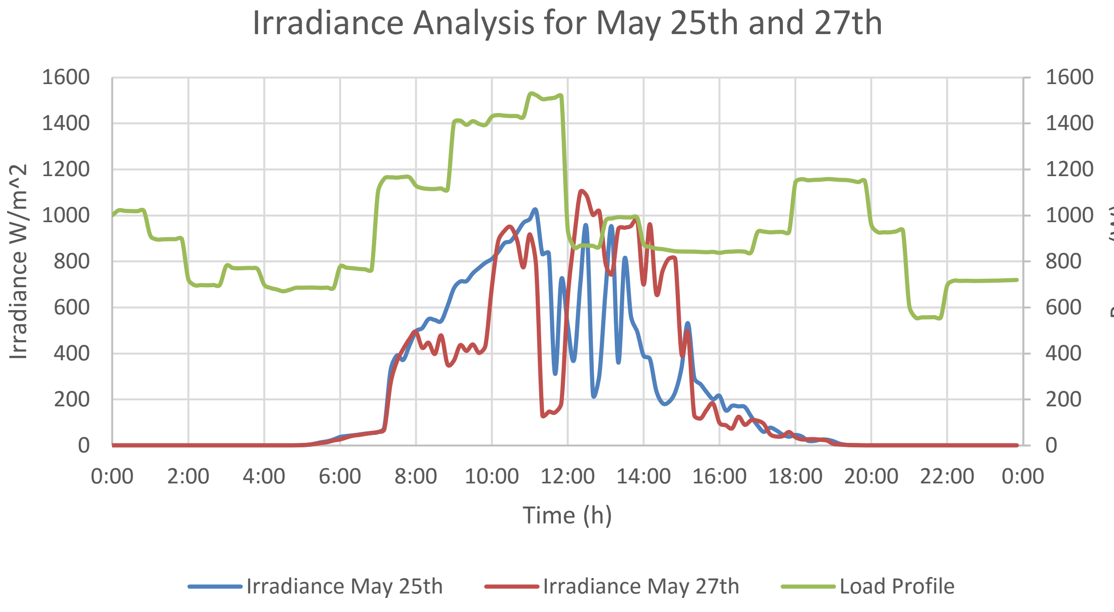


Figure 33. Irradiance analysis for May 25th and 27th.

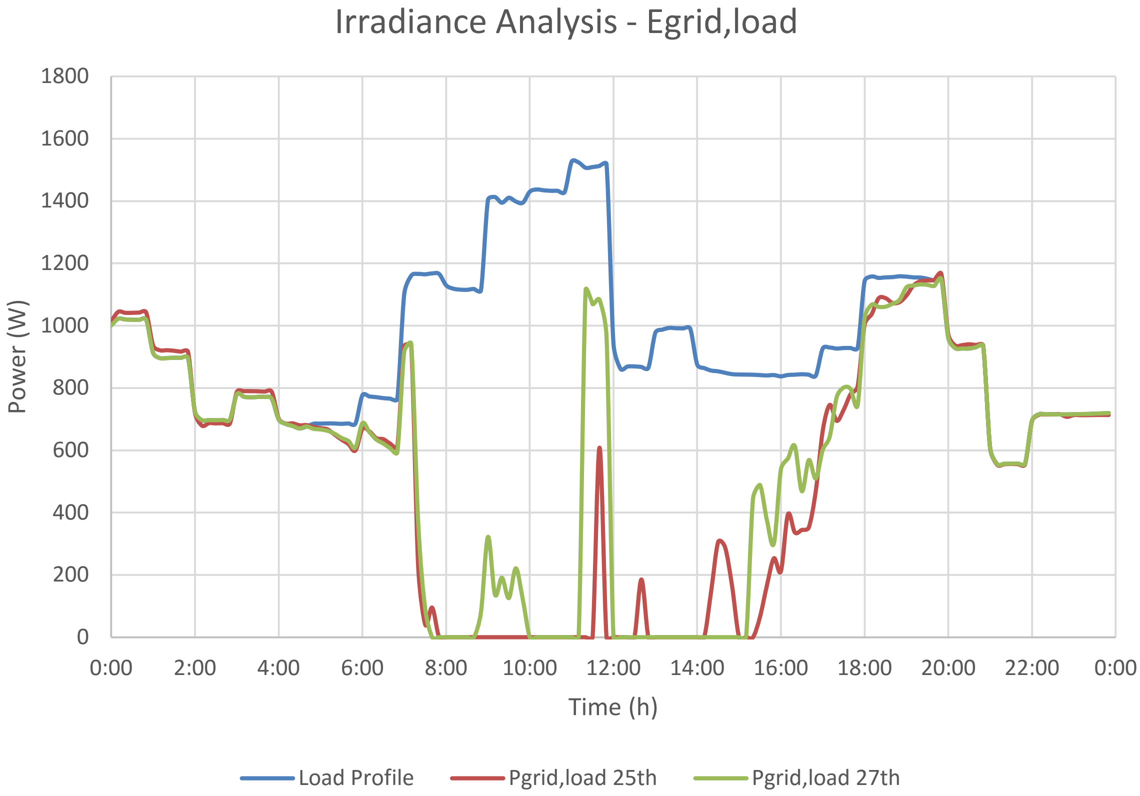


Figure 34. Irradiance analysis - *Egrid,load* - May 25th & 27th.

Grid Export Analysis

So far, all the analysis developed were able to reflect only the amount of self-consumption and, indirectly, grid imports for each system condition. However, it is important to analyze what is the behavior of power export to the grid. In order to do so, it is necessary to calculate the total amount of energy generated by the PV (E_{PV}), the total amount of energy sent to the loads from PV for the net metering system ($E_{PVnet,Load}$) and self-consumption system ($E_{PVsc,Load}$), and the total amount of energy used to charge the battery bank with PV ($E_{PV,Batt}$). Note that all those variables are calculated based on the PV power estimated by equation 7.

To represent the percentage of PV energy exported to the grid, a factor called Grid Export Rate (ι) was created and it is defined by the amount of PV energy used in the system divided by the total amount of energy generated by the PV. In other words, for a net metering system, ι is:

$$\iota = \frac{E_{PVnet,Load}}{E_{PV}} \tag{16}$$

For a self-consumption system, ι is:

$$\iota = \frac{E_{PVsc,,Load}+E_{PV,Batt}}{E_{PV}} \tag{17}$$

Table 6 contains a summary of all findings related to grid exports for all 23 sample days.

Table 6. *Summary of Grid Export Rate (ι)*

Mth	Day	Sun Hours	Load Profile	*ι* Net Metering	*ι* Self-Consumption	*Epvnet,load*	*Epvsc,load* (kWh)	*Epv,batt* (kWh)	*Epv,total* (kWh)
May	20	0.98	with 3h LM	4.1%	3.4%	3.07	2.72	0.37	3.2
April	30	1.92	without LM	22.5%	2.5%	4.65	4.11	1.74	6.0
May	19	1.93	with 3h LM	5.3%	4.8%	3.79	3.51	0.3	4.0
May	29	2.18	without LM	11.0%	2.9%	6.05	4.98	1.62	6.8
June	5	3.09	with 3h LM	16.6%	3.8%	8.01	7.34	1.9	9.6
June	2	3.43	without LM	31.4%	6.2%	7.27	6.29	3.65	10.6
June	1	3.44	without LM	39.2%	7.5%	6.44	5.53	4.27	10.6
May	31	3.88	without LM	40.0%	16.7%	7.2	6.38	3.62	12.0
May	26	3.95	with 3h LM	27.5%	5.2%	8.84	8.07	3.49	12.2
June	6	4.17	with 5h LM	15.5%	3.7%	10.9	9.67	2.75	12.9
May	30	4.44	without LM	44.3%	24.7%	7.63	6.57	3.75	13.7
June	4	4.71	with 3h LM	35.7%	15.7%	9.32	8.23	3.99	14.5
May	25	5.28	with 3h LM	34.8%	18.0%	10.56	9.64	3.65	16.2
May	27	5.48	with 3h LM	43.9%	28.5%	9.42	8.13	3.89	16.8
June	10	6.1	with 5h LM	36.1%	24.2%	11.94	10.67	3.5	18.7
June	7	6.2	with 5h LM	42.8%	30.3%	10.87	9.82	3.43	19.0
June	3	6.26	with 3h LM	47.1%	35.7%	10.15	8.95	3.39	19.2
April	29	6.27	without LM	54.3%	41.7%	8.77	7.55	3.64	19.2
May	28	6.46	without LM	54.5%	42.4%	8.97	7.8	3.55	19.7
June	8	6.46	with 5h LM	41.0%	29.1%	11.63	10.29	3.67	19.7
June	11	6.65	with 5h LM	44.9%	35.3%	11.18	9.85	3.29	20.3
May	24	6.77	with 3h LM	51.1%	38.1%	10.12	9.06	3.75	20.7
June	9	6.92	with 5h LM	45.3%	34.4%	11.59	10.22	3.69	21.2

Based on the data presented on Table 6, it is possible to verify that, the increase in sun hours tend to increase the amount of energy exported to the grid for either type of system. It is simpler to check it for days with the same load profile. Also, regardless of the amount of sun hour or load profile, the self-consumption system will always export less energy than the net metering system, since the PV is also used to charge the battery bank.

Adding load management helps decreasing the amount of grid exports. For instance, comparing May 28th with June 8th, both with 6.46 sun hours, June 8th presented a decrease of about 68% as it performed a 5-hour load management.

CHAPTER 5: CONCLUSIONS

Effects of Sun Hours

For low levels of sun hours (less than 2 hours), it is not possible to predict any improvements in performance on a PV system when adding energy storage and load management. However, when the amount of sun hours is greater than 2 hours, it is possible to obtain a reduction in grid imports, meaning an increase in self-consumption. Figure 35 shows the trend of increase in self-consumption based on sun hours for a load profile without load management.

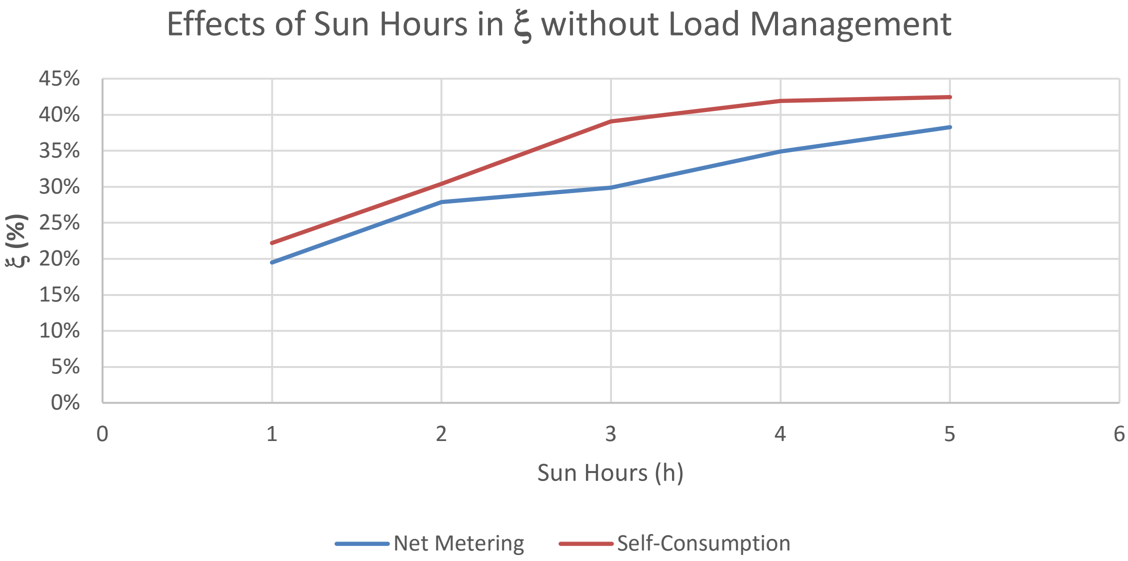


Figure 35. Average increase in ξ without load management based in sun hours.

Although ξ increased when the amount of sun hours increase, the amount of energy exported to the grid also increase since the PV generation also increases. Figure 36 shows the trend of ι based on the amount of sun hours.

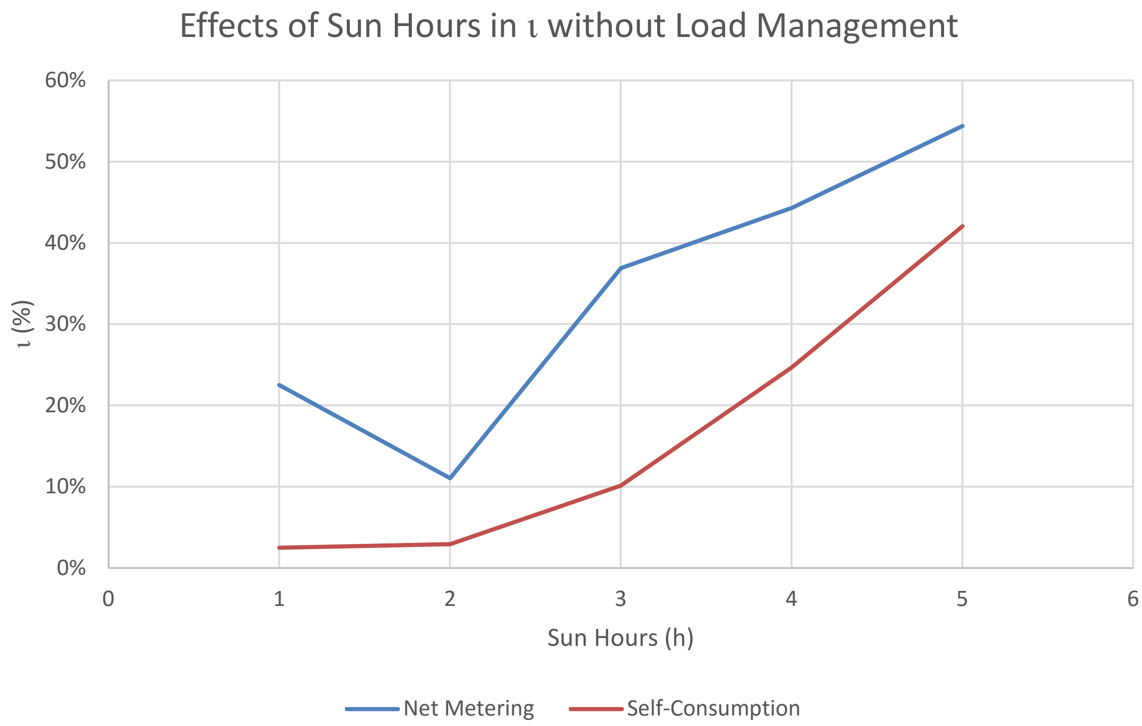


Figure 36. Average increase in *ι* without load management based in sun hours.

Effects of Adding Battery Storage

Assuming that a PV system has the capability of exporting power to the grid, adding a battery storage to this system means that the total amount of PV exports will decrease as the battery bank needs a daily charge according to its usage. However, the difference between both systems decreases with the increase in sun hours. That is due to the system reaching saturation in self-consumption. When that happens, as the systems cannot no longer have a significant increase in self-consumption, they start exporting more energy to the grid. Figure 37 presents the trend for the difference in grid export between the net metering system and the self-consumption system. There is a small difference for the 3-hour load management system for 1 sun hour because the amount of PV used to charge the battery is too low, therefore, the amount of PV sent to the loads for both systems are very similar.

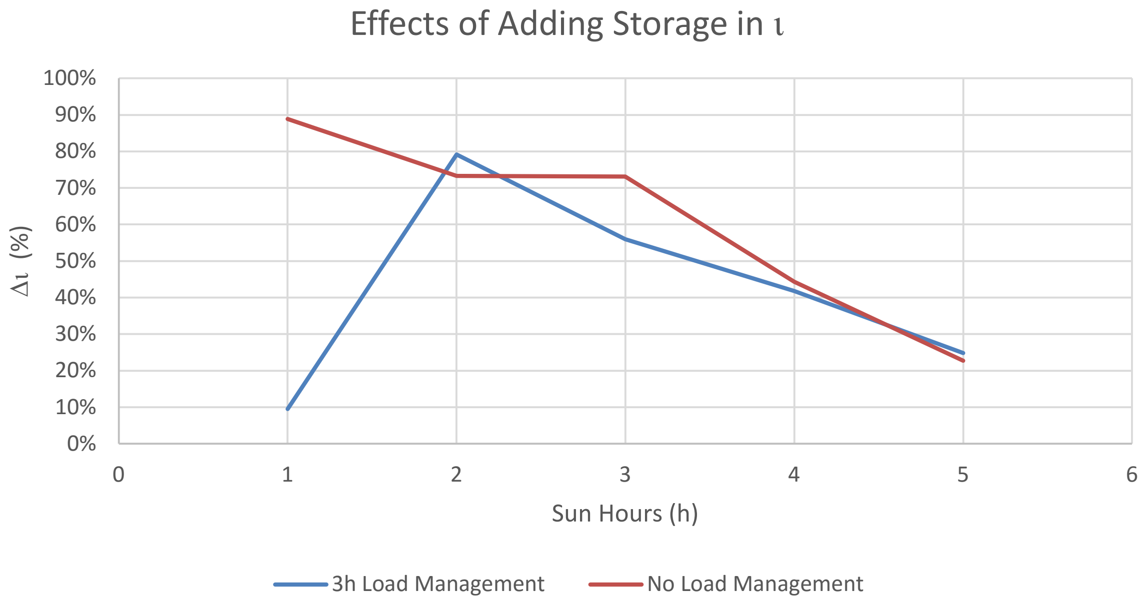


Figure 37. Average difference in ι between a net metering and a self-consumption system.

With the battery bank charged, the energy stored can be used in a time where there is not enough PV generation to supply the load or when there is no generation at all, like during the night. Hence, battery discharges contribute to an increase in self-consumption when compared to a net metering system. However, as mention before, each system reaches a point that self-consumption can longer increase significantly, leading to a decrease in the average difference in self-consumption between both systems, as it shows in Figure 38.

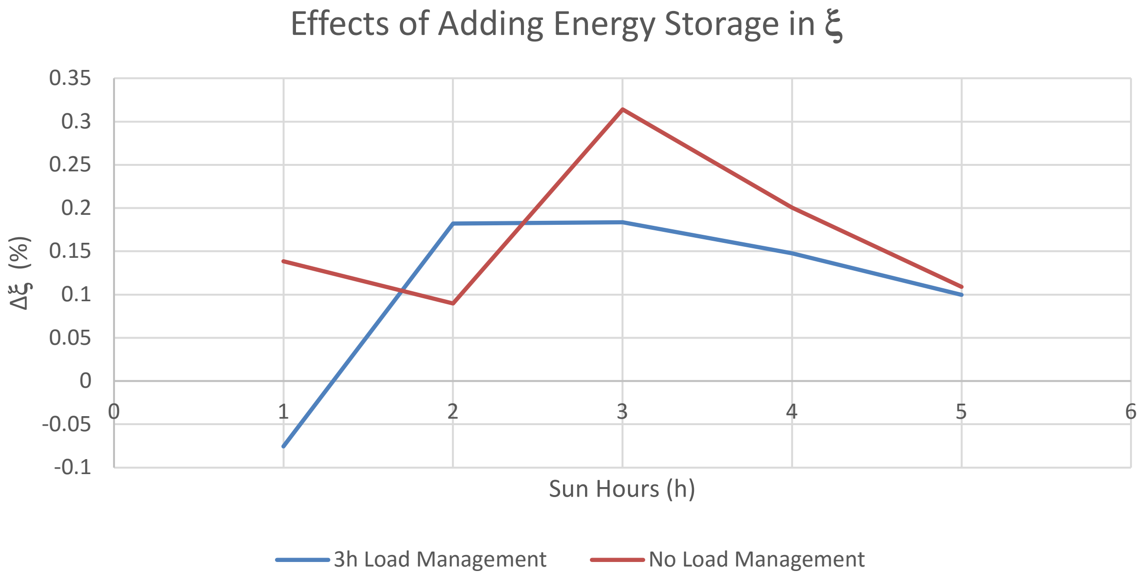


Figure 38. Average difference in ξ between a net metering and a self-consumption system.

Effects of Adding Load Management

When comparing days with a similar amount of sun hours, it is possible to verify improvements from having a system with no load management load profile to a 3-hours or 5-hours load management load profile since the loads that were supposed to be powered by the grid at night will be powered by the PV system when there is enough irradiance during the day. For instance, comparing May 28th (no load management) to May 24th (3 hours load management) there was an improvement in self-consumption of 11% for both net metering and self-consumption system. When compared to June 8th, there was an improvement of 23%.

The same happens for the amount of grid exports. As the total self-consumption increases with the increase in sun hours, the energy export will decrease since there will be more loads available to be powered by the PV system.

Effects of Irradiance Profile

It is known that a total amount of sun hours can be the same for 2 different days. However, the irradiance profile can be completely different. It can be sunnier around noon for one day while the other is sunnier in the afternoon. With that said, the load profile will make a difference when calculating the self-consumption factor. If the PV generation is high when the loads consume more power, the amount of power sent to the loads will be greater than when there is a high amount of PV generation for a small load consumption. May 25th and 27th are a good example for that. The increase is greater for a net metering system since the battery is not part of the equation, meaning that it can have different amount of discharges, but an improvement in self-consumption can still be seem when energy storage is added to the system.

Recommendations for Further Researches

This research was able to show methods that can optimize a self-consumption system. However, the performance might change for different load profiles and locations. With that said, creating a computer model that can reproduce the weather conditions, load profile, PV generation and battery charges/discharges, will help on sizing the PV array and the battery bank in order to reach higher levels of self-consumption.

Another topic that can be studied is the economic analysis for the system to verify the advantages that improving self-consumption can bring to the costumer. For the same study, the batteries can also be charged/discharged based on the energy ratings throughout the day.

As the irradiance profile affects the total self-consumption, a load management system can be developed to be dynamic by shifting loads based on the weather forecast.

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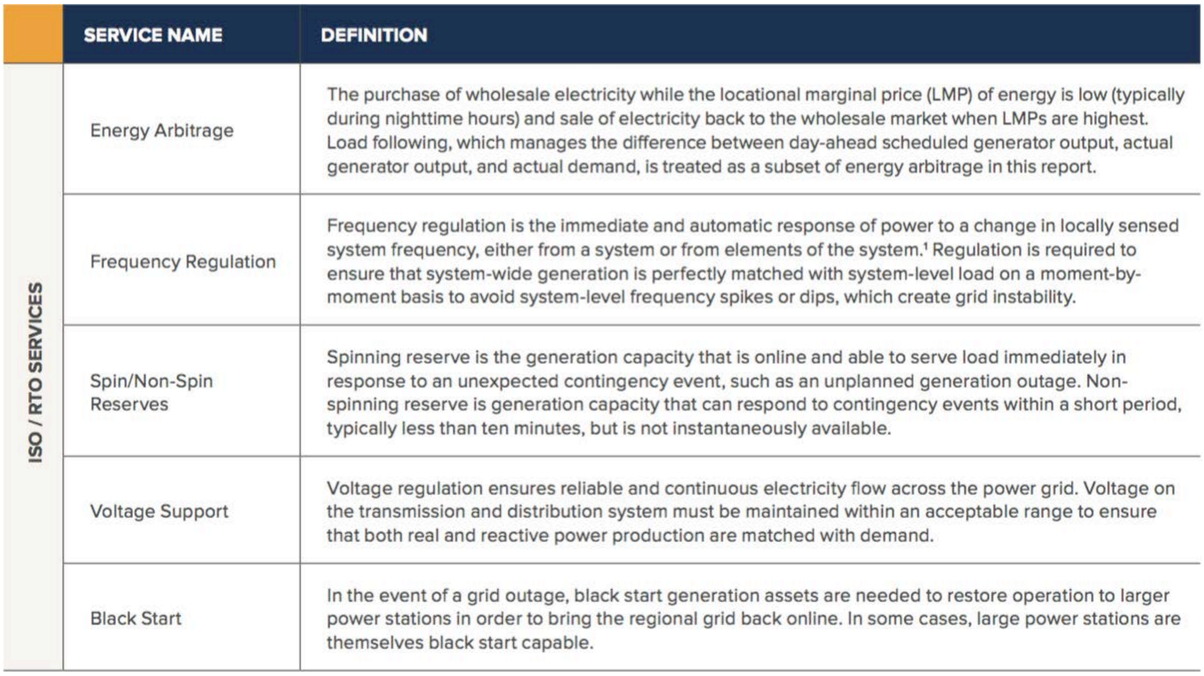
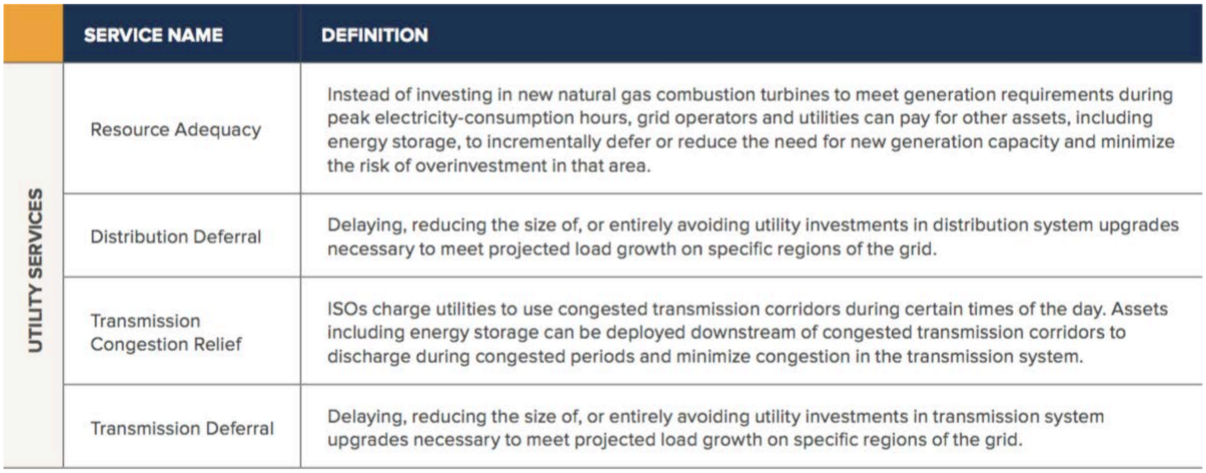
APPENDIX A: SERVICES PROVIDE BY ENERGY STORAGE

Table A. 1 *ISO/RTO Services (Rocky Mountain Institute, 2015, p. 6)*



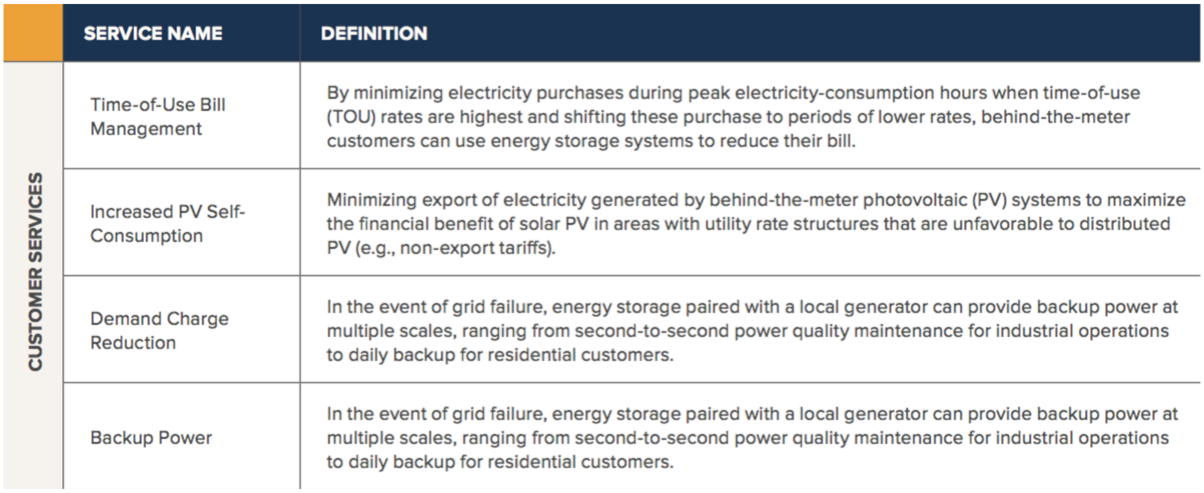
	SERVICE NAME	DEFINITION
ISO / RTO SERVICES	Energy Arbitrage	The purchase of wholesale electricity while the locational marginal price (LMP) of energy is low (typically during nighttime hours) and sale of electricity back to the wholesale market when LMPs are highest. Load following, which manages the difference between day-ahead scheduled generator output, actual generator output, and actual demand, is treated as a subset of energy arbitrage in this report.
	Frequency Regulation	Frequency regulation is the immediate and automatic response of power to a change in locally sensed system frequency, either from a system or from elements of the system.[1] Regulation is required to ensure that system-wide generation is perfectly matched with system-level load on a moment-by-moment basis to avoid system-level frequency spikes or dips, which create grid instability.
	Spin/Non-Spin Reserves	Spinning reserve is the generation capacity that is online and able to serve load immediately in response to an unexpected contingency event, such as an unplanned generation outage. Non-spinning reserve is generation capacity that can respond to contingency events within a short period, typically less than ten minutes, but is not instantaneously available.
	Voltage Support	Voltage regulation ensures reliable and continuous electricity flow across the power grid. Voltage on the transmission and distribution system must be maintained within an acceptable range to ensure that both real and reactive power production are matched with demand.
	Black Start	In the event of a grid outage, black start generation assets are needed to restore operation to larger power stations in order to bring the regional grid back online. In some cases, large power stations are themselves black start capable.

Table A. 2 *Utility Services (Rocky Mountain Institute, 2015, p. 16)*



	SERVICE NAME	DEFINITION
UTILITY SERVICES	Resource Adequacy	Instead of investing in new natural gas combustion turbines to meet generation requirements during peak electricity-consumption hours, grid operators and utilities can pay for other assets, including energy storage, to incrementally defer or reduce the need for new generation capacity and minimize the risk of overinvestment in that area.
	Distribution Deferral	Delaying, reducing the size of, or entirely avoiding utility investments in distribution system upgrades necessary to meet projected load growth on specific regions of the grid.
	Transmission Congestion Relief	ISOs charge utilities to use congested transmission corridors during certain times of the day. Assets including energy storage can be deployed downstream of congested transmission corridors to discharge during congested periods and minimize congestion in the transmission system.
	Transmission Deferral	Delaying, reducing the size of, or entirely avoiding utility investments in transmission system upgrades necessary to meet projected load growth on specific regions of the grid.

Table A. 3 *Customer Services (Rocky Mountain Institute, 2015, p. 16)*



	SERVICE NAME	DEFINITION
CUSTOMER SERVICES	Time-of-Use Bill Management	By minimizing electricity purchases during peak electricity-consumption hours when time-of-use (TOU) rates are highest and shifting these purchase to periods of lower rates, behind-the-meter customers can use energy storage systems to reduce their bill.
	Increased PV Self-Consumption	Minimizing export of electricity generated by behind-the-meter photovoltaic (PV) systems to maximize the financial benefit of solar PV in areas with utility rate structures that are unfavorable to distributed PV (e.g., non-export tariffs).
	Demand Charge Reduction	In the event of grid failure, energy storage paired with a local generator can provide backup power at multiple scales, ranging from second-to-second power quality maintenance for industrial operations to daily backup for residential customers.
	Backup Power	In the event of grid failure, energy storage paired with a local generator can provide backup power at multiple scales, ranging from second-to-second power quality maintenance for industrial operations to daily backup for residential customers.

APPENDIX B: ARDUINO SKETCH – LOAD PROFILE

```
#include <Wire.h>
#include "RTClib.h"
#include <SD.h>
#include <Adafruit_ADS1015.h>

// On the Ethernet Shield, CS is pin 4. Note that even if it's not
// used as the CS pin, the hardware CS pin (10 on most Arduino boards,
// 53 on the Mega) must be left as an output or the SD library
// functions will not work.
RTC_DS1307 rtc;
int Load_1 = 2;
int Load_2 = 3;
int Load_3 = 4;
int Load_4 = 5;
int Load_5 = 6;
int Load_6 = 7;

float power_load_1;
float power_load_2;
float power_load_3;
float power_load_4;
float power_load_5;
```

```
float power_load_6;


byte Loads[24][6]={
 {1,1,0,0,0,0},
 {0,1,1,1,0,0},
 {1,0,0,1,1,0},
 {0,1,0,0,0,1},
 {0,0,1,1,1,1},
 {0,1,0,0,1,0},
 {0,1,1,1,0,0},
 {1,1,0,0,0,0},
 {0,1,1,1,0,0},
 {1,0,0,1,1,0},
 {0,1,0,0,0,1},
 {0,0,1,1,1,1},
 {0,1,0,0,1,0},
 {0,1,1,1,0,0},
 {1,1,0,0,0,0},
 {0,1,1,1,0,0},
 {1,0,0,1,1,0},
 {0,1,0,0,0,1},
 {0,0,1,1,1,1},
 {0,1,0,0,1,0},
```

```
 {0,1,1,1,0,0},
 {1,1,0,0,0,0},
 {0,1,1,1,0,0},
 {1,0,0,1,1,0}
};

void setup () {

  pinMode(Load_1, OUTPUT);
  pinMode(Load_2, OUTPUT);
  pinMode(Load_3, OUTPUT);
  pinMode(Load_4, OUTPUT);
  pinMode(Load_5, OUTPUT);
  pinMode(Load_6, OUTPUT);

  Serial.begin(9600);

  rtc.begin();
  if (! rtc.isrunning()) {
    Serial.println("RTC is NOT running!");
    // following line sets the RTC to the date & time this sketch was compiled
    rtc.adjust(DateTime(F(__DATE__), F(__TIME__)));
    // This line sets the RTC with an explicit date & time, for example to set
```

```
    // January 21, 2014 at 3am you would call:
    // rtc.adjust(DateTime(2014, 1, 21, 3, 0, 0));
  }

  // see if the card is present and can be initialized:
  if (!SD.begin(chipSelect)) {
    Serial.println("Card failed, or not present");
    // don't do anything more:
    return;
  }
  Serial.println("card initialized.");
//**************************************************************
}
void loop () {
     DateTime now = rtc.now();
     digitalWrite(Load_1, Loads[now.hour()][0]);
     digitalWrite(Load_2, Loads[now.hour()][1]);
     digitalWrite(Load_3, Loads[now.hour()][2]);
     digitalWrite(Load_4, Loads[now.hour()][3]);
     digitalWrite(Load_5, Loads[now.hour()][4]);
     digitalWrite(Load_6, Loads[now.hour()][5]);
}
```

APPENDIX C: INVERTER CONFIGURATION

App State Univ Settings	-	-
Configuration is AC-coupled system.		
	-	-
Schneider Inverter Settings		
Setting Name	**Setting**	**Comments**
Type	XW5548+	Not an actual setting. Information provided for reference only. Record model #, serial # and firware revision, available under System Settings -> View Device Info Example: Model #: 865-5548-01 Serial #: 000018465944 F/W Rev.: 2.01.00 BN21
Inverter	Enabled	
Search Mode	Disabled	
Grid Support	Enabled	
Charger	Enabled	
Mode	Standby	***NOTE: Make changes to settings while in Standby Mode. Return to Operating Mode once complete.***
Inverter Settings		
LBCO	44V	Represents 3.14V/cell.
LBCO Hyst	1V	
LBCO Delay	10 sec	
HBCO	58.8V	Represents 4.20V/cell. Maximum recommended battery voltage from Samsung for charge.
HBCO Hyst	2V	This setting is not configurable with the Connext SCP programming tool. This is the default setting. NOT SHOWN.
Search Watts	50W	Search mode not enabled. Setting provided for reference only.
Search Delay	2 sec	Search mode not enabled. Setting provided for reference only.

Charger Settings		
Battery Type	Custom	
Custom Settings		
Equalize Voltage	57.4V	Represents 4.10V/cell (90% SoC per Samsung for 18650-22P cell). *NOTE: Equalize voltage is not used for LiIon battery pack and is not used when Equalize Support is disabled on the XW+ inverter, but it should be set in case the Equalize mode is inadvertantly enabled. SET THIS FIRST.*
Equalize Support	Disabled	
Bulk Voltage	57.4V	Represents 4.10V/cell.
Absorb Voltage	57.4V	Represents 4.10V/cell.
Float Voltage	57.4V	Represents 4.10V/cell. *NOTE: Float voltage is not used in 2 Stage, No Float charging mode, but Float Voltage should be set in case charge mode is inadvertantly changed to a mode which includes the float stage.*
Batt Temp Comp	-108mV/C	
Batt Capacity	172Ah	
Max Charge Rate	39%	Percentage is of Continuous Current Rating of inverter (140A on XW6448, 110A on XW5548). 39% on XW5548 yields 42.9A (which is approximately 1/4C for four 14S20P Nexcon battery packs: (2150mA / 4) x 20 x 4 = 43,000mA = 43A). ***NOTE:*** *this setting is NOT tied to the Max Bulk Current setting.*
Charge Cycle	2StgNoFloat	Two stage, no float charge type.
Default Battery Temp	Warm	
Recharge Voltage	51.3V	Represents 3.66V/cell. No charge occurs above this setting *from the grid, but charging from the PV system is not affected by this setting*. Voltage must drop to this level before charging from AC1 (IN) will start. *NOTE: In an AC-coupled system, the solar inverter output is tied to AC-LOAD, not AC1 (IN).*

Absorption Time	60 min	
Charge Block Start	6:00PM	Charge Block Start and Stop may be customer/region specific settings and subject to change based on local regulations.
Charge Block Stop	8:00am	

AC Settings		
AC Priority	AC1	
AC1 Breaker Rating	60A	This setting is tied directly to the breaker used in the inverter and MUST be changed if the physical breaker is changed to a lower/higher value.
AC1 Min Volt	106V	
AC1 Max Volt	132V	
AC1 Min Freq	55Hz	
AC1 Max Freq	65Hz	
AC2 Breaker Rating	60A	*NOTE(S):* *Typically no generator is attached to AC2 - review settings if installation includes a generator.* *This setting is tied directly to the breaker used in the inverter and MUST be changed if the physical breaker is changed to a lower/higher value.*
AC2 Min Volt	80V	*NOTE: Typically no generator is attached to AC2 - review settings if installation includes a generator.*
AC2 Max Volt	138V	*NOTE: Typically no generator is attached to AC2 - review settings if installation includes a generator.*
AC2 Min Freq	55Hz	*NOTE: Typically no generator is attached to AC2 - review settings if installation includes a generator.*
AC2 Max Freq	65Hz	*NOTE: Typically no generator is attached to AC2 - review settings if installation includes a generator.*

Grid Support Settings		
Grid Support Voltage	51.3V	Represents 3.6V/cell. Grid Support is the level to which the batteries will discharge to sell to the grid. Ideally this setting should be at or below the Recharge Voltage setting if the system is expected to charge cycle based on grid discharge.
Sell	Disabled	This setting is dependent on customer preference and/or local/regional regulatory requirements.
Max Sell Amps	5.0A	Typically this setting is set based on maximum available PV output. Unless Enhanced Grid Support is enabled, inverter will try to meet the Max Sell Amps setting by making up any shortfall from battery storage. ***NOTE:** Max Sell Amps is an AC setting (per AC line), not a DC setting. For example: if Vbat = 55V and Max Sell Amps = 5A (per AC leg, at two legs = 10A total), then (AC) 10A x 120V = 1200VA; thus (DC) 1200VA / 55V = ~21.8A (drawn from DC/battery).*
Load Shave	Disabled	
Load Shave Amps	48.0A	Load Shave disabled. Setting provided for reference only.
Load Shave Start	12:00AM	Load Shave disabled. Setting provided for reference only.
Load Shave Stop	12:00AM	Load Shave disabled. Setting provided for reference only.
Sell Block Start	11:00PM	
Sell Block Stop	6:00PM	
Generator Settings		
Gen Supp Mode	Disabled	
Gen Supp Amps	48.0A	*NOTE: This setting will be set based on the support generator if implemented. Typical installations have not included generator support.*

Aux Settings		
Manual Aux	ManualOff	*NOTE: Future JuiceBox control firmware may toggle this under its control to manually control a relay to control the output from an AC-coupled solar inverter.*
Active Level	ActiveHigh	
Advanced Features		
RPO	Disabled	*NOTE: Future JuiceBox control firmware may toggle this under its control to manually control Remote Power Output.*
Power Save	Disabled	
Sell Delay 40s	Disabled	
Gen Support Plus	Disabled	
AC_Coupling	Enabled	
Batt_Balance	Disabled	
Peak Load Shave Delay 2 Hours	Disabled	NOTE: Enabling this setting will allow the MPPT solar charge controller (in DC-coupled systems) to charge the batteries first, then (after two hours expires), Peak Load Shave mode (if enabled) would be entered for AC Load Support.
Miscellaneous (not settable with SCP)		
Max Bulk Current	80.0A	
Discharge Imax	150%	There is a mismatch between CommBox and SCP. One shows as Amps (CommBox) the other as percent (SCP). Changing the parameter on either side shows the SAME value (in native unit) on the other device when read. For example setting 60A will read as 60%, setting 140% will read as 140Amps.
Discharge Time	10 sec	

Vita

Pedro Rabelo Melo Franco was born in Belo Horizonte, Minas Gerais – Brazil. He attended primary and secondary school there and graduated from high school in the fall 2006. He then enrolled at the Centro Federal de Educação Tecnológica de Minas Gerais, and he was awarded the Bachelor of Science degree in Electrical Engineering in 2012. He completed his Master of Science in Technology degree with a concentration in Renewable Energy Engineering at Appalachian State University in summer 2016. While at Appalachian State University, he served as a member in the Renewable Energy Initiative, as the electrical director for the Solar Vehicle Team and as a graduate assistant in the Nexus Project.