MINIMIZING GRID INTERACTION WITH A RESIDENTIAL SELF-CONSUMPTION SYSTEM THAT INCLUDES PV AND BATTERY STORAGE

A Thesis
by
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Abstract

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As development of the solar photovoltaic (PV) industry continues to expand so too will concerns about the effects intermittency will have on the stability of the utility grid. In order to reduce concerns about PV's presence on the grid, as well as to preserve the value of PV electricity for residential PV homeowners, one solution may be the installation of self-consumption PV systems with battery storage. A self-consumption system can be defined as one that prioritizes electricity consumption by the electricity producer, therefore minimizing grid interaction. Self-consumption has been shown to be regularly enhanced by the accompaniment of a battery storage system, although the extent of this varies by system component capacity and installed region. This study examines the effect a PV and battery storage self-consumption system has on a model residential home in Boone, NC and its interaction with the utility grid. To quantify self-consumption this study deploys two means of measurement, demand reduction and grid import reduction. Demand reduction can be characterized as the difference in power between the load power and the grid power as a result of the self-consumption system. Grid import reduction is a measurement of how much energy the home can provide for itself relative to how much it would require from the grid if the self-consumption system was not present. In both scenarios the performance of the self-consumption system is compared to the performance of a model system that has installed PV but no battery storage. It is to be seen to what extent can a self-consumption system with PV and battery storage minimize grid interaction in Boone, NC.

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Special thanks to Pedro Franco and Zachary Sprau, the authors of the predecessor theses that much of my work here is based on. Here’s to hoping my work is not the last on the topic of self-consumption at the Appalachian State University solar lab. Best wishes to whomever may choose to follow this path.

Finally, I would like to thank my partner Margaret Anixter, my family, and all my friends. Without whom none of this would have been worth it anyways. Thank you for supporting me and my endeavors.

Table of Contents

List of Tables

List of Figures

CHAPTER 1: INTRODUCTION

Introduction and Problem Statement

Solar photovoltaic (PV) electricity generation has been on the rise for the past few decades and has been one of the top two electricity generating installed capacity sources in the United States for the past six years in a row, along with natural gas (Perea et al., 2019). This growth, however, doesn’t come without its share of drawbacks. PV modules only generate electricity when the sun is shining, leading to a disconnect between electricity generation and electricity demand. That disconnect means PV is non-dispatchable and cannot necessarily be relied on when energy needs fluctuate (Luthander, Widen, Nilsson, & Palm, 2015). This shortcoming can be analyzed in several ways, including looking at a generator’s capacity factor, which is a measurement of the time an electricity generator is available. PV generally has a capacity factor of only about 20%, while most fossil fuel facilities have a capacity factor between 85-90% (Letcher, 2014).

A large amount of electricity with limited reliability, as is characteristic of PV, can cause stress on utility companies who must accept PV even when it is not needed and must also supplement the electricity supply when PV is not producing (Luthander et al., 2015). Some utility companies have begun to combat the negative effects of PV by making residential PV less attractive to homeowners. This is being done by using such strategies as decreasing feed-in tariffs to below the value of the electricity for customers and by rejecting net metering policies in locations where they were once in place (Schwartz, 2016).

However, there are other ways to lessen these negative effects without stifling PV expansion. In order to reduce the strain on utility companies caused by residential PV, and to maximize and protect the value of a homeowner’s solar installation, one solution is installing a self-consumption system. A self-consumption system can simply be considered a system where PV-generated electricity is consumed by the PV owner rather than simply being sent to the grid. This is often done with the inclusion of energy storage (Luthander et al., 2015). It is important to understand to what extent a self-consumption system could impact the grid interaction of a home in Western North Carolina. By reducing grid interaction, the goal is to minimize the amount of electricity sent to, and drawn from, the grid, all the while earning higher value from the electricity produced on site. Previous research in this field of study was limited by its short data collection periods, a lack of consistent data sets, and poor load reliability (Sprau, 2017). Other research was also limited by its short data collection period as well as insufficient load profile modeling intervals, which did not accurately describe energy usage in a residential building (Franco, 2016).

Purpose of Study

This study's purpose is to examine a model residential building with a PV array and energy storage system that are configured to prioritize self-consumption. The loads in this study are fabricated, repeat daily, and are based on expected residential loads for a region similar to where the system is installed. While the loads are fabricated the PV array, energy storage system, and all other components are real and exist at Appalachian State University's State Farm Solar Lab. The goal of this study is to determine to what extent a self-consumption system with PV and battery storage can minimize grid-interaction.

Research Question

To what extent can a self-consumption system with PV and battery storage minimize grid interaction in a typical residential home in Boone, NC?

Limitations of the Study

The system used in the study is somewhat unique and the results of this study therefore hold more relevance to systems with similarly sized components. However, these findings have some applicability to differently sized residential self-consumption systems in general.

The load profile used in this study is fabricated based on models of a residential home in Bristol, TN made available by the U.S. Department of Energy (DOE). This model was chosen as the basis for this study as there is no load profile of any kind available for Boone, NC and Bristol, TN is the most similar region geographically to Boone, NC with load profile models available. The load profile emulates the expected loads of a typical residential home in the Boone, NC area but it is not a perfect model of a residential home in Boone, NC. In addition, the model the load profile is based on only provides hourly load profiles for an entire year while the load profile is based on a five-minute time stamp and repeats daily. The hourly to five-minute difference is fabricated. The same load profile is repeated daily although the solar irradiance and other weather conditions vary on the day.

This study has a time constraint. Ideally this study would be conducted over the course of at least one full year. Due to the need for this study to be completed by the Spring of 2020 the period of data collection only lasts a few months. It is a goal of this study to continue to collect data for this system past these dates, but any information collected past this period does not appear in the final report of this specific thesis.

Assumptions

There are several assumptions included within this study. It is assumed that the results only perfectly apply to a self-consumption system of equivalent size. If, for example, the size of the battery bank or PV array were to increase, one would expect at least slightly different results.

It must be assumed that an actual self-consumption system attached to real loads would differ from the loads modeled in this study. Loads don’t traditionally operate on a schedule that is perfectly divisible by the five-minute time stamp and that is what loads modeled in this study are limited to. The model used in this study is not a perfect model of real-time energy use.

In addition, it must be assumed that the home used for the load profile in this study is a reasonably typical home that has gas heating. It is difficult to understand and measure what a truly average home energy use profile would look like. This study assumes the load profile modeled is typical.

Significance of Study

The findings of this study are relevant to homeowners who have installed PV, renewable energy companies, and utility companies. Self-consumption offers a possible solution to preserving the value of PV-generated electricity for homeowners. Renewable energy companies may be interested in the application of the products used in this study because their impacts may drive customers towards or away from specific energy products. Utility companies may be interested in the ability of self-consumption to reduce stress on the electric grid by reducing demand peaks and allowing for renewable energy growth without causing disruptions or inconveniences for the electric grid.

In addition, the vast majority of self-consumption studies have been conducted in European markets (Luthander et al., 2015). No publishable data set has ever been produced by

Appalachian State University’s State Farm solar lab. This study expands the existing information available regarding the self-consumption of PV generated electricity in the United States.

CHAPTER 2: REVIEW OF LITERATURE

Residential PV System and Utility Company Relationships

The vast majority of residential solar PV installations are grid-connected (Luthander et al., 2015). Because of this, a complex relationship exists between these PV systems and the utility grids into which they feed energy into. The following section exists to provide some context into that relationship.

Installation Trends in Residential PV in the United States

In 2018 the United States added a total of 10.6 gigawatts (GW) of solar PV-generated capacity. This marks the sixth year in a row solar PV was one of the top two sources of new generated capacity in the United States, with the other source being natural gas. This growth is expected to continue, with the total installed solar PV capacity expected to double over the coming five years before the expiration of the residential federal investment tax credit (ITC) and the reduction of the commercial tax credit to just 10% for future projects (Perea et al., 2019).

Within the residential PV industry, 2018 saw the the addition of 314,600 new residential PV systems, totaling to 2.5 GW of newly installed capacity. This marks a 7% increase in growth within the residential market from 2017 (Perea et al., 2019). The majority of residential PV systems are grid connected, which means there is little incentive for PV system owners to attempt to match PV production and local consumption. This in contrast to off-grid PV system owners, who must match or account for these values to maintain an operating system (Luthander et al., 2015).

The Costs and Benefits of Residential PV in the United States

In order for PV-generated electricity to become a large portion of generated capacity in the United States it needs to have a levelized cost of electricity (LCOE) that is at or below the rates that utility companies charge. LCOE can be defined as a life cycle cost measurement, often measured in cost per kilowatt hour, that accounts for all up-front installation costs as well as any operating costs over the lifespan of the investment. It is also the break-even value that a PV electricity producer would need to reach in sales revenue to justify investment into PV. In many places this has been achieved and the rapid expansion of PV-generated capacity is largely due to falling prices of PV and its system components as well as policies that have been beneficial to PV installation and PV electricity production. The average cost of a PV module has decreased from about $4.00 a watt in 2007 to roughly $0.35 a watt in late 2017. The cost of PV system components such as inverters, trackers, structural components, and electrical components are falling annually at a rate of about 5-7% (Comello, Reichelstein, & Sahoo, 2018).

Policies that exist to promote PV installation operate by compensating for the gap between the cost of PV production and the revenue that is generated by utilizing or selling PV-generated electricity. Examples of these policies included feed-in-tariffs (FiT), quota and trading systems, portfolio standards, tax credits, and pricing laws. FiT account for the greatest share of these incentives globally (Luthander et al., 2015), but have seen somewhat limited deployment in the United States. In 2013 only Washington, Oregon, California, Hawaii, Vermont, and Maine mandating it by law and a handful of utility companies such as the Tennessee Valley Authority and Dominion Energy offer a similar program voluntarily (Energy Information Administration, 2013). Since then there has been some, but limited, development of FiT programs in the United States (Trabish, 2016). In the United States two of most important policies that have helped grow the PV-generated capacity up to this point are the federal investment tax credit and net metering, which is allowed by various utilities across the country (Comello et al., 2018).

The federal investment tax credit.

The federal investment tax credit currently provides a 30% rebate on PV, provided the investor owes a sufficient amount of income taxes that year. However, this percentage only applies to installations that begin construction before the end of 2019, because the United States Congress has enacted a “sliding scale” that will lower the value of the tax credit over a few years. In the year 2020 the tax credit steps down to 26%, then to 22% in 2021, then to 10% in 2022 (Comello et al., 2018).

Net metering.

Net metering is currently available in select locations in 43 different U.S. states and has been used to incentivize PV installation. Net metering is a utility structure wherein a residential PV owner has a meter that will run backwards when electricity is being generated beyond what is necessary for self-consumption; included in the utility bill will be a measurement of net imports rather than total imports. This means for utility customers that have a net metering system electricity exported to the grid holds the same value as the electricity imported from the grid (Gautier, Jacqmin, & Poudou, 2018). However, for utility companies this means that they are forced to purchase surplus PV electricity at retail rates when a utility would otherwise generate an equal amount of electricity at a wholesale rate. This increased cost to the utility company translates to a higher cost of energy for utility customers. The benefits net metering provides for PV-owning customers is therefore transferred to all utility customers as a cost, because of this some public utility commissions have begun to treat net metering as a regulatory issue and some utilities have started to formulate plans to discourage net metering. As a result, some utility companies have ended net metering program all together, some have decreased the value of exported PV-generated electricity (in the worse cases below the customer’s LCOE), and others have started to charge customers who net meter a higher monthly fixed cost (Comello & Reichelstein, 2017).

In addition, due to the equal value of imports and exports in net metering programs, true self-consumption is not promoted because electricity exports are of equal value to self-consumption. In effect the grid becomes an artificial energy storage system to the utility customer, and there is no incentive to further synchronize electricity production and consumption. This desynchronization is what leads to grid instability and strain on utility companies (Gautier et al., 2018).

Renewable portfolio standards, RECs, and SRECs.

Renewable portfolio standards (RPS) have been enacted in various states and mandate that utility companies must generate a certain percentage of their electricity from renewable energy resources. To help accomplish this, states with RPS create a system that allow for utilities to purchase credits to meet these goals. These credits are known as renewable energy credits (RECs), or in some cases as solar specific renewable energy credits (SRECs), and each credit represents electricity generated by a renewable resource. Each REC and SREC has a unique identification number which is associated with information regarding where the electricity was generated, what renewable resource was used, and the date the electricity was generated (Energysage, 2019). These RECs and SRECs are then traded on an exchange that allow for a utility to purchase or sell RECs in order to meet electricity portfolio requirements. These portfolio standards often evolve over time, and requirements generally vary between different state's RPSs (Comello et al., 2018). It is important to note that since it is impossible to trace what source electricity on the grid comes from RECs and SRECs merely represent the clean energy attributes of renewable energy not the energy itself. In other words, there is no buying or selling of electricity within a system that uses RECs and SRECs. It is also true that once purchased a REC and SREC cannot be sold again. The most important feature of a REC or SREC is that they allow for a utility company to meet RPSs without physically building renewable energy facilities themselves. This flexibility is especially important when a utility is unable or unwilling to construct renewable energy facilities themselves.

While RECs and SRECs are often associated with RPS's mandated by state-level governments in some cases RECs and SRECs can be purchased by individuals, organizations, or businesses voluntarily, which is done most often to reduce the REC/SREC buyer's carbon footprint or to generally support renewable energy resources. Voluntary buyers usually make the decision to buy REC/SRECs for environmentally conscious reasons rather than to meet government mandated standards (Energysage, 2019).

Utility Charges, Residential Energy Usage, and its Impacts on Residential PV

Traditionally, a utility company charges a customer base on how much energy they use. For a residential consumer this usually takes the form of a fixed charge that is paid monthly or seasonally, and an energy charge, that is based on how much electricity is used and comes in the form of a cost per kilowatt-hour (kWh) (Northwestern Energy, n.d.). While this is the case in the United States and has been relatively unchanged for about a century, recent development in fields such as smart metering, energy efficiency, and distributed electricity generation (e.g., solar) has caused utility companies to begin to reevaluate these pricing strategies (Hledik & Greenstein, 2016). This is because utility companies are facing, or are anticipating, stagnating electricity sales, especially in the residential sector due to reduced demand brought on by these aforementioned factors related to efficiency and distributed electricity generation. To make matters worse for utility companies it is often the case that cost associated with maintaining distribution infrastructure does not necessarily decrease with reduced electricity flow across said infrastructure. Thus far the most common responses to these changes are increasing fixed charges and implementing demand-based rates, but other strategies such as a minimum charge are being considered as well. Since PV users with no storage on average use the grid to satisfy 65% of their energy needs, and because PV adaption is highly sensitive to rate structures, this topic is highly relevant to the average residential PV system (McLaren, Davidson, Miller, & Bird, 2015).

Understanding residential energy usage trends.

Relevant to how utility companies charge customers for electricity is the topic of how residential customers use electricity. In 2011 the Energy Information Administration (EIA) published an article that described electricity generation in New England on October 22, 2010, Figure 1 is a depiction of said generation. Though this curve is a summary of electric generation and not residential energy usage some relevant phenomena can be observed. In the hours between 5:00am and 7:00am a steep increase in generation can be noticed, Figure 1 refers to this as a “morning ramp.” Between 5:30pm and 7:30pm a peak demand is reached; Figure 1 refers to this as “hourly peak demand.” It is during times of increased demand when the most electricity is required to be generated, and it is when customers are most likely to experience higher prices for electricity (Energy Information Administration, 2011).

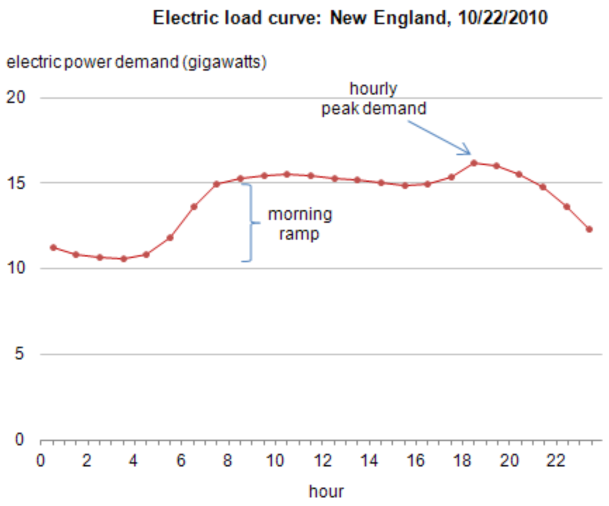

Figure 1. Hourly energy generation in New England on 10/22/2019 (Energy Information Administration, 2011)

Fixed costs versus a minimum charge.

All residential electric utility customers pay a monthly fixed charge that is set by the utility company. This charge is the same for all customers of the same type and is entirely independent of electricity usage by the customer. For some utilities, one type of customer that may have a different fixed cost is a customer that is net-metering, these customers are faced with a higher monthly fixed charge. Regardless of the customer type this fee is usually used to recover the cost the utility spends running facilities like call centers, as well as to cover various administrative fees. Usually this cost does not cover utility infrastructure, but some proposals in recent years have increased these fixed costs to help do so (McLaren et al, 2015).

A minimum charge is a cost recovery strategy that is somewhat similar to these fixed costs, and in some cases the minimum charge even covers the fixed cost. A minimum charge rate structure operates when a utility company specifies a total amount owed that is irrespective of the amount of electricity a customer uses. To meeting this total amount owed, customers would simply consume electricity assuming that, at a certain point of consumption, the cost of electricity would be greater than the minimum charge owed. This structure ensures that all grid-connected customers pay at least a specific minimum amount each month. The rate would be structured so that usage by (and therefore revenues from) customers without PV installed would easily pass the minimum charge while customers with PV, especially those on a net metering schedule or who are trying to increase self-consumption, would not. Customers who do not meet the minimum usage would then have to pay the difference between their actual cost and the minimum cost. The minimum charge rate structure has yet to be deployed by any utility and has been noted to discourage energy efficiency and self-generation. Minimum charge rate structures are also accused of being a source of discriminate against low-income customers (McLaren et al, 2015).

Demand charges.

A demand charge is a mechanism where a utility company charges its customers based on their maximum instantaneous demand for electricity. It is measured in kilowatts (kW) and has been deployed on the commercial and industrial scale for decades. The demand charge allows utilities to recover a portion of the cost that comes with maintaining grid infrastructure. Some of the costs the utility companies face, particularly transmission and distribution costs, have been growing and are expected to grow, representing an ever-increasing share of electricity cost in the coming years. Since demand costs are charged directly to customers using larger amounts of power, they represent a way to possibly improve the fairness and equity of cost recovery. This also means that demand charges tend to incentivize demand reduction. Methods for demand reduction include reduced consumption, as well as deployment of distributed energy and energy storage systems such as solar PV and battery systems. Some studies have shown that distributed energy storage can reduce utility demand charges and provide savings of between 13-28% (Hledik & Greenstein, 2016).

In the United States, utility companies have introduced both voluntary and mandatory demand charge structures. The most basic form of a demand charge is to charge a customer for their peak demand, in kW, over a single billing period. Another strategy known as peak window of demand operates on this principle as well, but only during a specified window of time during a billing period. The time interval of demand can vary as well; usually demand is measured in 15, 30, or 60 minutes intervals. A strategy known as coincidence with system peak is based on the customer's individual contribution to the overall system net peak. Yet another strategy is known as average of top demand, in which the average of a customer's five to ten highest demand readings is used as the peak demand charge. This strategy allows for the avoidance of peak demand penalization. Finally, a strategy known as a tiered demand charge has also been deployed in some places. This strategy serves as a function of a customer's peak demand where the first few kW of demand, for example, may be charged differently than the others, and so on (Hledik & Greenstein, 2016).

Time-varying charges.

In many places across the United States peak demand for electricity occurs during summer afternoons when temperatures are especially high. This is often due to high loads required to power air conditioning units added onto regularly occurring commercial lighting loads. Sometimes this causes utility companies to import additional electricity capacity that often comes at a premium cost. They may also switch to less efficient peak capacity electricity generators or encourage customers to reduce loads. Failure to accommodate these high loads can result in brownouts or blackouts (Newsham & Bowker, 2010).

Since a sizable portion of these large demands are caused by the residential sector some utility companies have modified existing rate structures to encourage customers to modify their behavior. These pricing programs are often referred to as time-varying pricing structures and they exist in several different forms. The most basic of these are time-of-use (TOU) charges, in which a day is divided into blocks and the cost per kWh changes between these blocks (but not within the blocks). With TOU charges pricing blocks remain constant and are applied every day. Another structure, referred to as Critical Peak Pricing (CPP), operates similar to TOU charges but only applies to special event days. Special event days are advertised in advance by utility companies and the pricing structure for event days are usually all the same. Generally, high prices when using a CPP model are higher than high prices in a TOU model. With Real Time Pricing (RTP) customers pay prices for energy that vary from hour to hour that are based directly on the real market cost of electricity. This means that no days have the same rate structure and there is no notice of price changes, which can lead to extreme highs that are even greater than CPP highs. With Peak Time Rebates (PTR) a customer receives electricity bill rebates for not using power during peak demand periods. This model is often applied in combination with other pricing program such as TOU or CPP (Newsham & Bowker, 2010).

To apply any of these time-varying models utility companies must first install meters that have the ability to record hourly energy usage. These meters are often referred to as advanced meters. Although the initial cost of installation is high these meters offer benefits beyond the ability to alter rate structures. For example, these meters eliminate the need for manual meter reading and can provide rapid power outage notifications to utility companies (Newsham & Bowker, 2010).

Another method that could be used to deal with high summer afternoon loads is a program known as Direct Load Control (DLC). DLC gives the utility company the ability to modify or even curtail the operations of residential loads during peak periods to reduce demand. Ideally the method would only be deployed during a very small number of event days. In addition, the success of this sort of program is entirely reliant on customer tolerance of these curtailments (Newsham & Bowker, 2010).

The effectiveness of time-varying pricing structures generally varies. In general, the high cost and low frequency of CPP have encouraged homeowners to take it more seriously than TOU charges. TOU on-peak reductions usually only decrease consumption by 5%. Some researchers suspect that it is more difficult for customers to maintain habit changes daily rather than to recognize and change behavior on event days. PTR programs are often more costly and have been found to be less effective than CPP programs (Newsham & Bowker, 2010).

PV Energy and Utility Stress

Utilities companies operate using a variety of techniques to match electricity generation rates with electricity demand. In scenarios when the total energy generation rates separate from total energy demand rates a utility company must deploy operating reserves to realign the energy balance. Utilities companies have long dealt with rapid electricity demand rates changes, or in rarer cases generating source failures, but PV energy presents a unique challenge to utility companies because solar energy is prone to generation intermittency throughout the day due to cloud cover. There are several types of operating reserves, and in the case of PV energy it is important to consider a variety of types (Ela, 2012).

Following reserves, also known as load-following or balancing reserves, correct anticipated grid imbalances. In the PV scenario these may be required when solar forecasting is not perfectly accurate but are somewhat accurate. Contingency reserves, or spinning and non-spinning reserves, provide generation in sudden events of severe balancing issues. An example of this would be an unexpected failure of a large generator or sudden loss of loads. In the case of PV contingency/spinning reserves are not often expected, as changes in PV generation are not usually instantaneous, and cloud cover can often be forecasted for. The final type of reserves that may be impact by PV are ramping reserves. Ramping reserves provide capacity during non-instantaneous loss of generation events. An event that would require ramping reserves would be one with large and unanticipated loss of generation, that occurred non-instantaneously, and could not have been forecasted for by more than an hour before the event started (Ela, 2012). It is expected that increased PV penetration into the energy market will require a greater capacity of ramping reserves (Cui & Zhang, 2017).

The most problematic factor when it comes to maintaining operating reserves is not failing to have enough reserve and therefore failing to react to imbalances, rather it is difficult to have and maintain reserves at a low cost. The issue PV energy poses is its characteristically intermittent and would necessitate the need for an increase in total reserve capacity. For utility companies this would translate into higher operating costs. However, new technology such as energy storage, demand management, better demand response practices, and enhanced PV forecasting methods may also provide means of avoiding some of that cost (Ela, 2012).

Residential PV Self-Consumption Systems

Self-consumption can be considered the share of the total PV production that is directly consumed by the PV producer, which is also often the PV owner. Self-consumption is usually considered instantaneous consumption or consumption that occurs within 15 minutes of electricity production. A self-consumption system is a system that utilizes various techniques, most often battery storage or load management, to match a user’s production and consumption levels and to minimize grid interaction (Luthander et al., 2015). One reason self-consumption is important is it allows energy that is generated by a PV system to be kept within the local system. This means that generated energy can be kept at retail value regardless of the utility rate structures it may otherwise be subject to. This is because the energy does not have to leave the system and therefore will not be subject to being exported onto the grid at an avoided cost (or other unfavorable) rate (Bhandari & Stadler, 2009). Additionally, self-consumption, especially with energy storage and load management, can help overcome one of the greatest challenges preventing PV from achieving high penetration rates of electricity production, which is PV’s lack of frequency regulation. Frequency regulation is the ability to start up and maintain an energy supply in order to match fluctuating consumption levels to avoid exceeding voltage limits. Self-consumption PV systems also have the benefits of all distributed generation systems such as grid-connected PV or small wind turbines, which is the ability to reduce peak power production needs and increase power quality (by means of helping stabilize voltage and frequency within the power supply), which can be beneficial to both electricity users and utility companies (Luthander et al., 2015).

Load Shifting or Demand Side Management

Load shifting, also referred to as demand side management (DSM), is an activity where the goal is to improve an energy system at the side of consumption by altering when loads are drawn relative to existing production and consumption levels. On a residential PV scale DSM is often done by shifting power demands of high energy need appliances such as washing machines or HVAC systems to time periods when there is a surplus of PV production rather than times where there is a surplus of consumption. DSM techniques can be practiced manually or automatically using different control algorithms that can be based on time-of-day, ambient temperature, solar irradiation, or weather conditions. Different DSM techniques include direct-load control, load limiting, and using smart metering or smart appliances. Studies have shown that DSM has been able to increase self-consumption in a system from 2-15% (Luthander et al., 2015).

Self-consumption Systems with Energy Storage

Studies have shown that a battery storage system with a capacity rating that is between half the size of and equal to size of the capacity of the PV system can improve self-consumption by anywhere between 13-24%. This size battery generally represents a storage capacity that can satisfy loads for less than a day, which is acceptable because unlike off-grid systems self-consumption systems are still attached to the grid so there is no need to accommodate for longer system autonomy. This smaller battery size also means that the energy storage system is less expensive, which can be helpful to system owners forced to deal with high battery costs. Within a residential PV system that includes battery storage there are two main layouts. There are AC coupled systems where the battery is connected to a charge controller which is then connected to the AC link of the inverter and there are DC coupled systems where the battery is connected to the DC link of the system’s inverter (Luthander et al., 2015).

It is very important to ensure when measuring self-consumption of a system based on grid interaction and power flows to not count storage losses as self-consumption. Management of an energy storage system will always include losses from charging, discharging, and storing energy. When power flows are measured at a connection point, there is a risk that management losses would be included in an assessment, which would then be counted as reduced production.

This would be inaccurate. In addition, losses from energy storage management also mean that it is always more efficient to use generated PV electricity instantaneously (Luthander et al., 2015).

Managing DSM and Battery Storage in a Self-consumption System

An important factor in maintaining a self-consumption system is managing how the battery storage and DSM system operates. The simplest method for storage control is to allow the batteries to charge when there is a surplus of PV-generated electricity and to allow the batteries to discharge when there is a surplus of consumption. This method is often optimal for self-consumption. However, there are other goals that can be prioritized such as peak shaving. Peak shaving can reduce the peak level of PV-generated electricity entering the grid and can be used to lessen stress on the grid. Peak shaving is only used when when there is a large volume of PV on the grid and is not optimal when daily PV production is greater than a battery system's storage capacity (Luthander et al., 2015).

Battery Storage

In recent years there has been a steep rise in battery storage installation. Between the years of 2012 and 2017 the annual deployment of battery storage (including utility-scale, commercial, and residential installation) grew by 37% for power capacity and 58% for energy capacity. These increases were most prevalent among utility scale applications and within the state of California, which recently enacted a subsidy that applies to batteries that can provide electricity needs for no more than six hours. Battery installation growth has been spurred by falling prices, in part thanks to the growing electric vehicle industry and their battery manufacturing. However, the cost of energy storage is still high, and general accounts for 40-50% of total system costs, so the availability of federal tax credits and state-level investment rebates will continue to be critical for the economic viability of battery deployment in coming years (Comello et al., 2018).

The reasons for this growth are many. Battery storage can provide protection from long outages, voltage sags, and voltage surges. Batteries are effective on-site generation sources for customers or entities looking to shave peak power demands. For renewable energy sources, like solar PV and wind, battery storage is complimentary during intermittent energy generation periods. In general, batteries are highly versatile in their use when transitioning to microgrids and decentralization. Often most importantly battery storage has proven itself as favorable in regard to life-cycle cost and has proven to be a worthy investment when proper energy use decisions are made (Letcher, 2014).

Within a PV self-consumption system battery storage can be a valuable asset; as previously mentioned, battery storage systems have the potential to increase the rate of self-consumption by as much as 13-24% (Luthander et al., 2015). Regarding self-consumption, some important financial considerations that must be taken into account when considering battery storage include the benefits of avoiding paying a premium for electricity during peak pricing hours (if time-of-use charges apply) and savings associated with reducing demand charges (if they apply) (Comello et al., 2018).

Battery Storage Options

When choosing a battery storage system there are many factors that should be considered such as rated capacity, cost, voltage limitations, cycle life, calendar life, and efficiency. The size of the battery is also important for more reasons than just nominal storage capacity, because the battery size in relation to usage levels can also greatly affect stress put onto a battery. A larger battery can allow for a lesser depth of discharge which will increase the battery's cycle life; this however does require a larger initial battery investment (Luthander et al., 2015).

There are a variety of battery technologies available for residential storage which include lead-acid, lithium-ion, sodium sulfur, nickel cadmium, and nickel metal hydride. Lead acid is the oldest of these battery technologies and the most mature, but lithium-ion has proven to have the greatest potential for future development and optimization due to its high storage efficiency and energy density when compared to other residential battery storage options. Lithium-ion, however, is also a more expensive battery option. In addition to the previously mentioned battery technology options, there are a few other potential options which may include sodium-ion batteries that have similar abilities to lithium-ion but are less energy dense and not as readily available, and flow batteries (Luthander et al., 2015). For this study, where a lithium-ion battery has already been chosen, further review with focus exclusively on lithium-ion and lead-acid battery technologies (which have both seen wide use for residential solar applications).

Lithium-ion batteries.

Lithium-ion batteries are energy dense and relatively lightweight and have grown in popularity in recent years. The growth in popularity is due to their favorable characteristics, as well as falling pricing which is largely thanks to the electric vehicle industry which uses lithium-ion batteries and produces them on a large scale. Lithium-ion batteries, however, are still a relatively expensive technology, and have been prone to high temperature and or fire when batteries are damaged (Letcher, 2014).

Lead-acid batteries.

Lead-acid batteries are the oldest battery technology, and although their costs are relatively low, they also have a low energy density. Lead-acid batteries come in two predominant types, flooded and sealed. Flooded lead-acid batteries also have the disadvantage of requiring regular maintenance. Regardless, lead-acid batteries have seen wide use in the telecommunication and renewable energy industries (Baxter, 2006).

The State Farm Solar Lab Self-Consumption System

Since its inception Appalachian State University's State Farm Solar Lab has been host to two studies on the topic of self-consumption, both were graduate students' thesis projects. This section provides an overview of these two studies, summarize some important conclusions made, and provide context for the shortcomings and limitations of these previous studies.

Pedro Franco Self-consumption Study

Completed in the summer of 2016, the first study related to self-consumption performed at the State Farm Solar Lab was an unpublished master's thesis written by Pedro Franco, a former Appalachian State graduate student and now alumnus. The thesis was titled *Performance Comparison of Self-consumption for a Photovoltaic System with Battery Storage and Load Management*. Within the study Franco analyzed the performance of a residential PV system with and without battery storage in order to compare the improvements battery storage made, or didn't make, to self-consumption. In addition, Franco compared two load management schemes (Franco, 2016).

To complete this study Franco used hourly consumption load data collected from a Boone, NC home in 2013 and used a series of light bulbs and space heaters to recreate hourly consumption at the State Farm lab (Franco, 2016). The components used in the State Farm lab included a 3.36 kW PV system made up of 12, 280-watt SolarWorld monocrystalline modules, an 8.6 kWh Adare Power lithium-ion battery bank, a Schneider Electric Conext 5548 XW+

inverter (Sprau, 2017), and a Midnite Solar Classic 200 charge controller (Franco, 2016). The entire system was connected through a Midnite Solar E-panel (Sprau, 2017).

To collect data Franco used two Campbell Scientific data loggers to measure grid power, load power, battery voltage, PV current and solar irradiance. In addition, the Adara Power battery bank monitored battery state of charge, voltage, current, and temperature in real time. This information was made available by a digital portal provided by Adara Power. Using these data loggers to measure results, Franco chose a total of six system conditions to be compared over the course of the study. These conditions included three power source scenarios where load management (DSM) techniques were used and three power source scenarios where there was no load management. The three power source scenarios were grid only, grid and PV, and grid and PV with battery storage (Franco, 2016).

The study conducted by Franco met a series of limitations that could be considered to have subtracted from his conclusions. Most importantly, regarding analyzing self-consumption it was found that the charge controller used in the study was unable to communicate with the other components of the system, which caused PV to begin to be curtailed when the battery reached a state of charge above 80% and entirely curtailed when the battery reached a state of charge of 100%. This largely prevented self-consumption when the battery was full. In addition, Franco’s study was limited by a shortened data collection period and a lack of side-by-side systems. This meant that only one set of components existed for each scenario modeled by Franco, and each was only operated for a short period of time before being switched to the next scenario (Franco, 2016).

Nevertheless, Franco was able to reach some relevant conclusions. DSM made a considerable impact on self-consumption, although daily solar irradiance had a greater impact. It was found that an increased number of sun hours always increased both self-consumption and the amount of grid-exports. Self-consumption systems were determined to always export less energy onto the grid than net metering systems (Franco, 2016).

Zach Sprau Self-consumption Study

Completed in the Spring of 2017, the second of the two self-consumption studies performed at the State Farm solar lab was conducted by Appalachian State University graduate student, now alumnus, Zachary Sprau. The unpublished master's thesis was titled *The Effects of Battery Storage and Load Management on Photovoltaic Self-Consumption*. It aimed to compare the levels of self-consumption achieved by a PV self-consumption system with and without the use of battery storage technology. In addition, the study compared four different load shifting profiles against a baseline profile with no load shifting (Sprau, 2017).

The self-consumption system used for the study was a DC coupled, battery-based, grid-tied, PV system. The system components used matched that of the Franco study except for the charge controller, which was now a Schneider Electric MPPT 80-600 charge controller. This change was made to avoid one of the problems faced by Franco where the PV was being curtailed once the battery was fully or approaching fully charged, because the charge controller was unable to communicate with the rest of the system. Communication within the system was conducted over Xanbus and was controlled by the System Control Panel (SCP) and the Schneider electric com-box (Sprau, 2017).

Similar to the Franco study the load profile was modeled with a series of light bulbs and space heaters and data was collected in a similar fashion. This time, however, a five-minute time stamp was utilized to model loads rather than a one-hour time stamp. This five-minute load profile was fabricated based on an hourly load profile of a home in Asheville, NC, and load measurements taken on a one-minute time stamp conducted for an entire day on a home in Boone, NC. These two measurements were then normalized to create a load profile for an entire year on a five-minute time stamp (Sprau, 2017).

The study used five different load profiles. As mentioned before, one was a baseline load profile without load shifting, and the other four profiles contained load shifting whereas deferable loaders were moved away from peak demand periods. Overall a total of 57 days of usable data was collected, with each of these profiles containing four to fifteen days of usable data each (Sprau, 2017).

The Sprau study also had a series of important limitations. In addition to a notably short data collection period, the study experienced issues with load reliability where light bulb burnouts were a recurring issue. Most important of all, on November 26, 2016 a change was made in the battery management system, believed to be caused by interference from Adara Power, which had the ability to change battery settings remotely. This changed the minimum battery voltage and recharge voltage. In addition, it was believed that a cell block setting was activated which prevented battery exports from 7:00pm to 10:00am, further preventing the battery from working during the peak demand hours that occur between 6:00am and 10:00pm. This caused self-consumption rates to be higher without the battery storage by an average of 5.5%, which was not the case prior to this change, whereas battery storage was increasing self-consumption by an average of 6.7% (Sprau, 2017).

Regardless of these issues Sprau was able to reach some meaningful conclusions. He found that previous day self-consumption did not affect self-consumption of the next day, rather, this was determined by battery voltages remaining largely constant between days. Self-consumption once again was increased with increased solar insolation, although this was only true for PV-only self-consumption. Issues with battery storage prevented findings in this regard for that scenario. Sprau found that self-consumption was consistently increased by load shifting, a finding true for all scenarios except one where the load shift was the smallest. It was also found that load shifting reduced grid exports (Sprau, 2017).

CHAPTER 3: METHODOLOGY

Background Information

Research for this study is conducted at Appalachian State University’s State Farm Solar Laboratory (seen in Figure 2). Data is collected from the lab’s self-consumption system which provides electricity to a series of resistors of varying sizes which are intended to model loads. Additional data is collected via a pyranometer that is mounted near the self-consumption system’s PV array as can been seen to the right side of the array in Figure 2. A load profile has been fabricated based on models made available by the DOE, the profile was configured to replicate the average daily energy use of a residential home during winter months. Self-consumption data was collected daily between December 14, 2019 and March 15, 2020. Data collected via the pyranometer was collected between December 20, 2019 and March 15, 2020. The State Farm Solar Lab has also been host to two other graduate student thesis projects over the past four years, these two theses laid the groundwork for much of the work conducted in this study.

Figure 2. 3.36 kW PV array, Appalachian State University's State Farm Solar Lab

Predecessor Theses

Pedro Franco (2016) and Zachary Sprau (2017), whose work was discussed in the literature review of this study, used a self-consumption system with components that are still present in the current iteration of the lab's self-consumption system, including the system's PV array, E-panel, and inverter. The charge controller that was used in the Sprau self-consumption system was also used in this study. Unlike these prior studies, the self-consumption system used in this study features a new battery bank and new load running apparatus.

The changes made to the self-consumption system were made at the behest of Zachary Sprau. The resistors that were used in this study to model loads are a replacement for the lightbulb system used in the previous two projects to model loads, these resistors don't have an issue cycling on and off like the lightbulbs did and cannot burn out like the lightbulbs did. The new battery bank used in this study is not subject to interference from the battery manufacturer, as occurred in Sprau's study.

Beyond changes in system components this study shares some similarities and alters from its predecessors in several ways. Like its predecessors loads enacted on the system are controlled by a Campbell Scientific CR-1000 data logger/controller and were modeled using similar methods. However, this study does not focus on load-shifting scenarios as was done in the Sprau study, instead one load profile scenario is repeated for an extended period. A goal of the expended period is to allow for an expanded data collection window which is intended to expose the self-consumption system to more conditions as well as result in a greater amount of raw data to be collected for a single operating condition.

The Self-Consumption System

System Components

The self-consumption system being utilized in this study consist of a 3.36 kW PV array that is made up of twelve 280 W Solar World monocrystalline modules, a 160 Ah 48 V Blue Ion lithium-ion battery bank manufactured by Blue Planet Energy, a Schneider Electric Conext MPPT 80 600 Solar PV Charge Controller, and a Schneider Electric Conext XW+ 5548 inverter/charger. All system components are connected within a MidNite Solar MNE250SW E-panel for Schneider Conext SW. The charge controller and inverter/charger in this system communicate over Xanbus and can be altered from the System Control Panel (SCP) and can be monitored from the Schneider Com-Box. Figure 3 depicts the system as it exists in the lab and Figure 4 elaborates energy flow within the system.

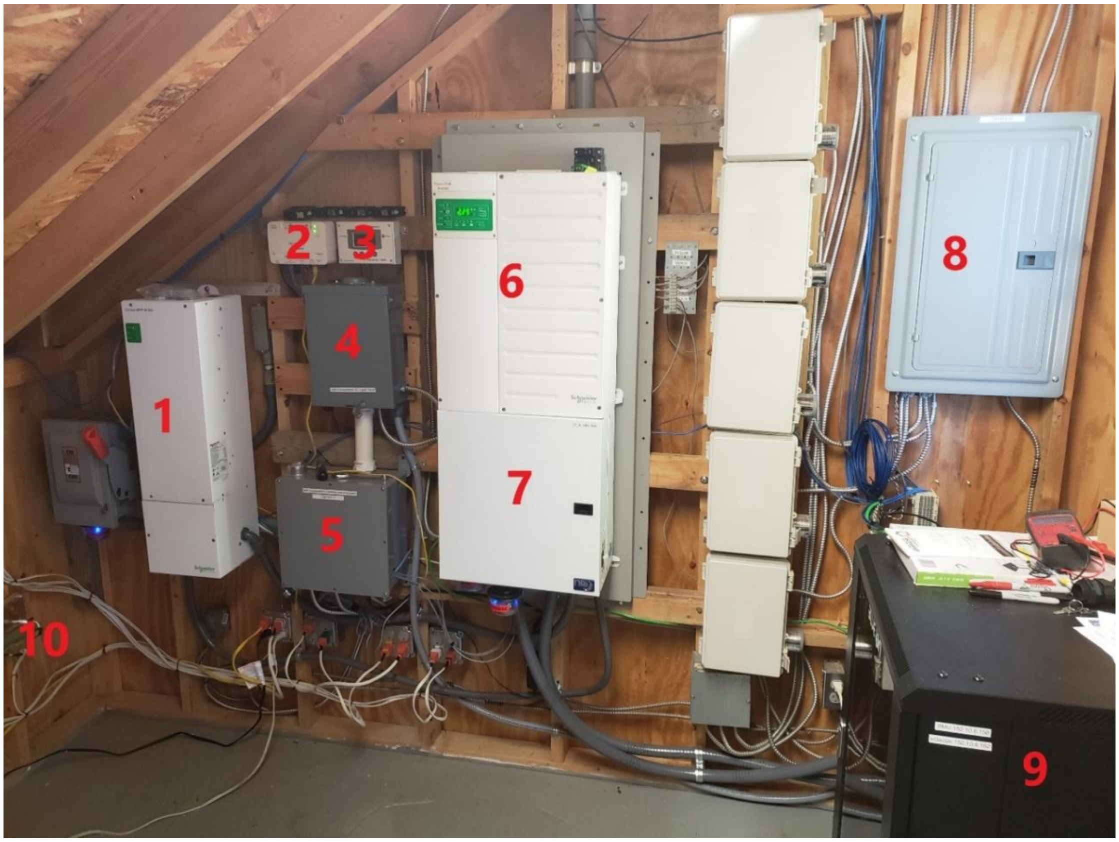

Figure 3. Self-consumption system and load apparatus, ASU State Farm Solar Lab.

The numbers present in Figure 3 correspond with the following system components, some of which have yet to be mentioned and will be the topic of discussion in a later section.

1. Schneider Electric Conext MPPT 80 600 Solar PV Charge Controller
2. Schneider Com-Box
3. System Control Panel
4. Load Subpanel
5. Campbell Scientific CR-1000 and Solid-State Relays
6. Schneider Electric Conext XW+ 5548 inverter/charger
7. MidNite Solar MNE250SW E-panel for Schneider Conext SW
8. Breaker Panel (For Grid)
9. Blue Planet Energy Blue Ion Lithium-ion Battery Bank
10. Resistors (Serve as loads, not entirely depicted see Figure 2.4.)

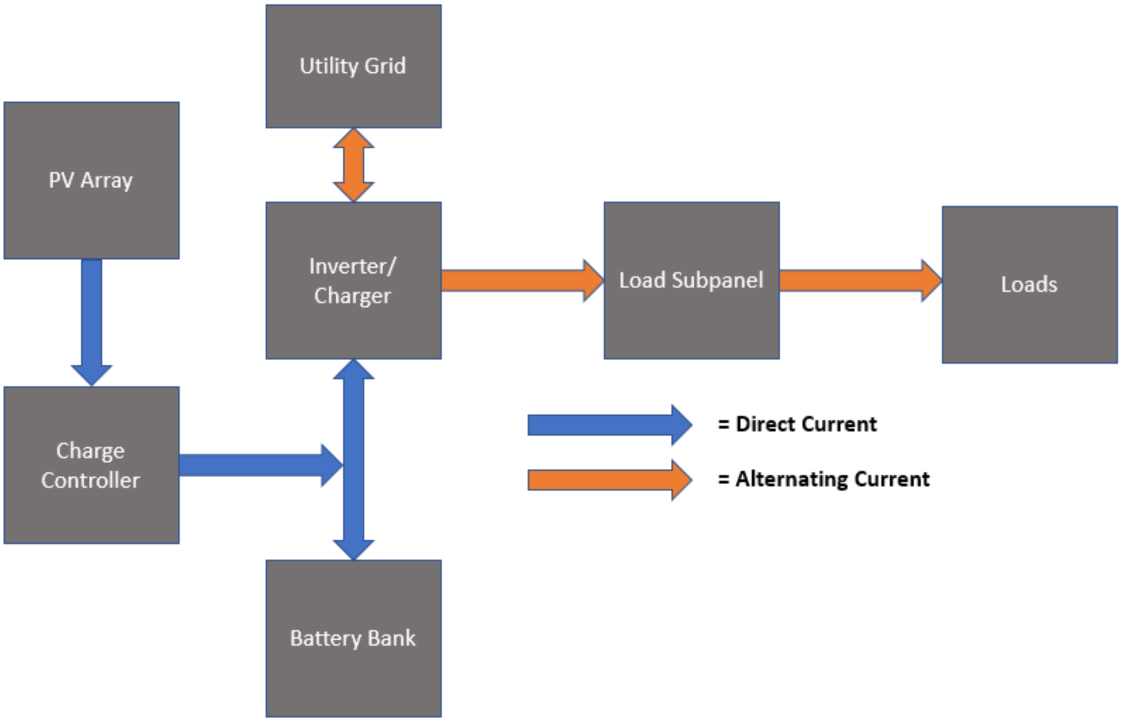

Figure 4. Simplified energy flow diagram for state farm self-consumption system.

Load-running Apparatus

In order to model loads a Campbell Scientific CR-1000 data logger/controller was installed to control eight solid-state relays that control eight different resistors sets of different values which can be added together in different groups to total various loads. The resistor set loads are summarized in Table 1 and are depicted in Figure 5, load values were chosen to allow for a large range of possible outputs. Model load values are rounded to the closest resistor set combination for this study; this will be discussed further in next section. It is important to note that the resistor set's load power described in Table 1 depict nameplate value and are not reflective of actual output in all conditions.

Table 1. Resistor Set and Load Association.

Resistor Set	Load Power (Watts)
1	25
2	50
3	100
4	100
5	200
6	500
7	1000
8	2000

Figure 5. Resistor sets used in study, red number correlates with resistor set number, Appalachian State University State Farm Solar Lab.

System Load Profile & System Component Settings

This study utilizes a fabricated load profile that is configured to replicate a residential building's energy use and is in effect throughout the duration of the study while self-consumption is being monitored. The load profile is associated with a set of system parameters that were prescribed or otherwise determined to allow for maximized self-consumption.

Load Profile

This load profile operates on a five-minute timestamp and repeats daily. The load profile is fabricated based on an hourly load profile for Bristol, TN, made available by the DOE, and uses the Building American House Simulation Protocols (BAHSP) model. The DOE hourly profiles exist for all typical meteorological year three (TMY3) locations, and Bristol, TN was chosen for this study due to its proximity and geographic similarities to Boone, NC.

A couple of important notes regarding the BAHSP residential building model. The model assumes homes are heated by natural gas; this holds true for the fabricated load profile used in this study so there is no heating load simulated. In addition, the BAHSP model provides three model classifications, base use, high energy use, and low energy use. This study uses the base energy use model.

To generate the fabricated load profile for this study the hourly average energy usage for the months of October, November, December, January, and February were averaged and then rounded to a value that can be modeled by a combination of the resistors. This profile can be viewed in Figure 6. These months were chosen to fit the originally expected data collection period. This profile was then expanded to a five-minute timestamp by manually selecting load values that are equivalent to the trends present in the hourly profile. Loads in the five-minute timestamp were also specifically chosen to be equivalent to values that resistor combinations could model. Finally, demand spikes were added to the load profile to represent the surges that would occur in an actual residential building. These surges are normally caused by various home devices and appliances but don’t appear in the average hourly load profile in the BAHSP as these spikes only happen for a short period of time and are averaged out in an hourly profile. The result is the load profile used in this study are depicted in Figure 7. The 288 load profile values, each representing five-minutes of the day, were then translated into equivalent resistor set, and exported into LoggerNet and fed into the Campbell Scientific CR-1000 datalogger/controller. The list of all load profile values can be viewed in Appendix A.

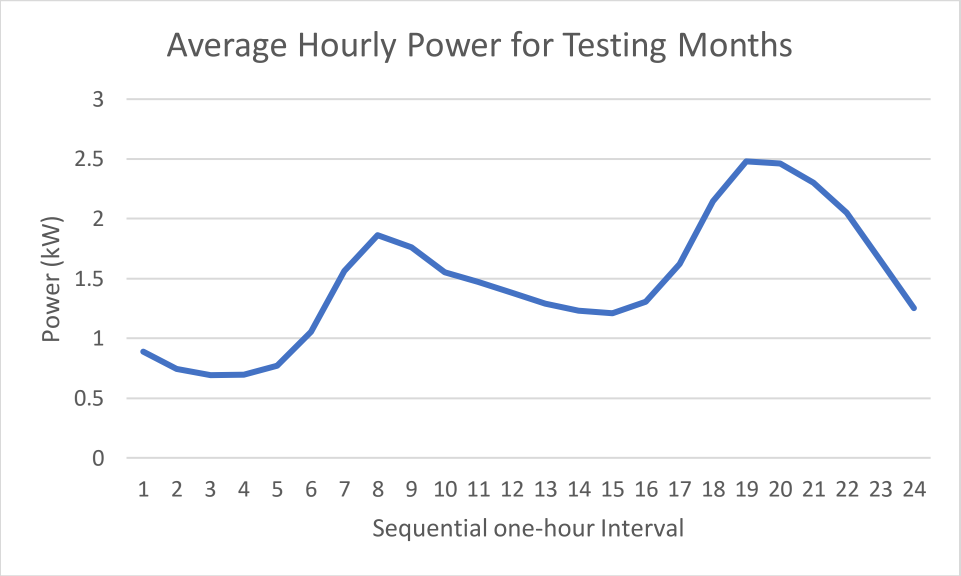

Figure 6. The hourly power for testing months based on the BAHSP model.

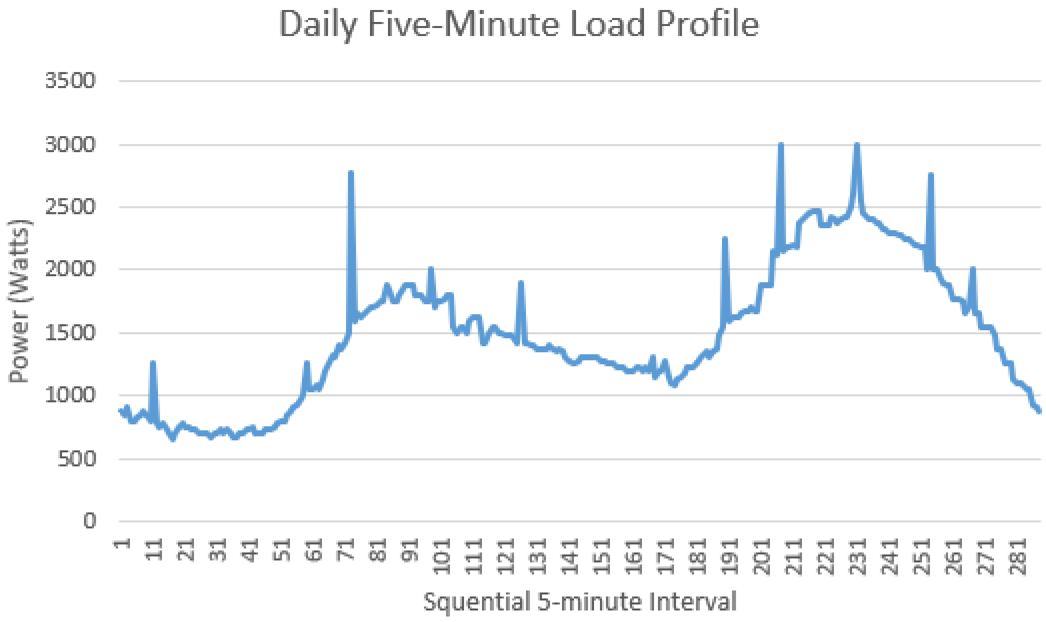

Figure 7. Five-minute load profile repeated daily throughout study.

System Settings for Load Profile

A complete list of system settings associated with the load profile are listed in Appendix B. Schneider Electric, the manufacturer of both the charge controller and inverter/charger used in this study's self-consumption system dictate that a few settings should be altered from default to prioritize self-consumption within the system. According to Sandra Herrera, an application engineering manager at Schneider Electric, these system settings important to self-consumption are Peak Load Shave (PLS), Recharge Volts, Charger, and Sell (S. Herrera, personal communication November 26, 2019).

According to the Conext XW+ Inverter/Charger Owner's Guide, PLS is activated by the setting "Load Shave" (which can be set to "Enabled" or "Disabled") and is intended to allow customers to lessen peak grid demand by mandating when loads should be satisfied by an in-system energy storage source rather than the utility grid. The "Load Shave Amps" setting sets an amperage limit the system can draw from the utility grid before load shave is activated. In the self-consumption scenario Load Shave Amps is set to 0 amps, whereas if the battery can contribute to satisfying loads which are not already being satisfied by PV generation, the battery will. The settings “Load Shave Start” and “Load Shave Stop” then set a time frame for when this behavior will occur. In a self-consumption scenario Load Shave Start is set to 12:00am and Load Shave Stop is set to 12:00am, meaning that PLS is always active (Schneider Electric, 2014).

The setting “Recharge Volts” in integral to the successful operation of PLS, though this setting is not part of the PLS suite. Recharge Volts is a parameter that defines the lower limit of when PLS can occur based on battery voltage. In the self-consumption system used in this study, the Recharge Volts setting is set to 52.0 V, meaning the system battery is required to be at or above 52.0 V in order for PLS to be allowed to activate. If the battery voltage were to fall below 52.0V the system would not be allowed to discharge the battery to satisfy loads (Schneider Electric, 2014).

Within the SCP the Charger setting can be set to enabled or disabled, this setting controls whether the utility grid can be used to charge the system battery. For this study, the charger has been disabled, as in a self-consumption scenario where the goal is to use the battery to store excess PV generated electricity for later use and minimize grid interaction, battery grid interaction is unnecessary. Additionally, the SCP contains a Sell setting (which also can be set to enabled or disabled), this setting controls whether the system is allowed to export excess PV to the utility grid. According to the Schneider Electric definition of self-consumption a customer is only interested in maximizing self-consumption if they are not permitted to export excess PV electricity to the grid, because of this in order to prioritize self-consumption within Schneider Conext XW+ equipment Sell must be disabled (S. Herrera, personal communication November 26, 2019). While this reasoning behind the desirability of self-consumption is not shared with this study, this setting must be adhered to for proper system behavior requirements to be met. Disabling sell curtails excess PV that cannot be used to satisfy loads or be stored in the battery bank. Table 2 provides a summary of the system settings altered form a default state to achieve self-consumption within the Schneider Conext XW+ equipment.

Table 2. SCP settings used to achieve self-consumption characteristics.

Load Shave	[Enabled]
Load Shave Amps	0 A
Load Shave Start	12:00am
Load Shave Stop	12:00am
Charger	[Disabled]
Sell	[Disabled]

Data Collection

Data is collected from several sources to complete this study. An eGauge meter and datalogger housed within the battery enclosure log and store information about the system's battery such as battery state of charge and battery voltage. Also connected to the eGauge are two JS16FL-100-333mV current transformers that are installed onto the AC breaker panel, one of these is used to measures load voltage and the other measures grid voltage. Contained within the E-panel are two DC current transducers, one CR5210S-150 current transducer that measures DC battery current, and one CR5210-75 current transducer that measures DC PV current. In addition, one CR5310-100 DC voltage transducer measures DC voltage which is a value shared by both the PV and battery. Finally, contained within the load subpanel are two JS24FL-200-333mV AC current traducers that measures grid current and load current. All devices contained within the E-panel and the load subpanel are connected to the Campbell Scientific CR-1000 datalogger where data is stored and extracted in the form of measured power. Both the CR-1000 datalogger and the eGauge collect data at one-minute time intervals continually throughout the entire data collection window.

Additionally, a pyranometer mounted near the self-consumption system feeds weather data to a Campbell Scientific CR-3000 datalogger that resides inside the laboratory that contains the self-consumption system. A measurement of plane of array irradiance (POA) from the pyranometer is used to measure daily sun hours, the equation used to make this calculation is described in a later section. The reason for this measurement is to analyze the effect number of daily sun hours has on self-consumption. The CR-3000 datalogger also collects data at one-minute intervals.

Equations and Means of Data Analysis

AC and DC Power Measurements

In this study measurements of power are collected from the load, grid, PV, the battery bank. For these measurements to be compared directly, it is important to make sure all measurements are in either alternative current (AC) or direct current (DC) form. Power measurements for the utility grid and the system loads are already measured as AC, however, both PV power and battery power measurements are in DC, so they need to be converted. (Equation 1) below shows the conversion of DC power to AC power used for this study, whereas an inverter efficiency factor is applied to the power measurements for a DC source to find a resulting AC power equivalent. For the battery bank an additional adjustment must be made to account for the losses associated with the flow of energy from DC to storage and back to useable DC again. This efficiency factor is referred to as round-trip efficiency and has a peak listing of 98% according to the battery manufacturer (Blue Planet Energy, 2019). (Equation 2) depicts the modified version of the DC to AC power conversion equation to accommodate for round-trip efficiency. Figure 8 depicts typical inverter efficiency for Schneider Electric Conext™ *XW+* inverters, including the XW+ 5548 inverter used in this study. Programmed load values in the fabricated load profile range from 650 watts (W) to 3000 W. An inverter efficiency factor of 96% was recommended by Schneider Electric personnel, this value is reflected in Figure 8, and is used throughout this study (S. Herrera, personal communication, October 24, 2019).

$$DC\ Power\ Measurement\ \times Inverter\ Efficiency\ Factor = AC\ Power\ Equivalent \tag{1}$$

$$DC\ Battery\ Power\ \times Roundtrip\ Efficiency\ \times Inverter\ Efficiency = AC\ Battery\ Power \tag{2}$$

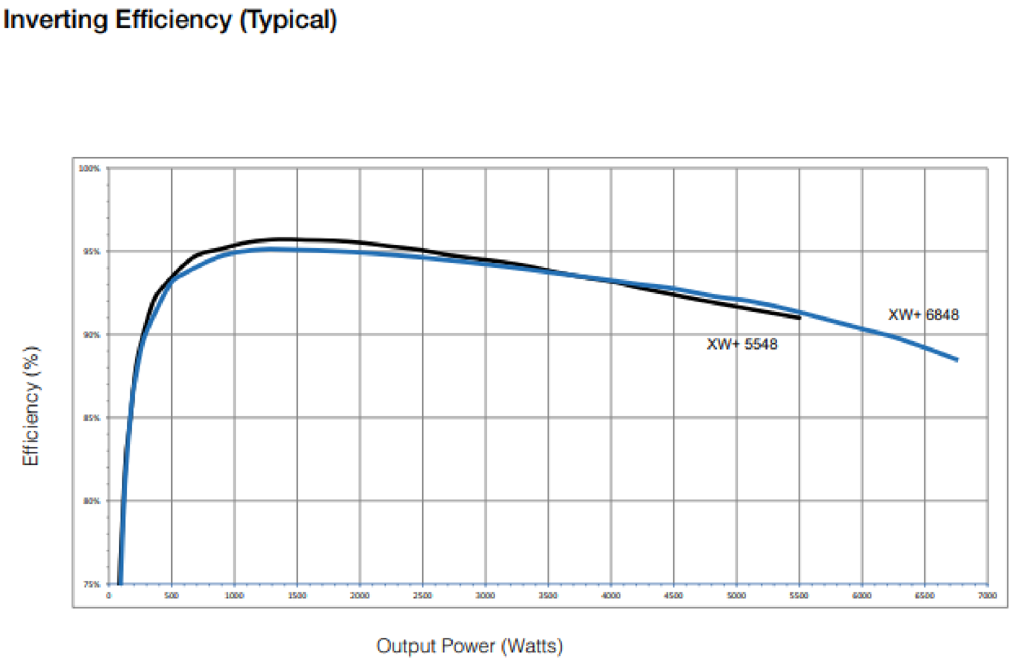

Figure 8. Typical inverting efficiency for Conext™ XW+ inverters (Schneider Electric, 2014).

Calculating Sun Hours

To gain a better understanding of the solar resource that impacts this study's self-consumption system daily sun hours are calculated via data made available by the laboratory's near-PV array mounted pyranometer. This is accomplished by translating the daily POA power data into kilowatt-hours (kWh), as seen in (equation 3).

$$\frac{Daily\ Sum\ of POA\ radiation}{1000 \times 60} = Daily\ Sun\ Hours \qquad (3)$$

Quantifying Self-consumption

In order to quantify self-consumption this study use two metrics to judge system effectiveness. The first metric used is reduction in peak demand. The second metric is grid energy import reduction. The self-consumption system's impact on the load profile is compared to a model system with an equivalent load profile but with no battery bank, henceforth referred to as the PV only model. For the PV only model, it is important to note that PV power measurements can only be equal to 100% of the load, whereas the self-consumption system PV power measurements can be greater, as additional PV energy is allowed to charge the battery.

Demand reduction.

Demand reduction can be a desirable characteristic of a self-consumption system in areas where the providing utility company mandates demand-based charging structures; it is also beneficial to the utility company as a reduction in demand results in a less necessary supply, which is particularly beneficial during peak electricity use hours. To examine demand reduction this study compares load and grid power at equivalent intervals. The difference between load power and grid power is considered demand reduction. This is illustrated in (equation 4) below. The value of demand reduction is expressed in kilowatts (kW). To compare the result of the self-consumption system to the PV only model an additional equation is required. Whereas for the PV only model the PV power measurement is the demand reduction. This is illustrated in (equation 5)

$$Load\ Power - Grid\ Power = Demand\ Reduction \tag{4}$$

$$Solar\ Power = Demand\ Reduction \tag{5}$$

Grid import reduction.

Grid import reduction is a characteristic of a self-consumption system that is beneficial to a utility customer as it will result in lower energy use charges (but has no impact on fixed charges). For the utility company this equates to lower energy demands from customers. In this study grid import reductions are defined in kWh and are measured daily. For this measurement different means of calculations are utilized for the self-consumption system and the PV only model. To calculate import reduction in the self-consumption system (equation 6) is utilized, whereas all energy demanded by the load that is not satisfied by the grid (and therefore must be satisfied by the solar PV or battery bank) is considered a reduction of grid import energy. The daily grid import reduction can also be considered the contribution of the self-consumption system to satisfy daily loads.

$$Daily\ Load\ Energy - Daily\ Grid\ Energy = Grid\ Import\ Reduction\ for\ Self\ consumption\ System \tag{6}$$

To make the same calculation for the PV only model (equation 1) is utilized to define PV power in AC. This AC PV power value is summed into a daily value then translated into kWh to find a daily value of energy satisfied by PV, see (equation 7). For the PV only model PV energy values are considered the daily grid import reduction.

One important caveat of this PV only model, as mentioned previously, is rated PV power output is limited to match 100% of the load power per measurement interval, as to avoid counting PV power that is being utilized to charge the battery bank as contribution to its own rates of grid import reduction.

$$\text{Daily Sum of AC PV Power Values} = \text{Grid Import Reduction for PV Only Model} \tag{7}$$

In addition to presenting grid import reduction for the self-consumption system and PV only model as a kWh value, another measurement described as a "percentage of grid import reduction" is made. Percentage of grid import reduction is equivalent to the percentage of the daily load that was satisfied by the self-consumption system or PV only model. For the self-consumption system this calculation is depicted in (equation 8), whereas the the grid import reduction for the self-consumption system is compared to total daily load to display a percentage of grid import reduction.

$$\frac{\text{Grid Import Reduction for Selfconsumption System}}{\text{Daily Load}} \times 100\% = \text{Daily Grid Import Reduction Percentage} \tag{8}$$

To define a grid import reduction percentage for the PV only model a similar method is used, though instead of using the self-consumption system's grid import reduction values the PV only model's grid import reduction values is used. This new calculation takes the form of (equation 9), as seen below.

$$\frac{\text{Grid Import Reduction for PV Only Model}}{\text{Daily Load}} \times 100\% = \text{Daily Grid Import Reduction Percentage} \tag{9}$$

CHAPTER 4: RESULTS

Introduction to Data

Data were collected daily over a three-month period between the dates of December 14, 2019 and March 15, 2020, for a total of 93 days of data. Due to minor complications with equipment data extracted from the CR-3000 datalogger were reduced by six days to December 20, 2019 to March 15, 2020, a total of 87 days of data. The actual load profile recorded in this study differs from the fabricated load profile, as actual load values tend to be slightly smaller and are not identical from day to day as programmed loads are. An additional equipment malfunction believed to have occurred within the eGauge caused reported grid and load power values to fluctuate and appear stunted for a 20-day period beginning January 11, 2020 and lasting until January 31, 2020. Data within this period were not included in the self-consumption analysis, the reason for this is discussed within the section regarding data validation.

Data Validation

Figure 9 depicts the load power measurements as recorded by the eGauge between December 14, 2019 and March 15, 2020, the intended data collection period. Clearly visible in Figure 9 is a reduction in load power that ranges from a span of time in between January 11, 2020 and January 31, 2020. However, as noted in the methodology section, only one load profile was programmed for this study. Therefore, it can be assumed that some technical difficulty occurred and impacted recorded measurements. An enhanced view of this timeframe shown in Figure 10 depict a more detailed view of this apparent shift. Figure 11 shows the eGauge measurements for grid power during the same timeframe, as can be noted results have been impacted as well. The cause for this stunting of measured eGauge values is unknown, and only occurred between the dates previously identified. Due to uncertainties surrounding the data collected within this region, and because new load and grid values are not reflective of average residential home energy use this set of data are not be included in self-consumption analysis.

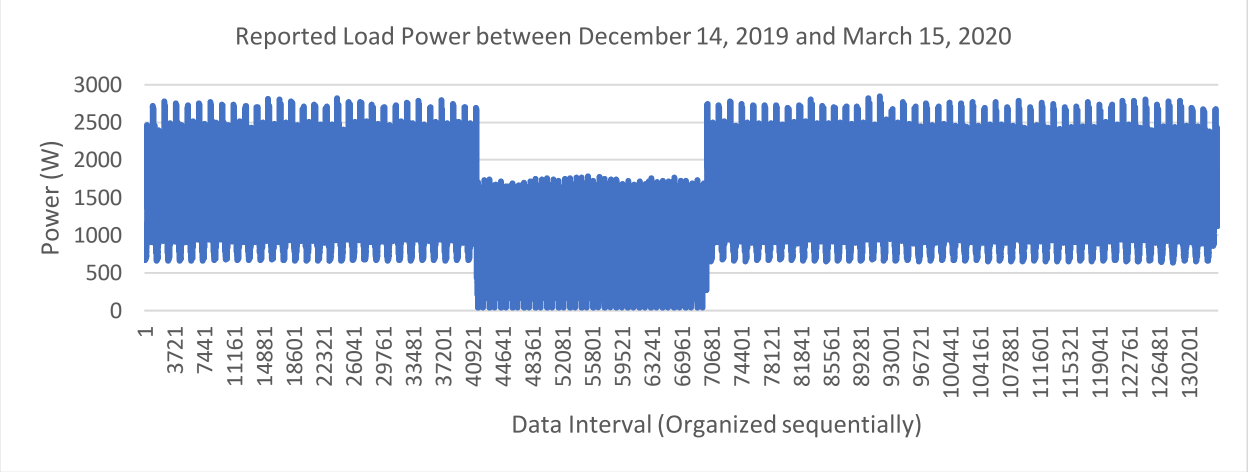

Figure 9. Reported load power throughout data collection period.

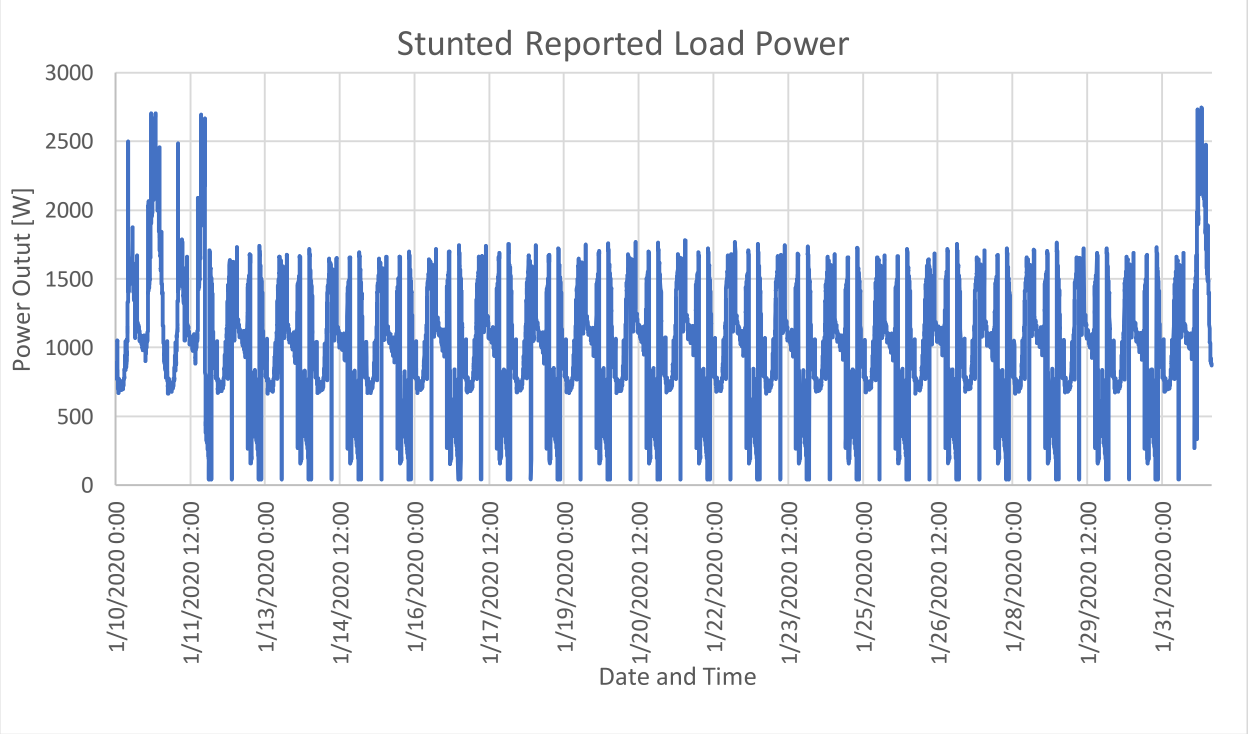

Figure 10. Stunted reported load power profile between January 11, 2020 and January 31, 2020.

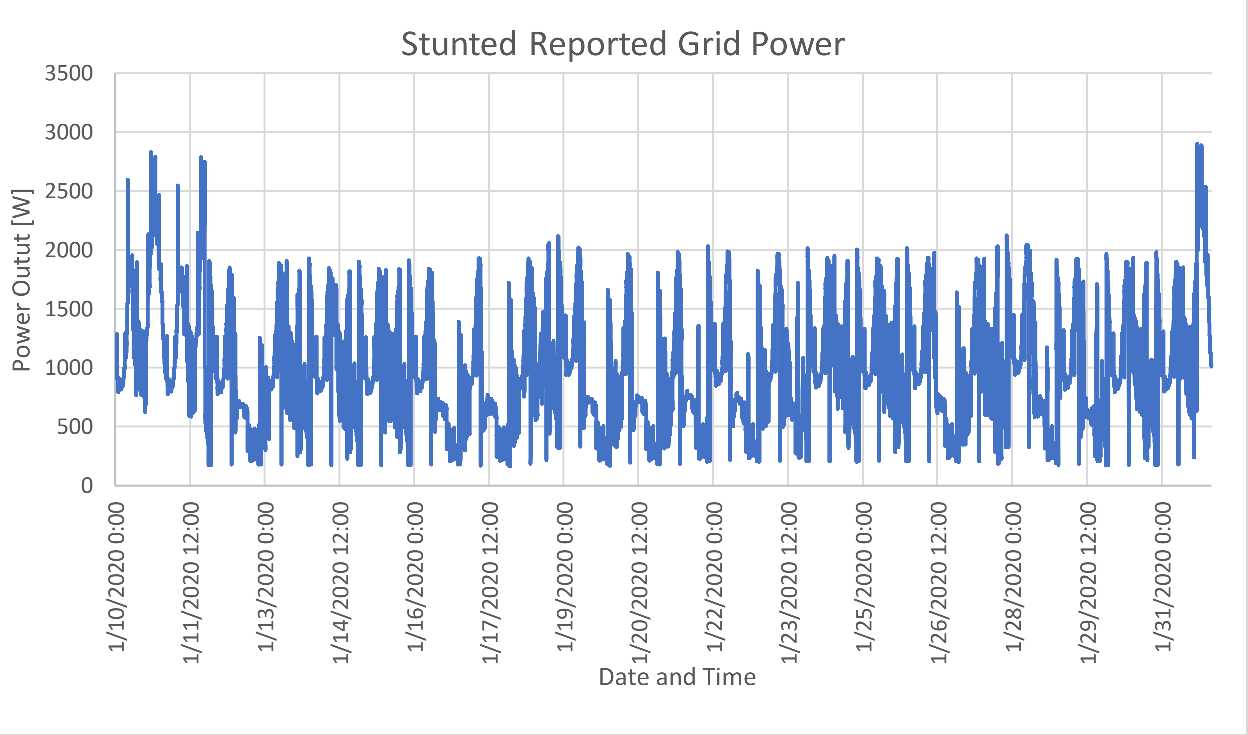

Figure 11. Stunted reported gird power profile between January 11, 2020 and January 31, 2020.

Daily Sun Hours and the Solar Resource

A value for daily sun hours was calculated for every day between December 20, 2019 and March 15, 2020 using (equation 3) described in the methodology section. Figure 12 depicts results for daily sun hours, Table 3 summarizes this information. Throughout the data collection period the self-consumption system experienced a wide range of conditions in regards to incoming solar irradiation. It can be concluded that daily sun hours on average increased over the course of the data collection period, from December 2019 to March 2020.

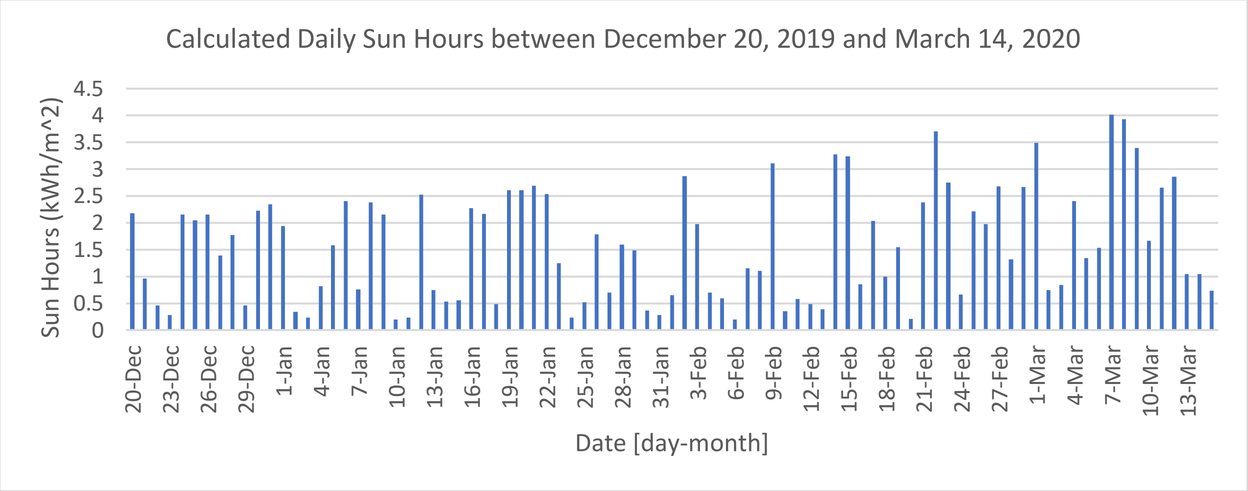

Figure 12. Calculated daily sun hours between December 20, 2019 and March 14, 2020.

Table 3. Summary of daily sun hours throughout data collection period in parts and overall.

Date Range	**Avg. Daily Sun Hours [kW/m^2]**
December 20-31	1.54
January 1-15	1.16
January 16-31	1.57
February 1-14	1.24
February 15-29	1.95
March 1-15	2.11
Overall [December 20 – March 15]	***1.58***

Figure 13 depicts representative generated solar power over the course of a section of the data collection period, in this example that sample period is the first 14 days of March. Relevant to this data is the condition programmed into the self-consumption system that prohibits the export of PV power to the grid. This causes the PV power to be curtailed at certain points and as a result solar generation doesn’t reflect values that sun-hour calculations would have otherwise predicted.

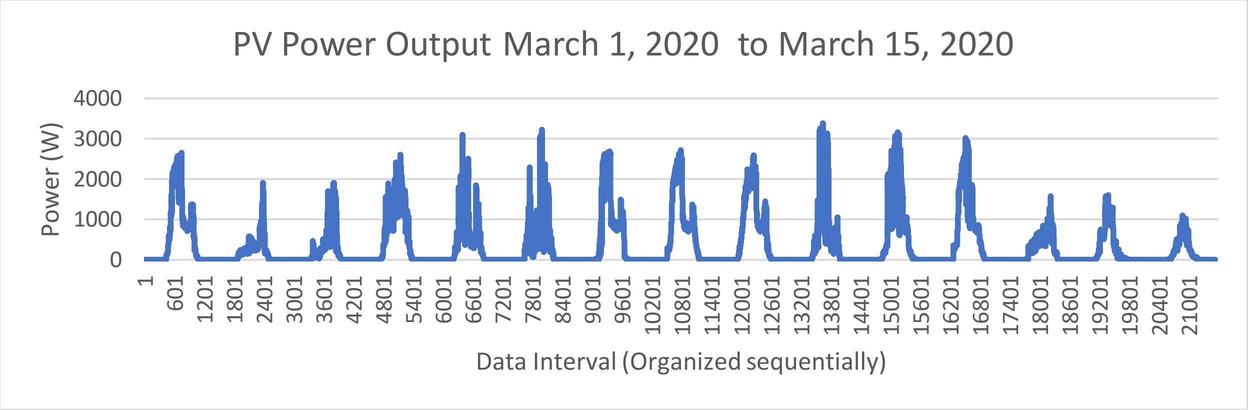

Figure 13. PV power output between March 1, 2020 and March 15, 2020.

PV power curtailment was discussed in the methodology section and is due to parameters that had to be configured into the self-consumption system to achieve desirable self-consumption characteristics as described by the inverter and charge controller manufacturer. Specifically, the setting the “Sell” function to “Disabled” prohibits PV export. As a result, when incoming PV power can satisfy 100% of the load and the system battery is at or near 100% state of charge (SOC) any addition incoming PV power is curtailed. This occurs periodically throughout the data collection period, most often during the afternoon when incoming solar radiation is high, and the load is at its mid-day low point in between the morning and evening peaks. Figure 14 depicts an example of this between March 7, 2020 and March 9, 2020, whereas PV power output is shown relative to load power and battery SOC. A sharp decline in PV output can be noted in association with a charged battery and near satisfied loads. No measurements were made to distinguish how much PV power was curtailed due to these limitations. It should be noted that this is acceptable because curtailment of PV power does not impact rates of self-consumption as the curtailed power would be exported to the grid and therefore not self-consumed.

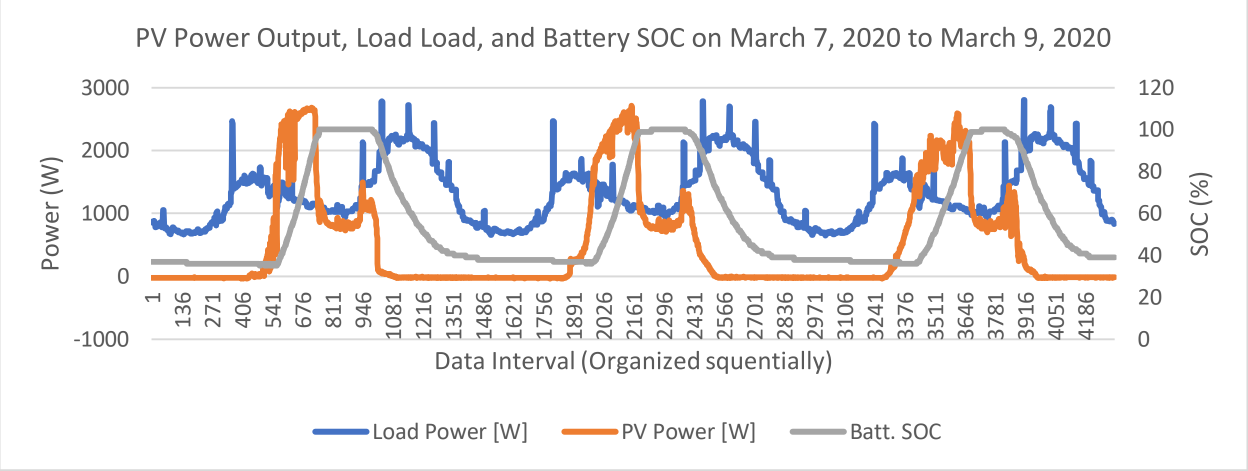

Figure 14. PV power relative to battery SOC and load power to illustrate PV curtailment.

Figure 15 depicts generated solar power by minute over the course of the entire data collection period. Figure 16 translate this data into a calculation of PV generated energy per day, shown in units of kWh.

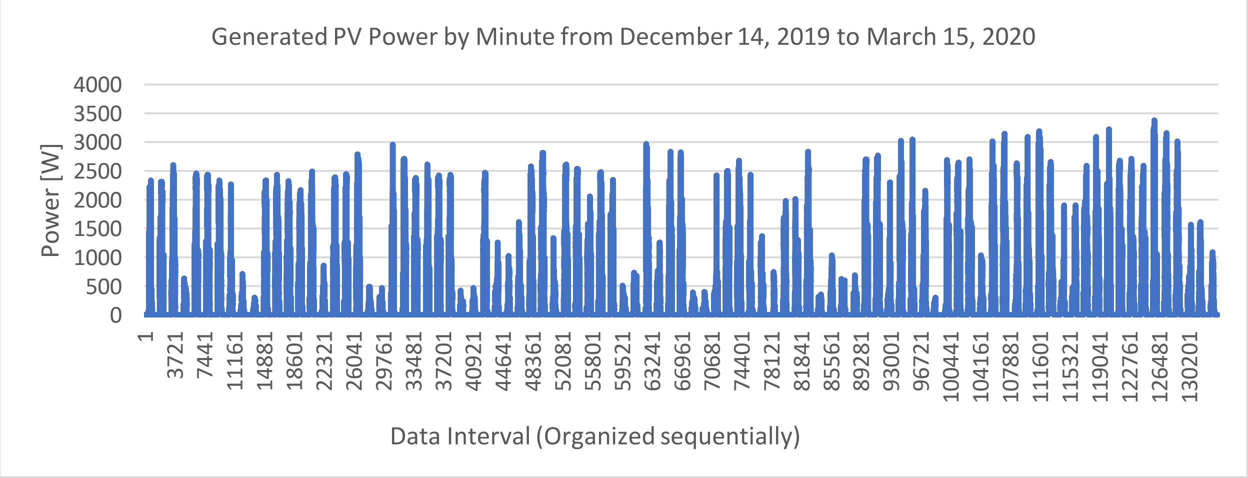

Figure 15. Generated PV power values collected during data collection period.

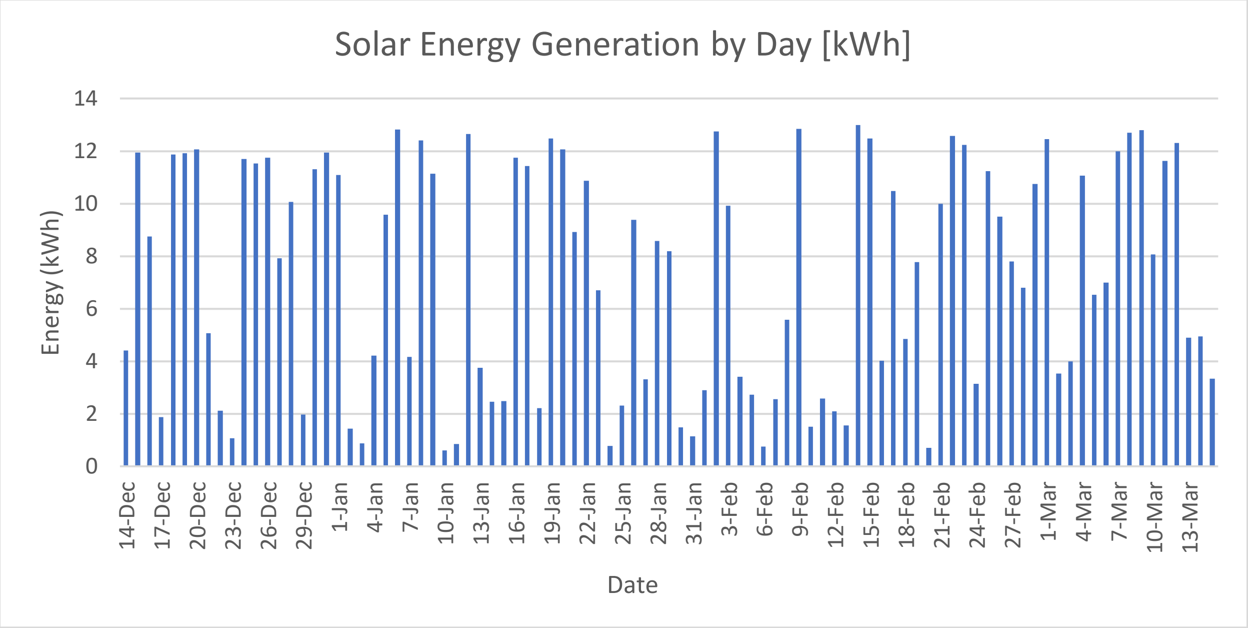

Figure 16. Daily PV energy generated during data collection period expressed in kWh.

Battery Bank Behavior

The battery's performance over the course of the data collection period is illustrated by the following data. Figure 17 depicts battery SOC, each line on the x-axis marks the beginning of a new day. The battery follows a district behavioral pattern. The battery is charged by PV power when it becomes available, the battery discharges to satisfy loads when PV power fails to generate enough power to satisfy 100% of loads, and discharge continues until the battery voltage reaches its cut-off point defined in the inverter as "Recharge Volts." Once at this cut-off point, battery discharge is limited to satisfying the small constant load drawn by charge controller. During this time the battery also experiences self-discharge. The battery remains in this limited state until PV power becomes available again and the battery can begin to charge.

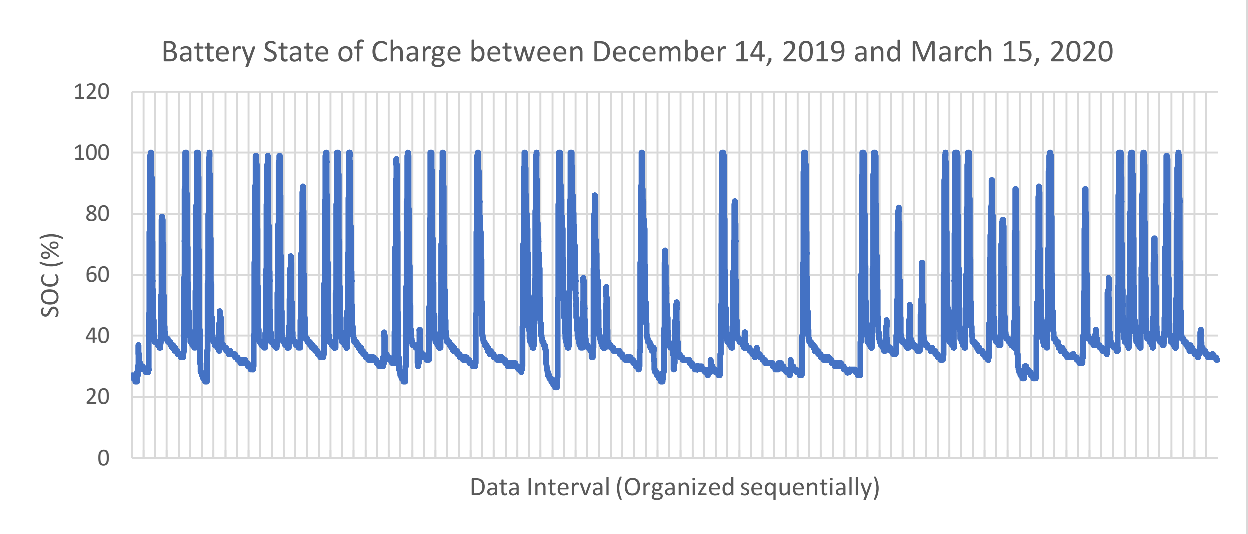

Figure 17. Recorded battery state of charge between December 14, 2019 and March 15, 2020.

The effect of the recharge volts setting on the battery is illustrated over a limited range in Figure 18. As depicted the recharge volt setting prevents battery discharge from satisfying loads when the battery voltage is at or below 52.0 volts (V). In this figure a decrease in battery voltage is equivalent to battery discharge. By enabling “Load Shave” and matching the “Load Shave Start” and “Load Shave Stop” time to 12:00am the battery is mandated to discharge energy to satisfy loads so long as battery voltage is above 52.0 V and PV power generation is not great enough to satisfy 100% of loads. Another effect of this setting, and because the load sizes are too large for the battery to satisfy independently for long periods of time, is a result where useful battery charge is unable to be carried between days. Or as described alternatively, the battery discharge to satisfy loads always results in the battery reaching the recharge volts limiter before the end of the day. This limits previous day influence in this self-consumption system and allows for the calculation of a meaningful daily self-consumption value. Figure 19 illustrates the battery’s SOC over the course of the second half of February, in this figure the battery is seen to cease major discharge before the end of each day (once again day is defined by the vertical lines on the x-axis).

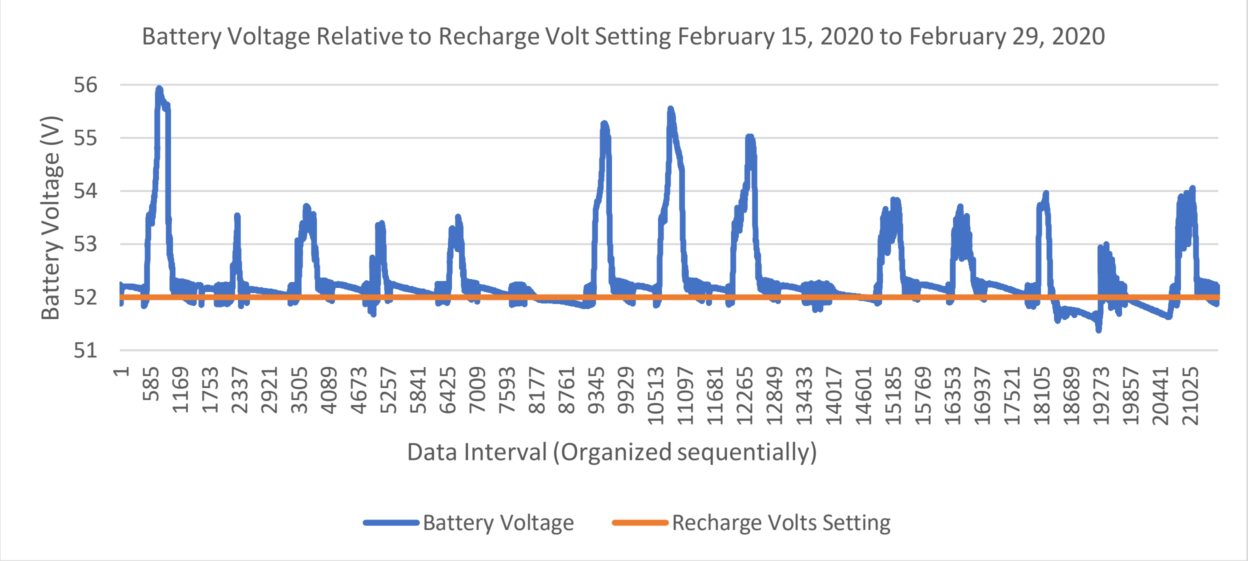

Figure 18. Battery voltage recorded in late February 2020, with recharge volts setting reference.

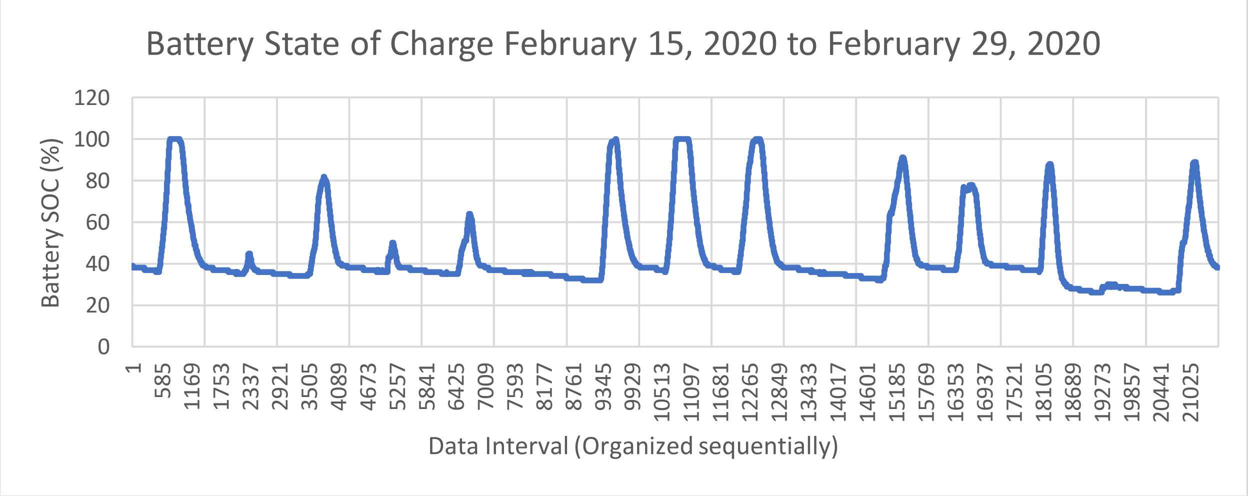

Figure 19. Battery SOC relative to end of the day, denoted by vertical line, late February 2020.

Figure 20 shows that battery voltage over the course of the entire data collection period. In this figure the effects of the recharge volts setting are once again observable, whereas the battery limits discharge beyond 52.0 V, with the exception of discharge to maintain internal operations.

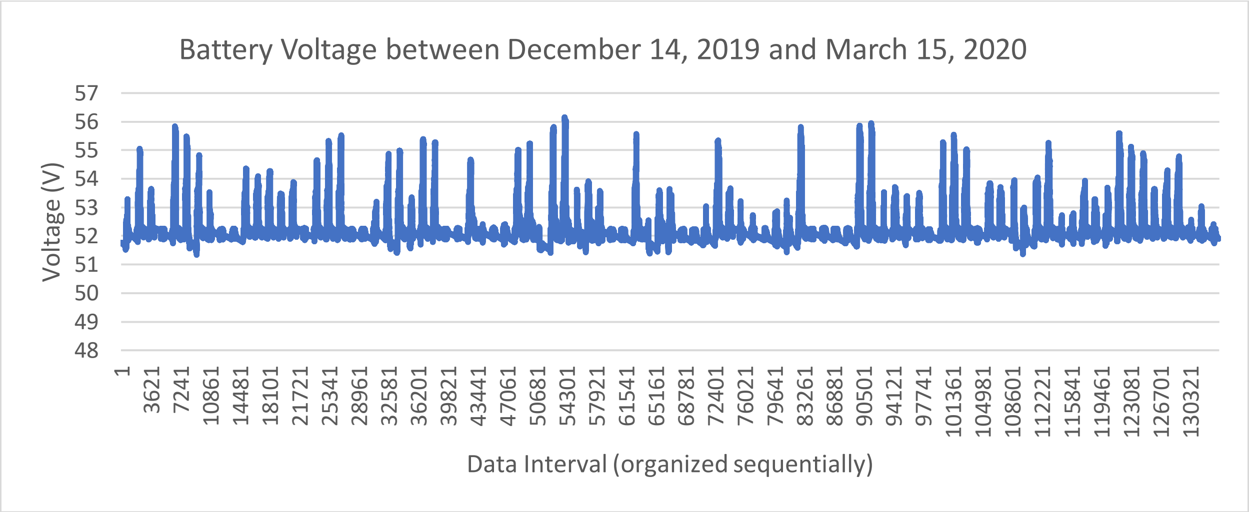

Figure 20. Battery voltage during data collection period, December 14, 2019 to March 15, 2020.

Finally, battery discharge and charge over the course of the data collection period are described in Figure 21 whereas a negative value represents battery discharge and positive values represent battery charge.

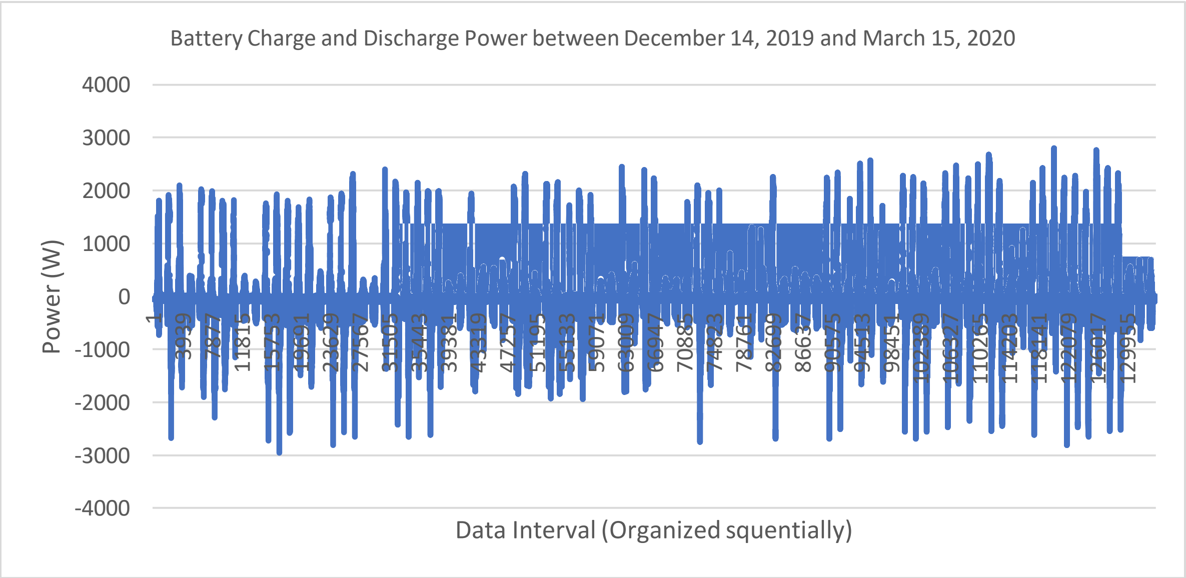

Figure 21. Recorded battery charge and discharge power values during data collection period.

System Load and Grid Imports

Load and Grid Power Calibration Curves

Figure 22 depicts power measurements for load as recorded by the eGauge datalogger from December 14, 2019 to December 31, 2019 in units of kW. Figure 23 depicts the power measurement for grid as recorded by the eGauge over the same time period in the same units.

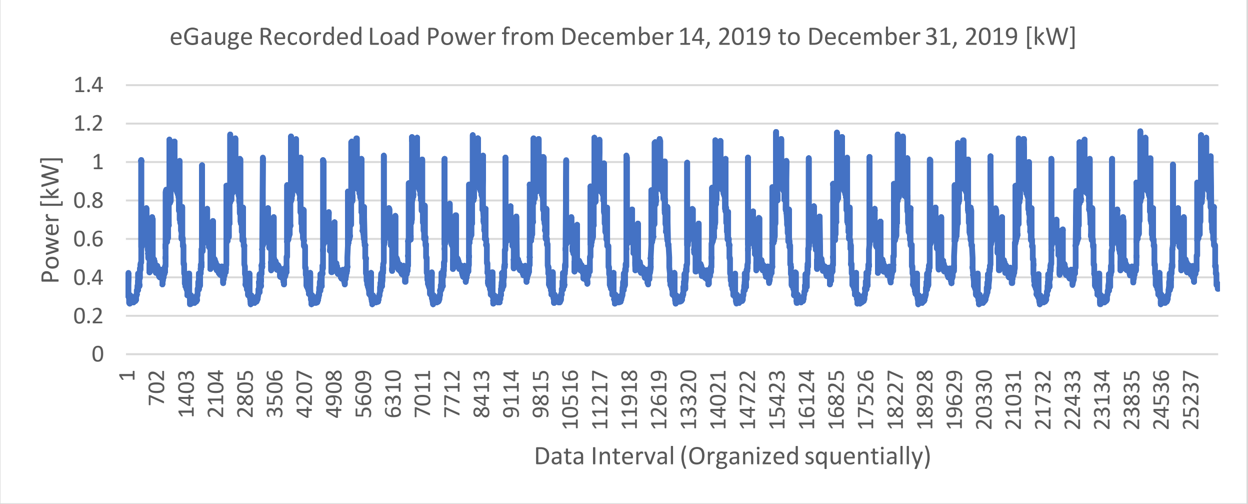

Figure 22. eGauge recorded values for load power in December 2019.

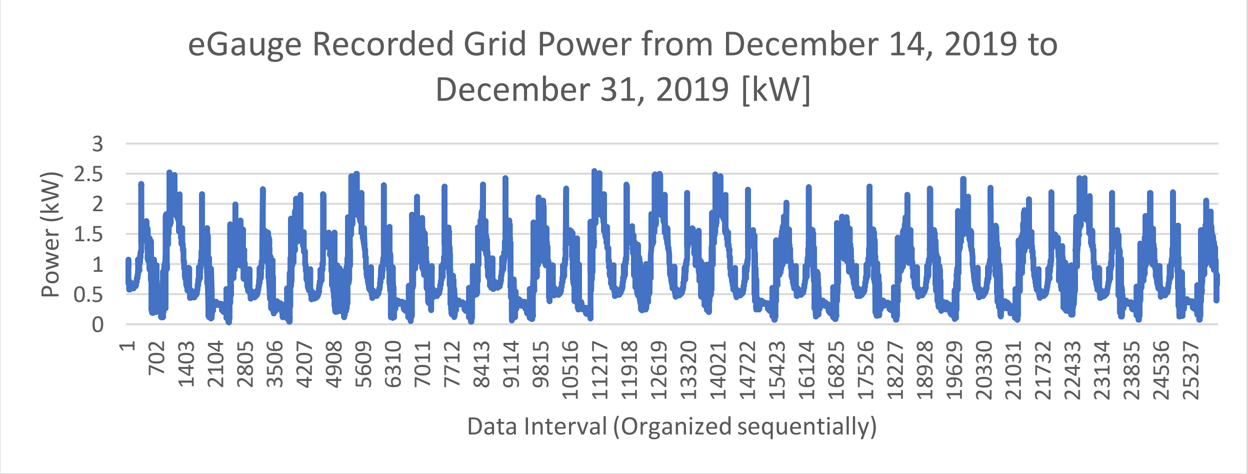

Figure 23. eGauge recorded grid power values in December 2019.

During nighttime hours when there is no PV generation and the battery has been discharged to the recharge volts limiter it can be expected that grid should satisfy 100% of the load. The information presented in Figure 22 and 23 do not reflect this information, this prompted the manual measurements of load and grid power in order to verify the eGauge measurements. Manual measurements were made using a pair of multimeters and a pair of clamp-on ammeters to calculate voltage and current in both the grid and load. These values were used to calculate power. The full set of measurements and equivalent eGauge reading for a variety of resistive loads can be found in Appendix C During manual measurements the inverter was switched into bypass mode, meaning the PV and battery were effectively disabled, and therefore unable to contribute to load satisfaction.

Figure 24 shows the relationship between the measured value of power and the eGauge power reading, along with a calibration curve and equation for the load. This calibration equation for load power is also displayed below as (equation 10).

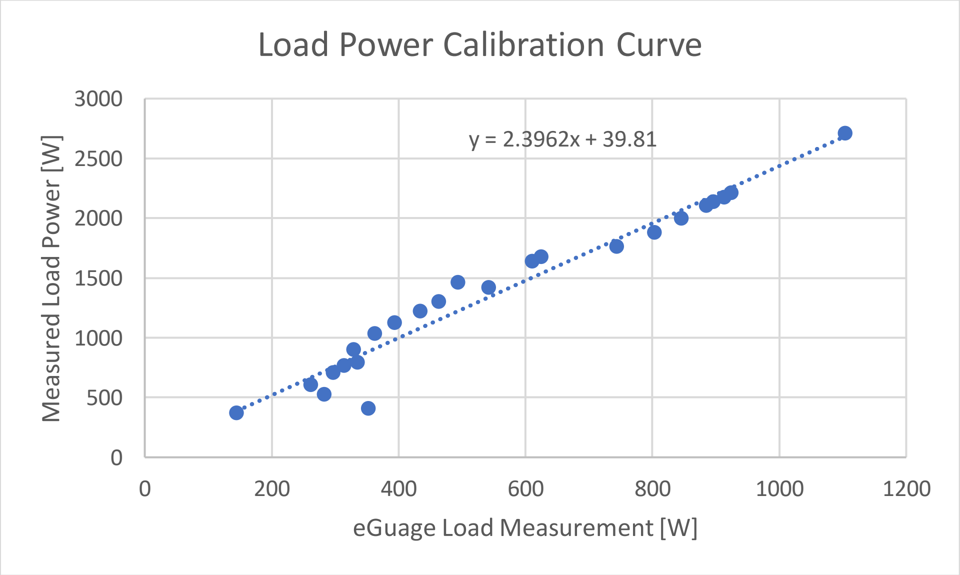

Figure 24. Load power calibration curve.

$$eGauge\ Load\ Measurement\ \times 2.3962 + 39.81 = Calibrated\ Load\ Power \qquad (10)$$

Figure 25 shows the same relationship between the measured value of power and the eGauge power reading along with a calibration curve and equation for the utility grid. (Equation 11) depicts the calibration curve for the utility grid power.

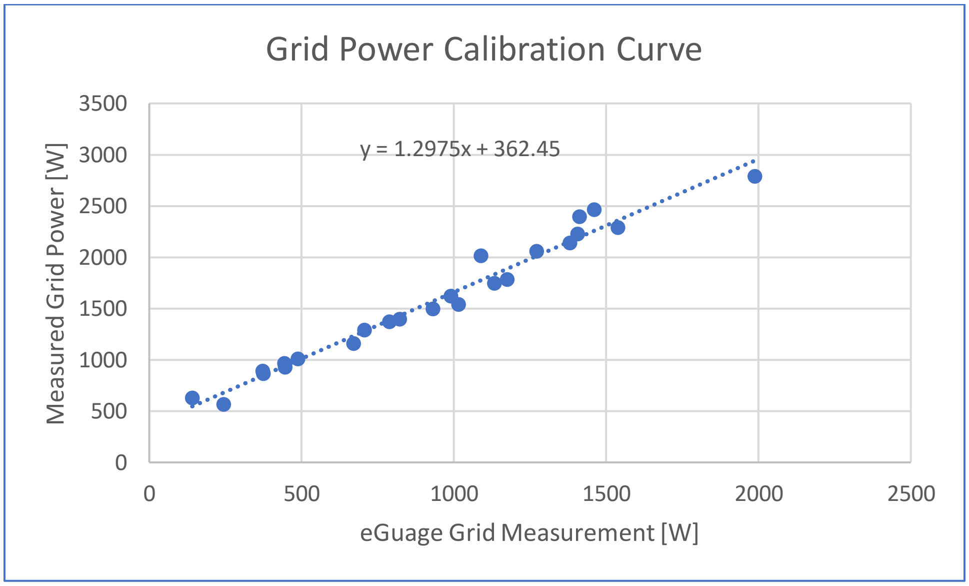

Figure 25. Grid power calibration curve.

$$eGauge\ Grid\ Measurement\ \times 1.2975 + 362.45 = Calibrated\ Grid\ Power \qquad (11)$$

As previously noted, PV and battery power were disabled from contributing to the load while these manual measurements were made. This allows for the assumption that in this scenario grid power should be equal to load power, which is not reflected in the data. It was concluded that the calibrated eGauge measurement for grid was oversized, and an additional offset was needed. An offset value of -360 W was chosen to be applied the grid calibration curve; this value reflects the approximate reading of the eGauge measured grid power when there was no load on the system and agrees with the offset in the calibration curve. The finalized method used to calculate for a grid power is shown in (equation 12) below.

$$eGauage\ Grid\ Measurment\ \times 1.2975 + 362.45 - 360 = Calibrated\ Grid\ Power \qquad (12)$$

Demand Reduction

For the self-consumption system demand reduction was previously defined as the difference between the load power and the grid power during that same interval of measurement, this was also referred to as (equation 4) in the methodology section. For the fabricated load profile, the largest demand programmed to occur each day is 3000 W and occurs between 5:10pm to 5:14pm. Figure 26 shows a duration curve of the measured across the data collection period. Note how fabricated load values do not exactly match measured values, as seen in the lack of 3000 W measurements, and instead instances of near 3000 W values.

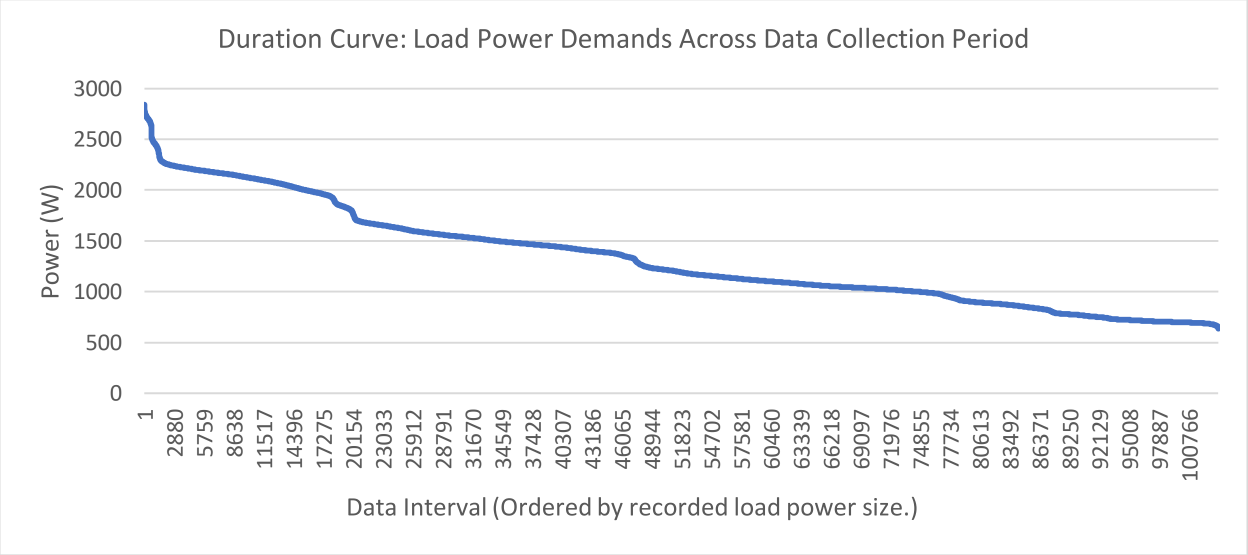

Figure 26. Duration curve of recorded load power values across data collection period.

Figure 27 shows the grid power measurements and load power measurements across the data collection period. Using this data, load reduction can be calculated using (equation 4), this is displayed in Figure 28 where the load duration curve is presented with equivalent load reduction values. The load reduction is the amount of power that was offset by the self-consumption system. When load reduction is close to the load duration curve that is suggestive of the self-consumption system being able to offset a large amount of the demand that would otherwise be on grid power. When the space in between the load curve and load reduction is greater that indicates that the self-consumption system is able to offset a smaller amount of the demand, or none at all if the peak load reduction value is at zero.

Figure 28 represents a large amount of data and because many load values are similar (because the same load profile is repeated daily) load data appears as a line. Calculations of load reduction varies depending on such conditions as available solar irradiance and battery SOC, because of this the load reduction line appears as an area or range rather than a line, but this is not actually the case. The conditions that impact demand reduction values will be discussed in the analysis section of this study.

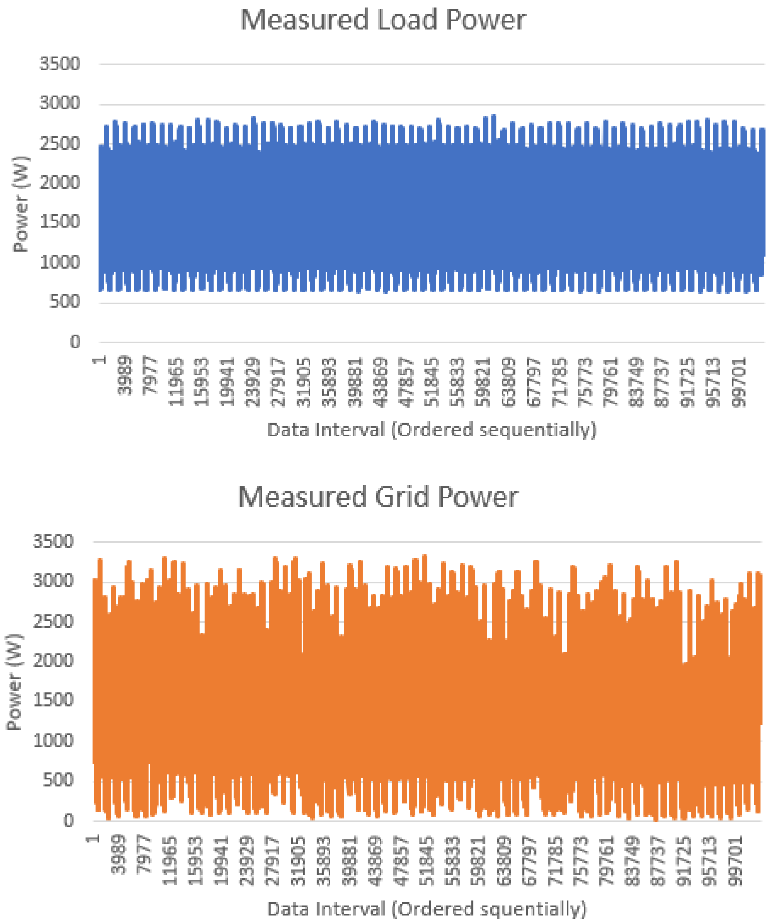

Figure 27. Measured load and grid power throughout the data collection period.

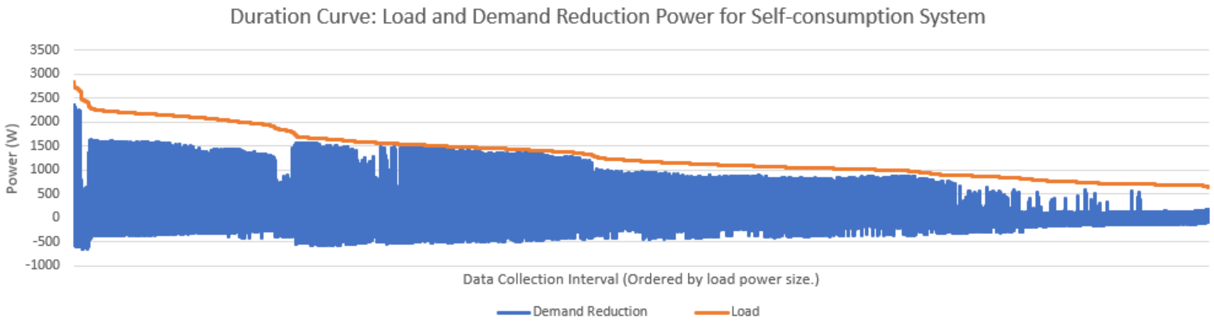

Figure 28. Duration curve of demand reduction and load power for self-consumption system.

Figure 29 depicts the results of demand reduction for the PV only model. This figure depicts data in the same fashion as Figure 28 except instead of the offset being a result of the self-consumption system the offset is simply a result of the PV power.

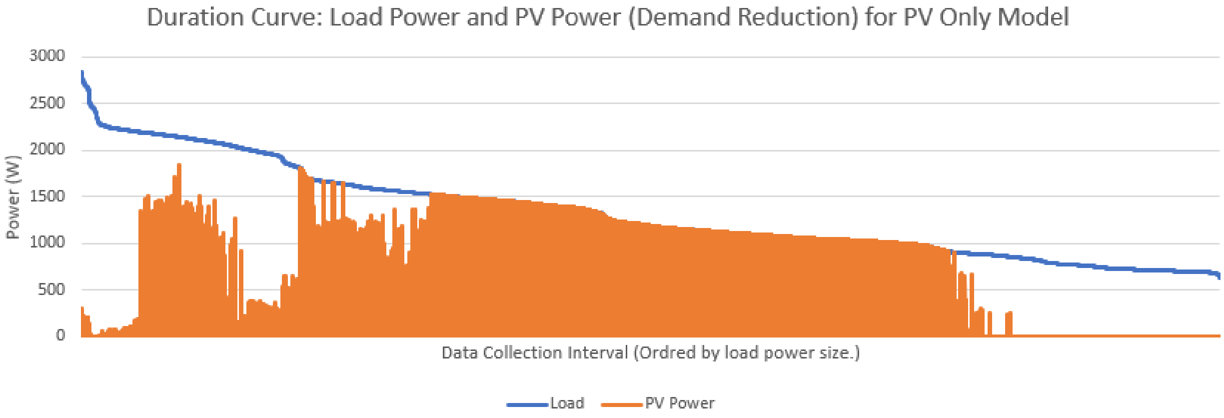

Figure 29. Duration curve of PV power (demand reduction) and load power for PV only model.

Grid Import Reduction

Grid import reduction calculations for the self-consumption system and PV only model created using (equation 6) and (equation 7) as described in the methodology section. Figure 30 and Figure 31 show the results of these two equations in kWh.

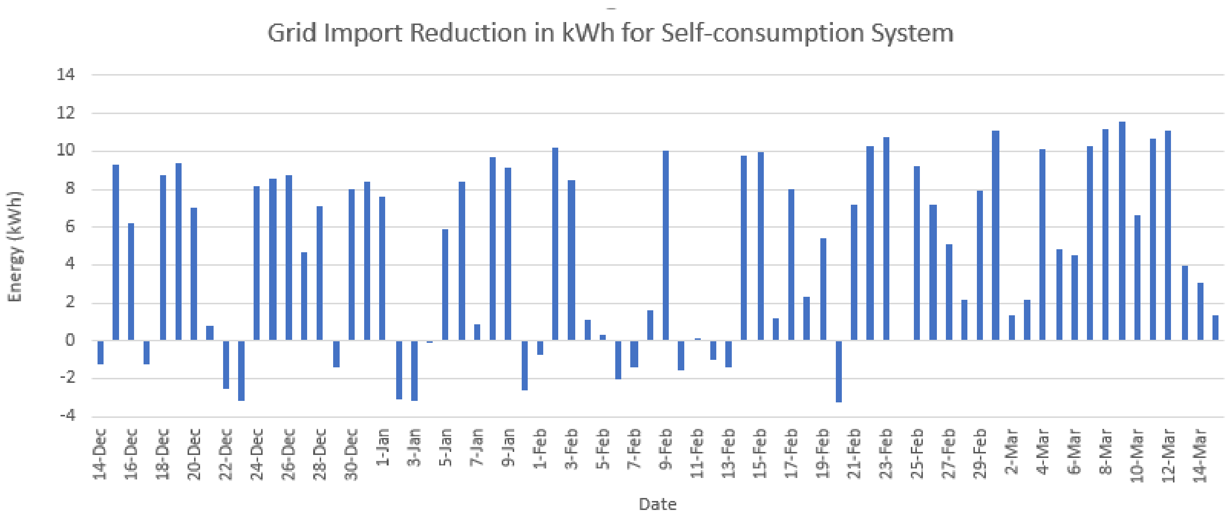

Figure 30. Initial grid import reduction results for self-consumption system calculated in kWh.

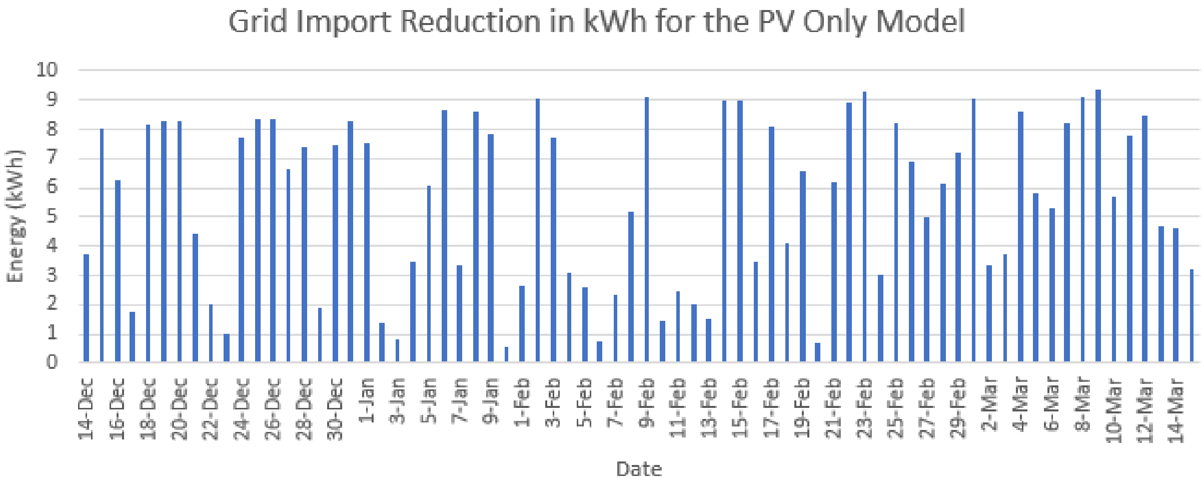

Figure 31. Initial grid import reduction results for PV only model calculated in kWh.

In terms of a percentage of grid import reduction the same results in Figure 30 and 31 can be be described in Figure 32 and Figure 33 respectively. These figures are representative of results derived from (equation 8) and (equation 9), once again respectively.

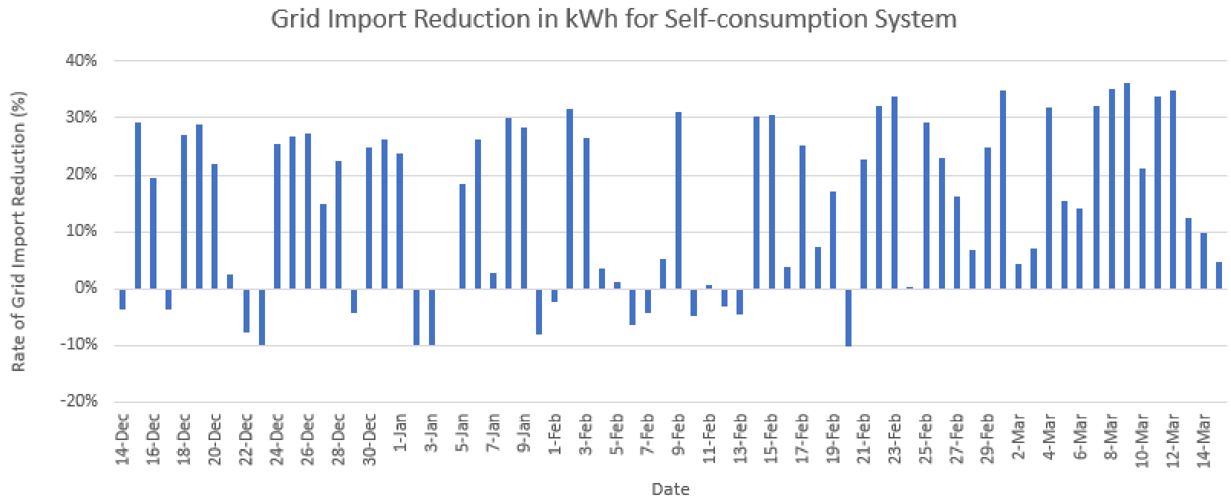

Figure 32. Percentage of grid import reduction for the self-consumption system.

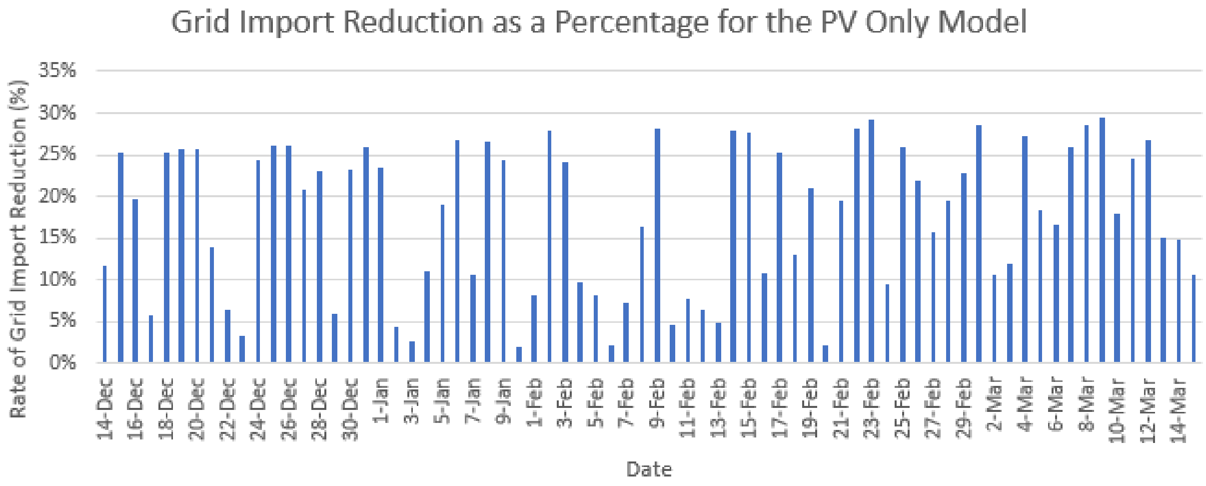

Figure 33. Percentage of grid import reduction for the PV only model.

CHAPTER 5: ANALYSIS AND CONCLUSION

Data Uncertainty

Power Balance

One method that can be used to understand how electricity flows through the self-consumption system is to analyze power balance. In other words, for any given interval of measurement throughout the data collection period of this study the sum of the power suppliers (PV, utility grid, battery discharge) should equal to the power consumers of the system (load, battery charge, losses). To determine the power balance of the self-consumption system first all power sources must be converted to the same current form, in this case AC power is chosen, and this can be accomplished through the use of (equation 1) and (equation 2) as described in the methodology. An additional measurement that should be considered in this power balance equation that has not been otherwise addressed thus far is the small parasitic load that is reported in the PV power measurement. This parasitic load is representative of the load that the charge controller pulls from the battery while not otherwise in use. Other parasitic loads exist as well, but are factored into the battery discharge power value. With all these factors under consideration a power balance equation can be formed and is seen below as (equation 13). For power balance to be achieved the result of (equation 13) should always be zero. Figure 34 shows the result of the power balance equation across the data collection period.

$$\begin{aligned} &Load\ Power - Grid\ Power\ - PV\ Power - Battery\ Discharge\ Power \\ &\qquad + Battery\ Charge\ Power + PV\ \ Parasitic\ Load = Power\ Balance \end{aligned} \tag{13}$$

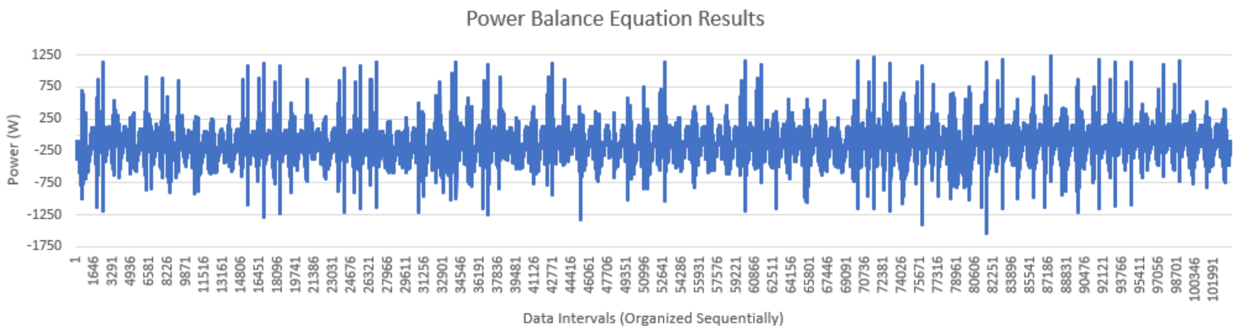

Figure 34. Power balance equation results depicted sequentially through data collection period.

As can clearly be seen the power balance results deviate to various degrees away from zero. Positive values in these results might suggest the loads are higher than the power supply, and negative results might suggest that there was more supply than load. However, in this equation it must be remembered that in this study all loads and all supplies are subject to measurement, this means this power imbalance suggest that some measurements of power are incorrect.

It is possible that any or all the factors in the power balance equation may be the source of this imbalance. The eGauge, for example, yielded power results that had to be fit with a calibration curve, as described in the data section of this study. It is possible that the calibration curve contains some error that skews the resulting load power, grid power, or both. Also suspect is the additional offset that was applied to the calibrated load power due to the circumstantial evidence that it was simply too high after the calibration.

The efficiency factors applied to the battery and PV power to allow for DC-to-AC power translation may also have been the source of some error. As was shown in Figure 8 inverter efficiency is not a constant value, though a constant value was chosen for calculations. This could be responsible for some small error in equivalent AC power for the PV and battery power data.

Power balance is a complex topic, especially in systems where there are multiple power sources like the self-consumption system of this study. When attempting to analyze power balance using simplified means there is room for error. Dissecting the means of power balance for this self-consumption system and finding a means to measure power with less uncertainty should be considered as a topic of future research. With the current measurements of power and the power balance equation chosen, this study is unable to resolve power balance.

The effect of power imbalance on self-consumption results.

Figure 35 shown below is a calculation of daily energy supply from power sources relative to the daily load, it should be noted that in this figure the contribution of the PV and battery have built into one calculation. As can clearly be seen it is apparent that the sum of the power sources outweighs the load. This is not possible as load is an independent measurement of the sum of these power sources. It can also be noted that in this figure that on some instances grid outweighs load, which when considering equations like (equation 4) or (equation 6) where grid is subtracted from load to find some rate of self-consumption the result yields a negative value. This is exactly what can be seen in the data, such as in the previously depicted Figure 28 and 30.

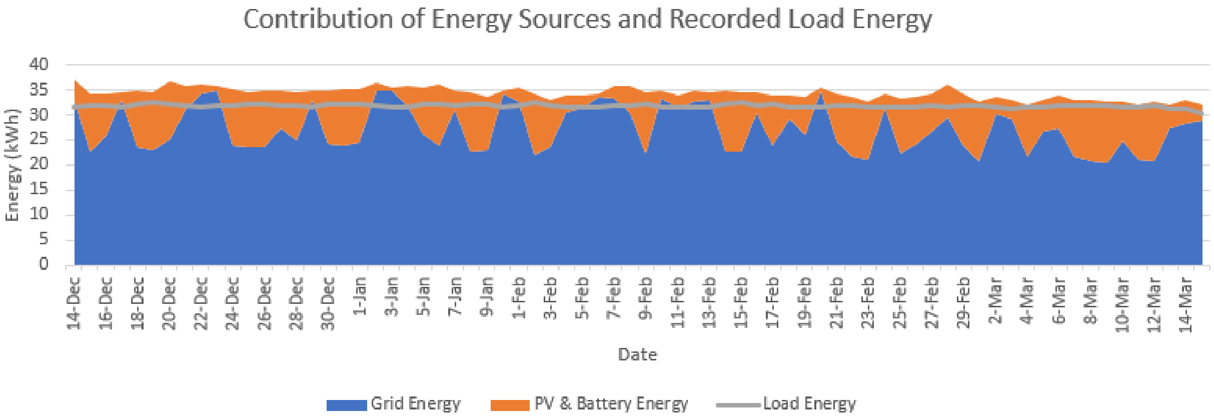

Figure 35. Contribution of energy sources relative to the daily load energy.

Figure 36 describes the imbalances as energy in kWh and as a comparative percent of the measured load. On average there is a difference of 2.28 kWh of energy that cannot be reconciled, which is an amount equal to 7.12% of the measured load. The largest day for energy imbalance was December 14, 2019 where 5.12 kWh cannot be accounted for or approximately 16.01% of the measured load. While the smallest was March 4, 2020 where 0.29 kWh cannot be account for or approximately 0.91% of the measured load.

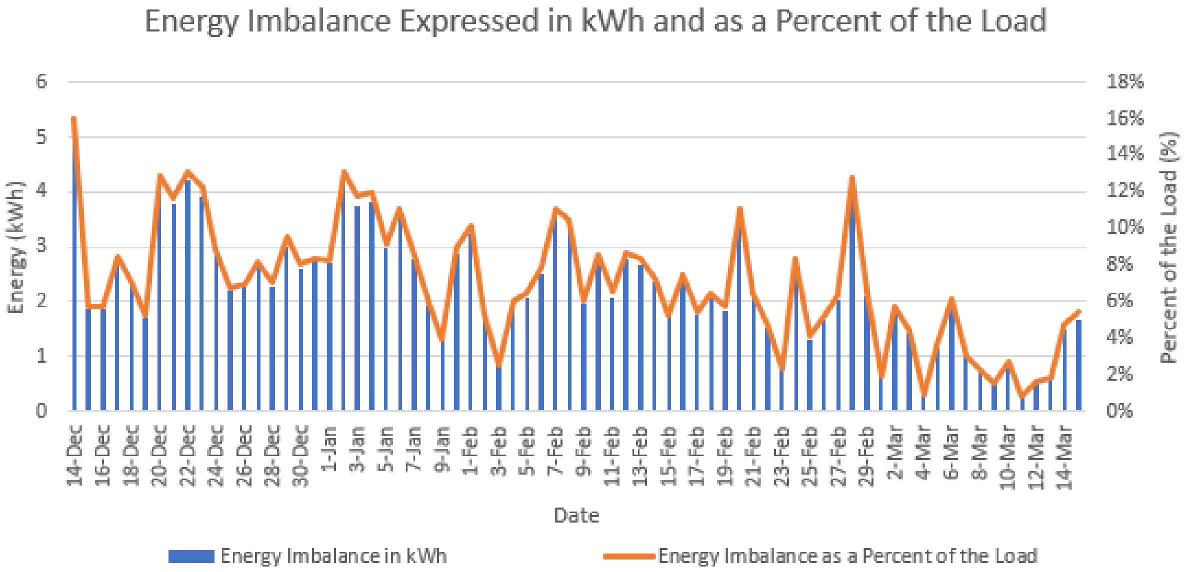

Figure 36. Imbalance expressed in kWh and a relative percentage of the load.

With these imbalances recognized some can be said for the uncertainty regarding the self-consumption data. It is unknown what combination of power sources and load has been recorded incorrectly. For that reason, some self-consumption results may be inflated or deflated. It is also possible that these results are mischaracterizing the PV only model data to some degree. Any measured rate of self-consumption, however, is certainly is not a negative value and in the analysis section any such result is normalized to zero. For these reasons imbalance values will be applied to data related to grid import reduction as uncertainty in a following section.

Self-consumption: Demand Reduction

Figure 37 depicts the 100 largest recorded load power values and equivalent demand reduction power values throughout the data collection period. All these loads occur between 5:00pm and 5:14pm, a time previously established as having the largest power demand of the day. Therefore, all these loads can be considered peak loads. Table 4 summarizes the demand reduction power values.

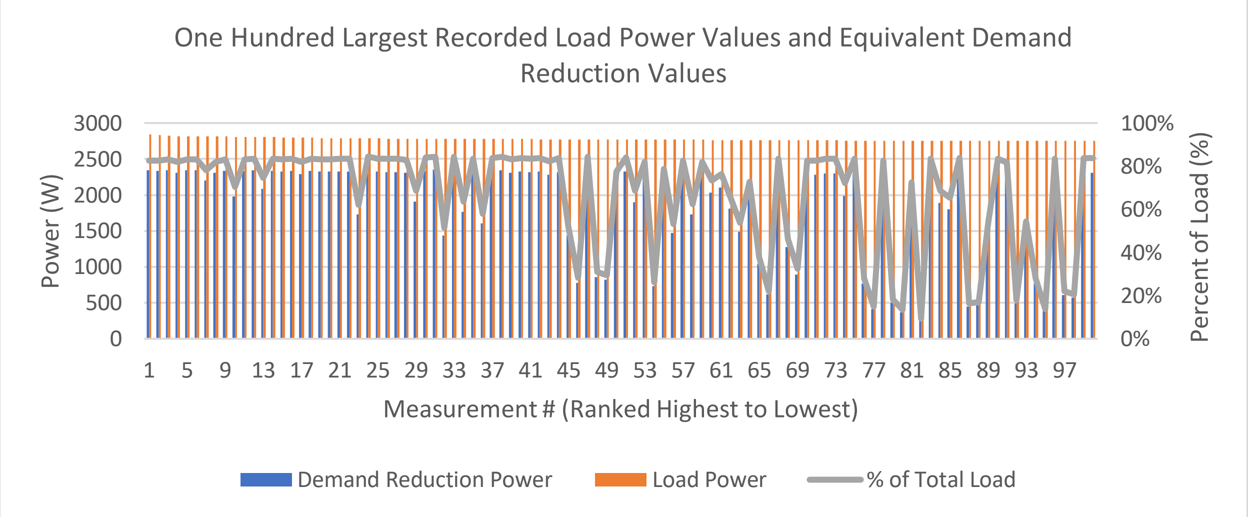

Figure 37. 100 largest measured loads power values and equivalent demand reduction values.

Table 4. Trends in demand reduction relative to 100 largest recorded load power measurements.

	Load Power (W)	**Demand Reduction (W)**	**% of Load**
Largest Demand Reduction	2785.0	2352.0	84%
Smallest Demand Reduction	2755.1	255.3	9%
Average Demand Reduction	2774.5	1860.6	67%

Figure 37 and the information in Table 4 indicate that the self-consumption system is able to reduce peak demand by considerable amounts, but not necessarily always. To explore this relationship further Figure 38 shows the demand reduction power for the peak load power values recorded each day. In other words, Figure 38 is showing the result of subtracting the grid power from the load power on the data interval with the highest recorded load each day, this is (equation 4) in the methodology section. Also depicted in Figure 38 is the daily sun hours recorded for each day. Table 5 summarizes the information in Figure 38.

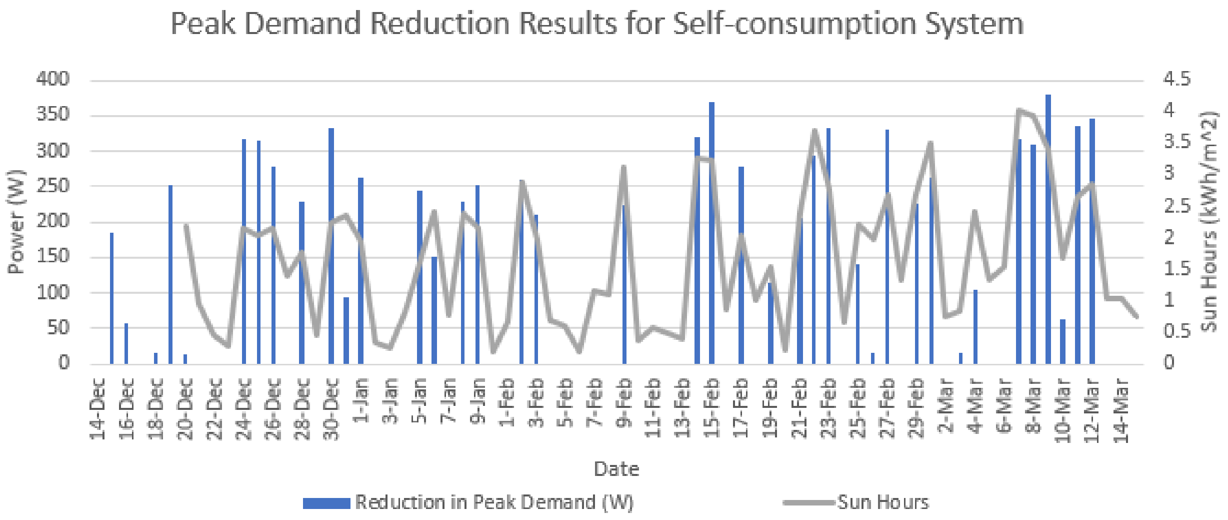

Figure 38. Peak demand reduction for the self-consumption system with sun hours.

Table 5. Summarization of results related to demand reduction in self-consumption system.

Largest reduction in peak demand.	379.9 W - March 9, 2020
Number of days with reduction in peak demand.	39 days
Number of days with no reduction in peak demand.	33 days
Average daily reduction in peak demand only counting days with reduction in peak demand.	222.6 W
Average reduction in peak demand overall.	120.6 W

The relationship between sun hours and peak demand reduction are better illustrated in the scatter plot shown in Figure 39. In this figure daily calculated sun hours are shown on the x-axis and peak demand reduction results are shown on y-axis. A positive correlation between sun hours and peak demand reduction is visible. With this information it is reasonable to conclude that peak demand reduction within the self-consumption system tends to increase with increased available sun hours.

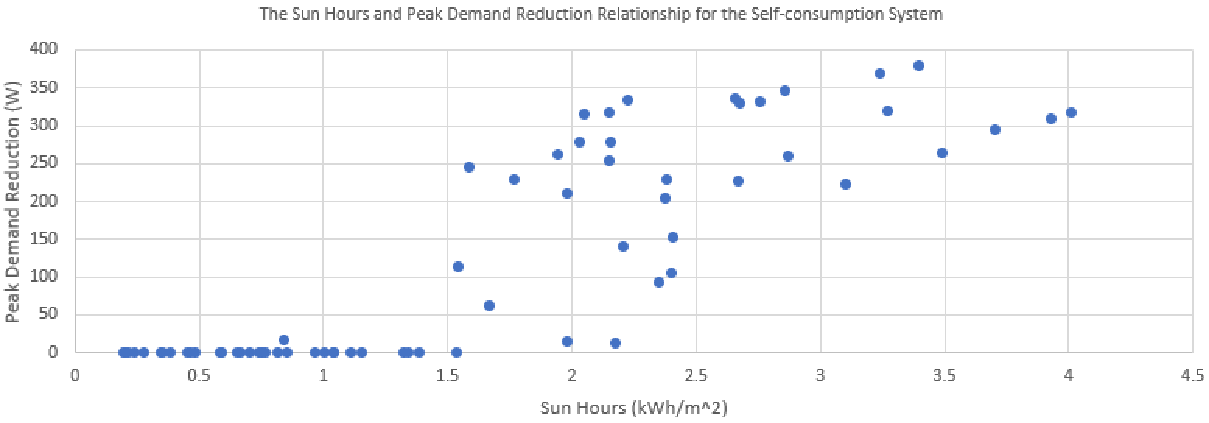

Figure 39. Self-consumption system's reduction in peak demand versus sun hours.

Self-consumption System Versus PV Only model, Impacts on Demand Reduction

The primary difference between the self-consumption system and the PV only model is battery storage. For this reason, when comparing the model and the self-consumption system, what is really being analyzed is the impact battery storage has on self-consumption. Figure 40 depicts a duration curve similar to the ones found in the data chapter of this study, however, in this instance the measured value is the difference between demand reduction in the self-consumption system and the demand reduction in PV only model. This figure helps illustrate the impact the battery storage has on demand reduction. In other words, Figure 40 shows to what extent the battery is capable of satisfying loads that are present throughout the load profile.

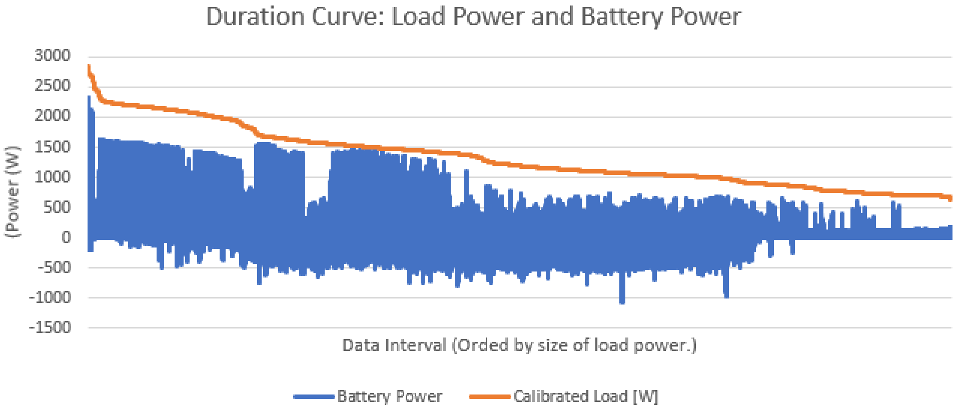

Figure 40. Duration curve of load power and battery power.

Figure 40 illustrates that the battery is capable of satisfying varying portions of the loads present throughout the load profile, notably the battery seems to be able to contribute meaningful amounts of power to large loads that the PV only model was not able to. Also present in Figure 40 are negative battery power values which are suggestive of instances where the PV only model is more effective than the self-consumption system at delivering to loads at certain measurement intervals. The reason for this may be related to the self-consumption system diverting power to charge the battery rather than satisfy loads. This behavior is not controlled by any setting in the inverter or charge controller. It is also possible that these values have been affected by power imbalance, a further analysis of how PV power is delivered to battery for charging within a self-consumption system may be a meaningful topic of future research.

To better illustrate the impacts of battery storage on demand reduction relative to the PV only model Figure 41 shows the daily reduction in peak demand for the self-consumption system (shown previously as Figure 38) compared directly to the same results for the PV only model. This figure is accompanied by Table 6 which summarize some findings.

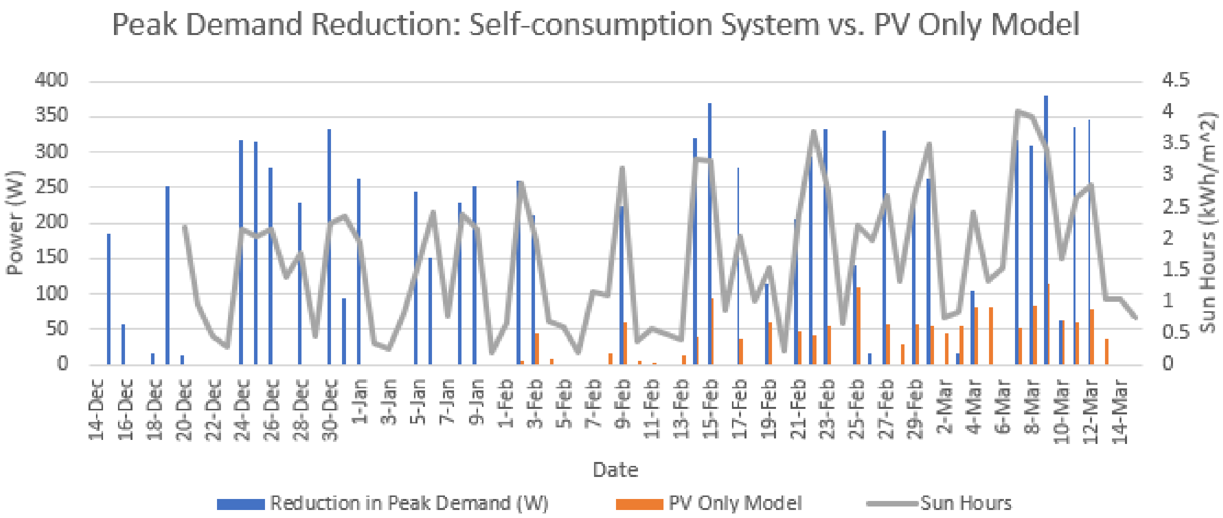

Figure 41. Comparison of daily peak demand reduction, self-consumption system and PV model.

Table 6. Summarization of results for peak demand reduction self-consumption versus PV only.

	Self-consumption System	***PV Only Model***
Average daily reduction in peak demand only counting days with reduction in peak demand.	222.6 W	50.8 W
Average reduction in peak demand overall.	120.6 W	21.9 W
Number of days with reported peak demand reduction.	39	47

The average peak demand reduction for the PV only model is significantly less than the peak demand reduction results reported by the self-consumption system. However, it is notable to point out that although the PV only model reduces peak demand by a significantly less amount, it reported demand reduction on a greater number of days. It is possible that this phenomenon is a byproduct of the previously discussed power imbalance issues where grid power outweighs load power. In which case self-consumption rates are always forced to zero.

Regardless, it can clearly be seen that the self-consumption system outperforms the PV only model. The benefit of battery storage is substantial, and the reason why the battery allows the self-consumption system to exceed the PV only model in this regard is related to the time in which peak demand occurs and when daily solar irradiance is available. As previously noted, peak demand occurs from 5:10pm to 5:14pm, and for the majority the data collection period (which all takes place in the winter) the sun is set or is setting by the time the peak demand arrives. The self-consumption system can store excess PV power in the battery bank that is otherwise being curtailed by the PV only model and utilize after the sun goes down. The storage of excess energy, after all, is the primary feature of a battery.

Further illustrating the difference in performance between the self-consumption system and PV only model is Figure 42 which shows peak demand reduction in relation to sun hours. This data set illustrates how increased sun hours correlates with the self-consumption system's ability to reduce peak demand; a characteristic not exhibited as well by PV only model. Although, the PV only model's peak demand reduction performance does improve to some degree during days where there is a higher number of available sun hours.

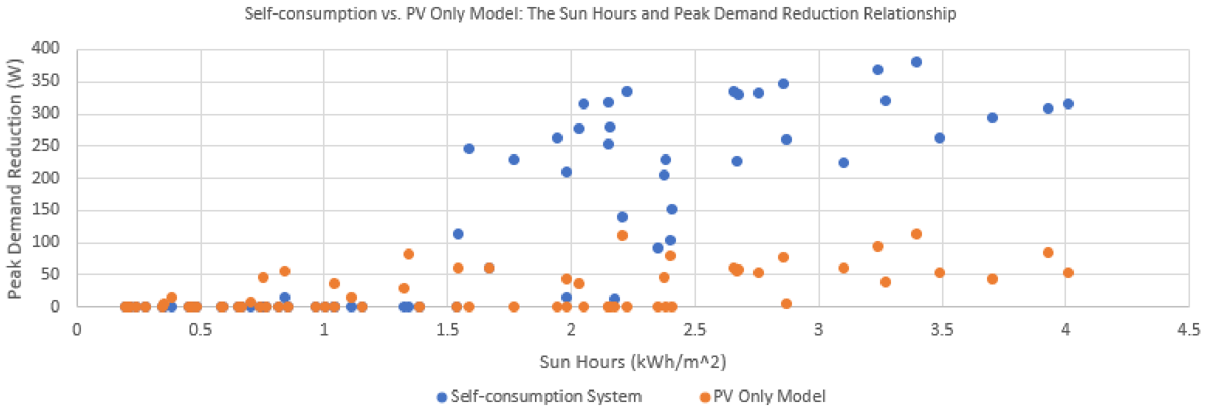

Figure 42. Self-consumption system versus PV only model, peak demand reduction and sun hours.

Self-consumption: Grid Import Reduction

Grid import reduction has previously been described as the energy the self-consumption system or PV only model has been able to satisfy in place of the utility grid. As discussed in the methodology section these values were solved for using (equation 6) for the self-consumption system. Initial data for results related to grid import reduction were displayed as Figure 30. Grid import reduction values for the self-consumption system are based on subtracting daily grid energy from daily load energy. Due to some power balance errors that were previously discussed in the data uncertainty section of this chapter some grid import reduction results yielded negative values. These values are not physical, and all less than zero values related to grid import reduction are reset to zero for this analysis.

A representation of grid import reduction for the self-consumption system is shown in Figure 43, in this figure negative self-consumption energy values were removed and replaced with zero values. Also included in Figure 43 are daily sun hours results. For the self-consumption system there is a positive correlative between a greater amount of sun hours and a greater grid import reduction. The relationship between sun hours and grid import reduction for the self-consumption system are better illustrated in Figure 44. Figure 45 displays these same results as a percentage of the total load. Table 7 summarizes findings regarding self-consumption system.

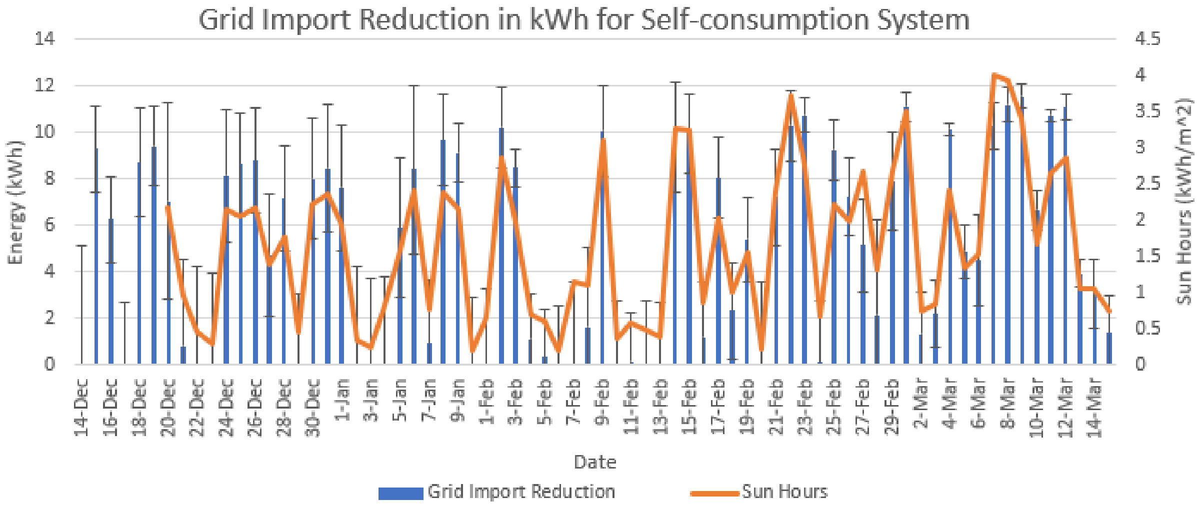

Figure 43. Grid import reduction for self-consumption system.

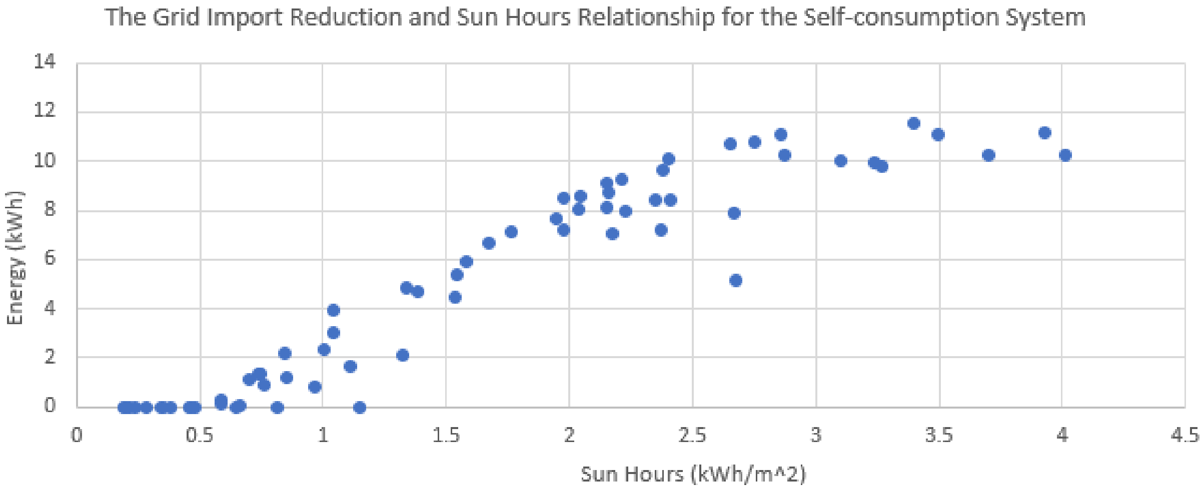

Figure 44. Grid import reduction versus sun hours, self-consumption system data set.

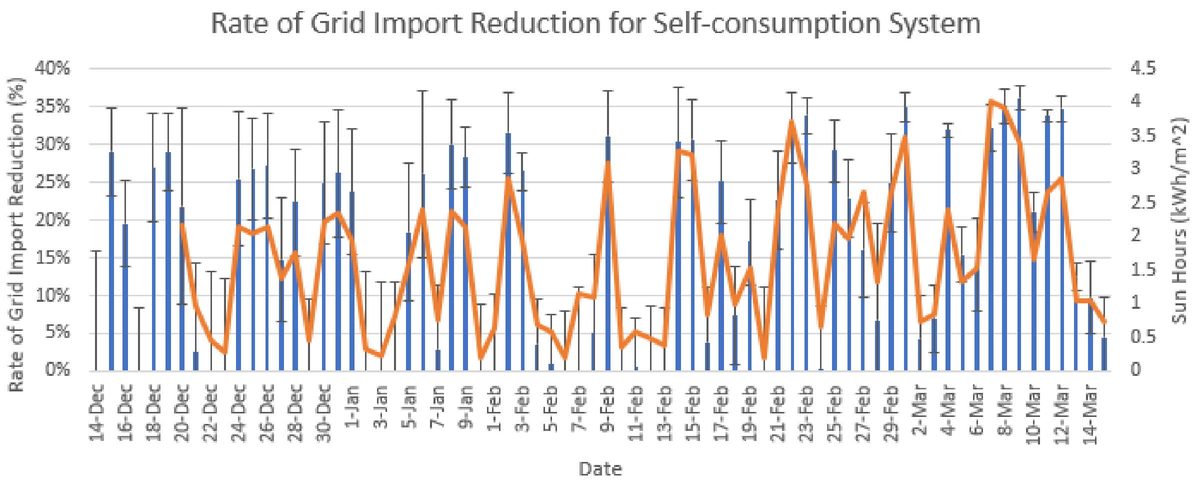

Figure 45. Percentage of grid import reduction for the self-consumption system with sun hours.

Table 7. Summarized results regarding grid import reduction in self-consumption system.

Average kWh of grid import reduction.	5.1 kWh
Average rate of grid import reduction.	22.1%
Number of days with grid import reduction.	56
Number of days with no recorded grid import reduction.	16
Average kWh of grid import reduction on days with recorded grid import reduction.	6.6 kWh
Highest recorded kWh of grid import reduction	11.5 kWh – March 9, 2020
Highest rate of grid import reduction.	36.2% - March 9, 2020

As discussed in the data uncertainty section of this study power imbalance issues resulted in an average daily imbalance of energy of 2.28 kWh or 7.16% relative to recorded load. In this study energy imbalance is equated to energy uncertain and it is not known exactly how power imbalance impacts daily measurements of grid import reduction. For this reason, error bars are included in Figure 43 and 45 that depict a likely range of grid import reduction values. The bars are representative of the energy in each daily measurement, and are specified in Figure 32.

Energy uncertainty varies from day to day; however, it also appears to be higher on average when the daily PV energy is lower. There are days within the data set where there is PV power present but no grid import reduction. This is not indicative of understood system behavior because as it has been otherwise understood that PV should primarily satisfy loads which would provide a self-consumption value, or PV should charge battery whose discharge would provide a self-consumption value. As a result, it is unknown exactly how this uncertainty impacts grid import reduction. The data presented in Figure 46 suggest that it is possibly more likely that self-consumption is being underrated, but ultimately it is not known.

Other issues related to balance in the data section of this study showed self-consumption results yielding some negative value. These negative values were removed in the analysis as discussed but would imply the self-consumption system caused the grid to import more energy than if the self-consumption system was not installed. Negative self-consumption is not a reasonable outcome in this study; the lowest reasonable value for self-consumption is zero. These imbalances make it possible that the actual rate of grid import reduction is higher or lower than presented values. As reiterated several times through this analysis section, power balance is a complex issue in this system and needs to be reevaluated if more definitive results about self-consumption are to be extracted from this data set.

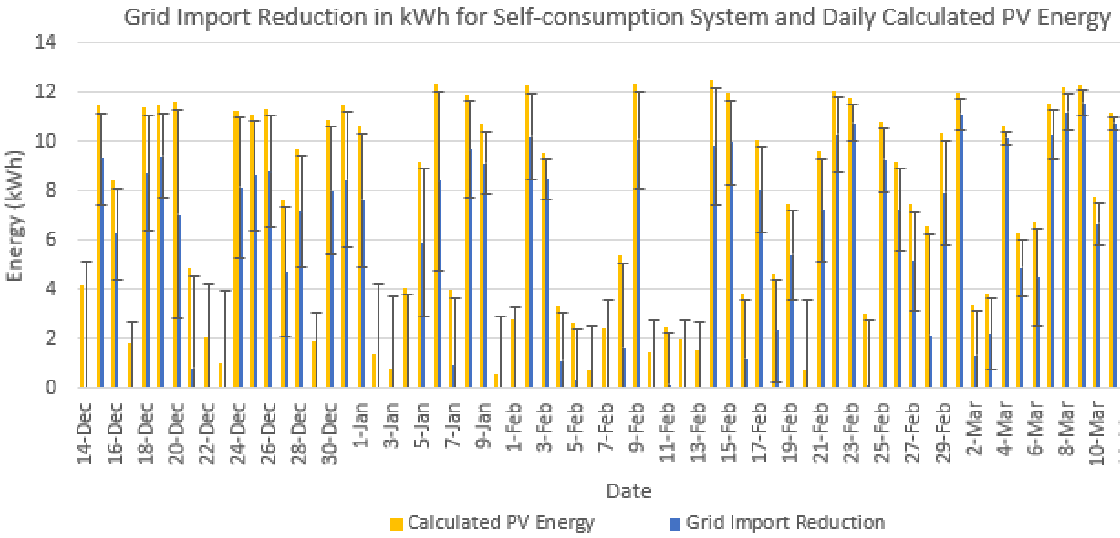

Figure 46. Grid import reduction and measured PV energy for self-consumption system.

Self-consumption System Versus PV Only Model, Impacts on Grid Import Reduction

In Figure 47 the grid import reduction for the self-consumption system is compared to the grid import reduction results generated by the PV only model. Figure 48 shows both as a percentage of self-consumption. In both figures error bars are included.

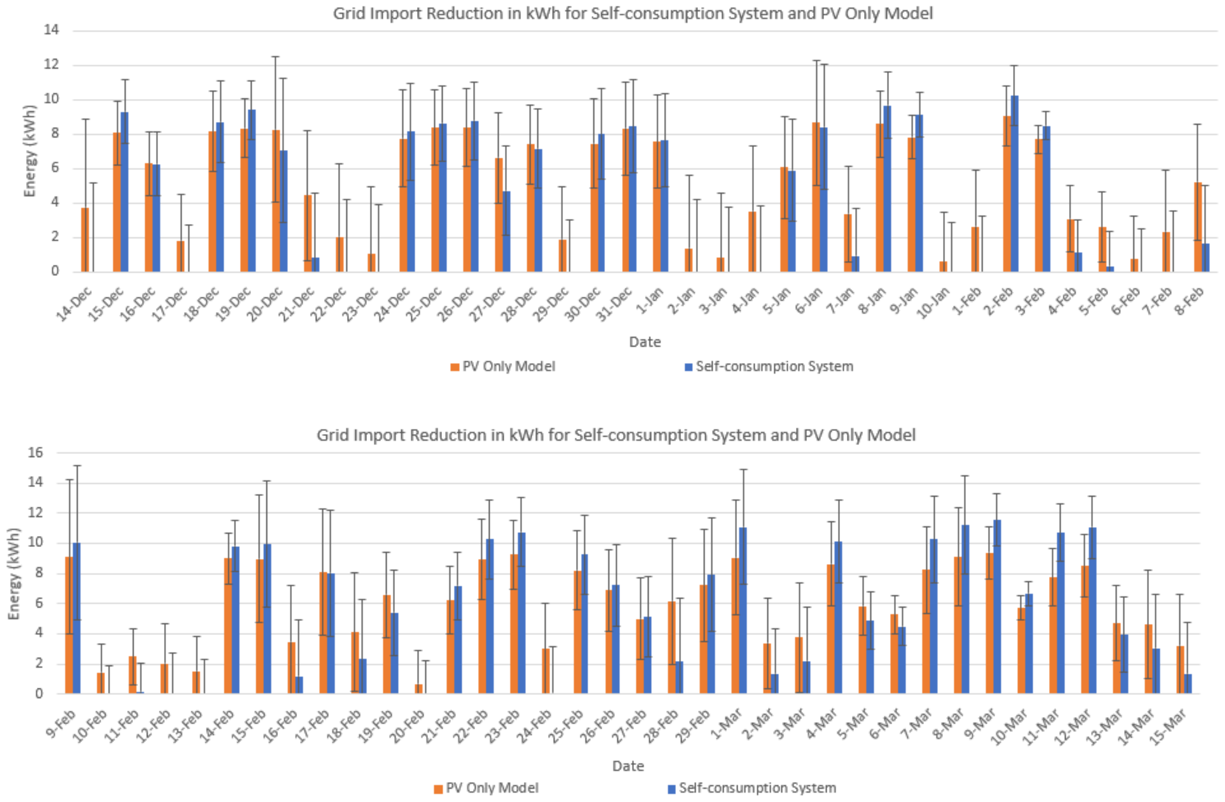

Figure 47. Grid import reduction for self-consumption and PV only model in kWh.

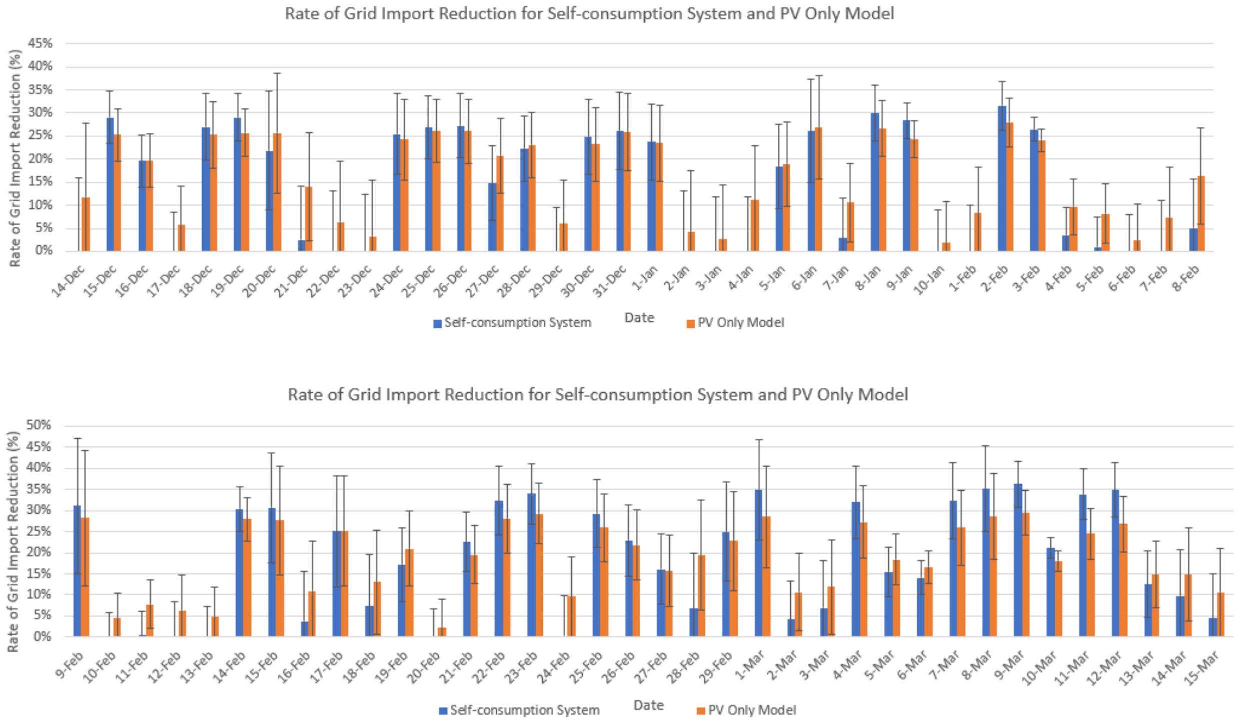

Figure 48. Grid import reduction for self-consumption and PV only model as a percentage.

The data shows that during days where there is a greater amount of grid import reduction overall the self-consumption system increases grid import reduction to a greater extent than the PV only model. However, the PV only model reports better performance on days where there is less overall generation between the system and model. To better illustrate this, Figure 49 shows grid import reduction in kWh vs. daily sun hours.

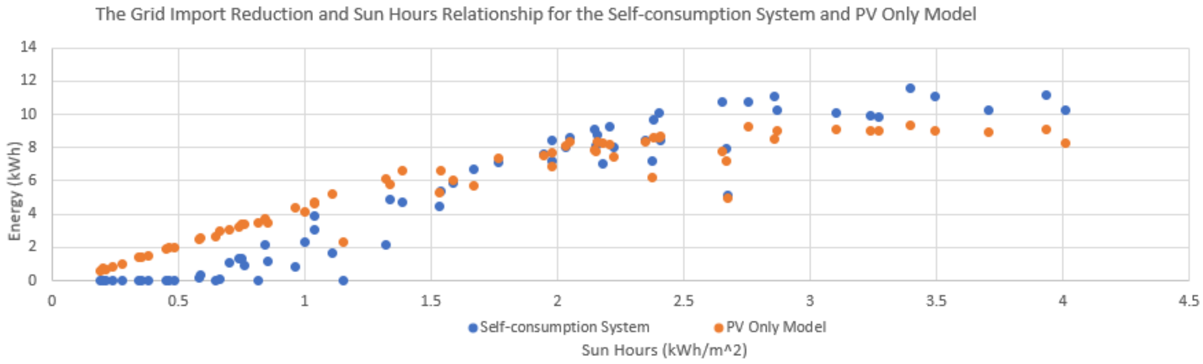

Figure 49. Sun hours and grid import reduction in kWh for the self-consumption system and PV only model.

As previously discussed, there are low performance days in the data where self-consumption rates are zero even though there is reported PV power. Such results are dubious. It is also during these low performance days where uncertainty can outweigh self-consumption results, if they even have a non-zero value, and sometimes these uncertainties even outweigh PV model results. Characteristic of the power and energy imbalance issues are conditions where reported grid power values exceed reported load power values, when the self-consumption system rates are determined by subtracting grid from load, this leads to situations where if it really is to be believed that measured grid values are too high then surely the calculated self-consumption rates are being diminished. Even still, it is unclear to what extent that could be occurring, as previously stated the source of these balance issues are unknown.

A reasonable assessment of the grid import reduction data would suggest that self-consumption system reduces grid imports to a greater extent than the PV only model when there is a greater amount of solar irradiance. However, due to uncertainties within the data and the prevalence of results that show the PV only model outperforming the self-consumption system, it cannot be concluded that the self-consumption system has an overall better performance than the PV model. It would be meaningful to reassess grid import reduction data when power balance can be accounted for.

Conclusions

Simply put the question raised in this study was to what extent can a self-consumption system with battery storage decrease grid interaction in a typical residential home in Boone, NC? While there are certainly still some unknowns several statements can be made to address this question. First in regard to a reduction in peak demand, the self-consumption system was shown to on average decrease daily peak demand by approximately 120.6 W. Results showing increased peak demand reduction correlate with available solar irradiance. On days with low sun hours it was reasonable to find that there was a lower or no reduction in peak demand while on days where there was a larger amount of sun hours peak demand reduction was higher. When comparing results in reduction of peak demand to the PV only model, it was shown that the demand reduction in the self-consumption system was greater than the PV only model by around 100 W, and this can largely be attributed to the battery bank. On days with very low solar irradiance demand reduction between the self-consumption system and the PV only model was far more similar, with some results even showing the PV only model outperforming the self-consumption system by a small degree. It is to be noted errors related to power balance, as discussed, likely played a role in the finding related to demand reduction and it is possible that a better power balance result may have shown different overall results. Other considerations regarding peak demand data should include the fact that the data collection period occurred mostly during the winter when solar irradiation is characteristically lower, if the same study was conducted in the summer or over an entire year different results may have been found. Additionally, the battery bank used in this study is undersized and was used due to its availability rather because it was believed to be ideal for any reason. A larger battery bank, or any different component size for that matter, likely would impact the results for demand reduction as well. It could be predicted that a larger battery bank would have increased demand reduction.

As for results related to grid import reduction. The self-consumption system was shown to have contributed an average of 5.1 kWh of energy to the daily load demand, equal to 22.1% of the daily load. Again, higher grid import reduction results correlated with increased available solar irradiance. With the average grid import reduction was 5.1 kWh the data also shows days with little to no contribution to grid import reduction and other days where the self-consumption system contributed as much as 11.6 kWh or 36.2 % of the daily load. Comparing the self-consumption system to the PV only model results data showed the self-consumption system outperformed the PV only model on days with more than around two sun hours, but also indicated the PV only model outperformed the self-consumption system on days where there was less solar irradiance. Again, due to issues with power and energy balance these results are somewhat dubious, and surely if the power and energy balance were resolved it is likely results would be different at least to some degree. Within this study, it cannot be concluded that the self-consumption system always reduces grid import reduction move than can equivalent PV only system. In addition, and similar to the results regarding demand reduction, a system with differently sized components would have different results. As was discussed, the battery used in this system was undersized, but it is also true that the 3.36 kW installed PV system used in this system is considered undersized if it was supposed to be equivalent to the size of a PV system on the average residential home.

Recommendations for Further Research

The following section covers a variety of recommendations that should be considered topics of future research related to residential self-consumption systems.

Power Balance

Solving for power balance and fully understanding the flow of energy and power throughout the self-consumption system proved to be a major source of error and frustration throughout this study. Future researchers who are able to resolve these issues and find power balance conditions that are resolved, or as described earlier consistently result in zero or near zero values would be able to better characterize the rates and behavior of the self-consumption system. One suggestion may be to eliminate grid and load measurements from the eGauge, which to a certain degree behaved as a black box more than a datalogger throughout this study. I would recommend that these measurements be moved to a device that can independently be controlled and verified. The ability to log load and grid measurements that are consistent with measured values would be highly beneficial and would improve on the uncertainties of this study.

Expand Data Collection Period

Data was collected between December 14, 2019 and March 15, 2020 a timeframe equivalent to approximately three-months. It would be beneficial to examine the data over the course of at least one year, as seasonal conditions impact the performance of PV systems, like the self-consumption system of this study. For example, sun hours tend to grow into the summer and diminish in the winter, the self-consumption system in this study consistently performed better on days where there was a greater amount of sun hours. It would be interesting to see the peak performance of the self-consumption system, which likely would happen during a non-winter season.

Economic Analysis of Self-consumption System Performance

As discussed in the literature review section of this study utility rate structures vary, and self-consumption systems can be deployed and utilized in a variety of ways to benefit the system owner economically. Though self-consumption system performance was characterized as benefits to peak demand and grid import reduction it remains unknown what the economic implications of these conditions are. It would be valuable to evaluate performance of the study's self-consumption system in terms of costs benefit or losses under various utility rate structures. It would be important to consider system costs as well as the value of energy in this regard. An additional consideration beyond utility rate structures and equipment costs may also include the impacts different tax or other PV and battery promoting incentives would have on the economic performance of this self-consumption system.

Installed Systems Capacity

As discussed, the installed battery and PV system capacity used in this study are considered undersized. Therefore, it is not unreasonable to assume that the self-consumption system does not entirely reflect what the average residential self-consumption system homeowner has installed. It could be beneficial to increase the installed capacity of the PV system, battery system, or both and reevaluate the effects the system has on demand reduction, grid import reduction, or some other metric that is used to value the performance of a self-consumption system.

Increased Load Profile Complexity

The fabricated load profile used in this study was based on one-hour energy use data provided by the DOE that itself was based on weather data for Bristol, TN. Though Bristol, TN and Boone, NC are geographically similar in a lot of a ways a better model to base a fabricated load profile off of may be based on weather data from Boone, NC or even be based on actual measurements in an average sized home in Boone, NC. In addition, the fabricated load profile was controlled in five-minute intervals that do not exactly reflect the energy use of a real inhabited home. For example, demand surges were characterized as five-minute spikes in power demand, when often demand surges don’t last exactly five-minutes and often are greater than what was presented in the fabricated load profile. Making enhancements to more closely model an actual residential home would be more beneficial to research as results may more closely align to the results that would be found if this study was conducted on a real residential home in Boone, NC.

Grid Export and Curtailment Analysis

This study focused on minimizing grid imports but in other scenarios it is not unreasonable to assume that a self-consumption system would be able to export power to the utility grid. The system in this study was additionally forced to forgo grid export due to requirements made by the inverter/charge controller manufacturer due to issues related to maintaining favorable self-consumption characteristics. It is possible that other inverter and charge controller model combinations would not be limiting in this manner. Implications of this change also may eliminate PV curtailment which was experience but not measured in the current configuration of the study’s self-consumption system. Therefore, another reasonable enhancement to this study may include the measurement of PV curtailment.

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APPENDIX A: LOAD PROFILE VALUES FOR LOAD PROFILE

Time Interval	Load (W)	Time Interval	Load (W)	Time Interval	Load (W)	Time Interval	Load (W)
1	875	73	2775	145	1300	217	2475
2	850	74	1600	146	1300	218	2475
3	900	75	1650	147	1300	219	2475
4	800	76	1625	148	1300	220	2350
5	800	77	1650	149	1300	221	2350
6	825	78	1675	150	1300	222	2350
7	850	79	1700	151	1275	223	2425
8	875	80	1700	152	1275	224	2400
9	850	81	1725	153	1250	225	2375
10	800	82	1750	154	1250	226	2400
11	1250	83	1750	155	1250	227	2425
12	775	84	1875	156	1225	228	2425
13	750	85	1850	157	1225	229	2500
14	775	86	1750	158	1225	230	2600
15	725	87	1750	159	1200	231	3000
16	700	88	1800	160	1200	232	2550
17	650	89	1850	161	1200	233	2450
18	700	90	1875	162	1225	234	2425
19	750	91	1875	163	1225	235	2400
20	775	92	1875	164	1200	236	2400
21	750	93	1800	165	1225	237	2375
22	750	94	1800	166	1200	238	2375
23	725	95	1800	167	1300	239	2325
24	725	96	1750	168	1150	240	2325
25	700	97	1750	169	1200	241	2300
26	700	98	2000	170	1200	242	2300
27	700	99	1700	171	1275	243	2300
28	700	100	1750	172	1150	244	2275
29	675	101	1750	173	1100	245	2275
30	700	102	1775	174	1075	246	2250
31	700	103	1800	175	1125	247	2250
32	725	104	1800	176	1150	248	2225
33	700	105	1550	177	1175	249	2200
34	725	106	1500	178	1225	250	2200
35	700	107	1550	179	1225	251	2175
36	675	108	1550	180	1225	252	2175
37	675	109	1500	181	1250	253	2000
38	700	110	1600	182	1300	254	2750

Time Interval	Load (W)	Time Interval	Load (W)	Time Interval	Load (W)	Time Interval	Load (W)
39	700	111	1625	183	1325	255	2000
40	725	112	1625	184	1350	256	2000
41	725	113	1625	185	1300	257	1925
42	750	114	1425	186	1350	258	1900
43	700	115	1425	187	1375	259	1875
44	700	116	1500	188	1475	260	1875
45	700	117	1550	189	1550	261	1775
46	725	118	1550	190	2250	262	1775
47	725	119	1500	191	1600	263	1775
48	725	120	1500	192	1625	264	1750
49	750	121	1475	193	1625	265	1650
50	775	122	1475	194	1625	266	1700
51	800	123	1475	195	1650	267	2000
52	800	124	1450	196	1675	268	1650
53	850	125	1425	197	1675	269	1650
54	875	126	1900	198	1700	270	1550
55	900	127	1425	199	1675	271	1550
56	925	128	1425	200	1675	272	1550
57	975	129	1400	201	1875	273	1550
58	1000	130	1400	202	1875	274	1475
59	1250	131	1375	203	1875	275	1375
60	1050	132	1375	204	1875	276	1375
61	1050	133	1375	205	2150	277	1250
62	1075	134	1375	206	2125	278	1250
63	1050	135	1400	207	3000	279	1250
64	1125	136	1375	208	2150	280	1125
65	1200	137	1350	209	2175	281	1100
66	1250	138	1375	210	2175	282	1100
67	1325	139	1350	211	2200	283	1075
68	1300	140	1300	212	2175	284	1050
69	1400	141	1275	213	2375	285	1050
70	1375	142	1250	214	2400	286	925
71	1425	143	1250	215	2425	287	900
72	1500	144	1275	216	2450	288	875

APPENDIX B: SYSTEM SETTINGS FOR SELF-CONSUMPTION SYSTEM

XW554-0100	
Meter	
Inverter	Enabled
Search Mode	Disabled
Grid Support	Enabled
Charger	Disabled
Force Chg	
Equalize	Disabled
Advanced Settings: Inverter	
Low Batt Cut Out	48.0 V
LBCO Hysteresis	2.0V
LBCO Delay	10 sec
High Batt Cut Out	65.0V
Search Watts	50 W
SearchDelay	2 sec
Advanced Settings: Charger	
Batt Type	[Custom]
Custom Settings	See Custom Batt Settings
Batt Capacity	160 Ah
Max Charge rate	100%
Charge Cycle	25tgNoFloat
Default Batt Temp	Warm
Recharge Volts	52.0V
Absorb Time	180 min
Chg Block Start	12:00am
Chg Block Stop	12:00am
Advanced Settings: AC	
AC Priotity	AC1
AC1 Breaker	60.0A
AC1 Low Volt	106V
AC1 High Volt	132V
AC1 Low Frequency	55Hz
AC1 High Frequency	65Hz
AC2 Breaker	60.0A
AC2 Low Volt	80V
AC2 High Volt	138V
AC2 Low Frequency	55Hz
AC2 High Frequency	65Hz

Advanced Settings: Grid Support

Grid Supoport Volts	52.0V
Sell	Disabled
Max Sell Amps	20A
Load Shave	Enabled
Load Shave Amps	0 A
Load Shave Start	12:00am
Load Shave Stop	12:00am
Sell Block Start	12:00am
Sell Block Stop	12:00am

Advanced Settings: Gen Support

(No generator.)

Advanced Settings: Aux Settings

Manual Aux	[ManualOff]
Active Level	[Active High]
Copy From	[None]

Advanced Settings: Multiunit Configuration

(No multiple units)

Restore Defualts
Advanced Features
Custom Battery Settings

Eqlz Support	Enabled
Eqlz Voltage	55.2V
Bulk Voltage	55.2V
Bulk Term Voltage	54.0V
Absorb Voltage	55.2V
Float Voltage	55.2V
Batt Temp Comp	[-108mV/C]

XW MPPT 80 600

Advanced Settings	
Meters	
Harvest Logs	
Force Chg	
Equalize	Disabled
Mode	Operating

Advanced Settings: Charging

Batt Type	Custom
Custom Settings	See Custom Batt Settings
Batt Capacity	160 Ah
Max Charge Rate	100%
Charge Cycle	3 Stage

Recharge Volts	52.0V
Absorb Time	180 min
Default Batt Temp	Warm
Batt Voltageg	48.0 V
Advanced Settings: Input	
MPPT AutoTrack	Enabled
MPPT Ref Volts	[this # is variable]
Advanced Settings: Aux	
Manual Aux	Manual Off
Copy From:	[None]
Custom Battery Settings	
Eqlz Support	Enabled
Eqlz Voltage	55.2V
Bulk Voltage	55.2V
Absorb Voltage	55.2V
Float Voltage	55.2V
Batt Temp Comp	[-108mV/C]

APPENDIX C: LOAD AND GRID POWER MEASUREMENTS EGAUGE VERSES MANUAL MEASUREMENTS

Resistive Load [W]	eGauge Grid [W]	Measured Grid Power [W]	eGauge Load [W]	Measured Load Power [W]
400	141	626.58	145	371.7
650	245	566.95	262	606.05
700	375	863.76	283	527.46
750	372	888.56	297	708.76
800	447	928.66	314	768.18
850	444	967.44	335	794.6
900	487	1007.72	352	409.46
1000	671	1157.9	329	901.16
1100	706	1288.76	362	1032.4
1200	788	1371.95	394	1123.55
1300	822	1397.8	434	1220.32
1400	932	1495.24	463	1305
1475	990	1621.68	493	1465.08
1500	1015	1536.21	542	1422.72
1700	1133	1747.58	610	1637.84
1750	1176	1780.62	625	1676.78
2000	1088	2013.445	744	1764.38
2175	1271	2057.18	803	1883.13
2275	1380	2137.2	846	2000.49
2400	1407	2224.4	885	2103.61
2475	1538	2289.17	913	2176.9
2500	1412	2394.47	896	2135.55
2600	1461	2465.88	924	2210.6
3000	1988	2789.55	1104	2711.6

Vita

Christopher Charles Lauer was born in Lebanon, PA, and spent much of his childhood in Williamsport, PA, before relocating to North Carolina where he would eventually graduate from Mooresville Senior High School in 2015. He enrolled in Appalachian State University in the Fall of 2015 and graduated with a B.S. in Sustainable Technology with a minor in physics in the Spring of 2019. During this time, he entered the accelerated admissions program and began to pursue a M.S. in Technology with a concentration in Renewable Energy Engineering. As an undergraduate at Appalachian State University, Chris spent several years in the Appalachian State University Sustainable Energy Society where he held the position of president for a year and a half. As a graduate student, Chris worked as the graduate research assistant at the state farm solar lab. Upon graduation, Chris plans to find a career in the solar industry.