CHARACTERISTICS OF ELECTRIC BATTERIES FOR RESIDENTIAL USE AND BETTER INTEGRATION WITH THE ELECTRIC DISTRIBUTION SYSTEM

By

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2018

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The purpose of this work is to study the characteristics of different battery technologies and the requirements of energy storage systems (ESS) for customer services in order to specify the parameters for an ESS which will operate in parallel with a grid. This work is addressed to end-use residential customers. To achieve this objective, a selection of the main battery technologies currently used were performed using the software ES-SELECT. The technologies evaluated in this work were: lead acid, and lithium ion. Using MATLAB/Simulink, two case studies with real data of temperature, irradiance and residential load behavior from Puerto Rico, were implemented in a scenario of a residential grid-tied PV system with batteries. First, we compared the performance of both battery technologies during a real blackout. Then, we analyzed the behavior of different battery banks when the system is grid-tied. We present a list of desired characteristics for a new battery technology combining the best attributes of each technology. Next, we compare the performance of the system using a single battery technology and using a hybrid battery bank that combines both Lead Acid and Lithium. Finally, we determined the associated monetary cost of the system using hybrid battery storage and compared it with the system using a single battery technology.

Resumen de tesis presentado a Escuela Graduada de la Universidad de Puerto Rico como requisito parcial de los requerimientos para el grado de Maestría en Ciencias

CARACTERÍSTICAS DE BATERIAS ELECTRICAS PARA USO RESIDENCIAL Y MEJOR INTEGRACIÓN CON EL SISTEMA DE DISTRIBUCIÓN ELÉCTRICA

Por

Karen Vanessa Montaño Martínez

2018

Consejero: Dr. Agustín Irizarry

Departamento: Ingeniería Eléctrica y Computadoras

El propósito de esta tesis es estudiar las características de diferentes tecnologías de baterías y los requerimientos de sistemas de almacenamiento de energía (ESS) para servicios de consumidores, con el fin de especificar los parámetros para un ESS que operará en paralelo con una red eléctrica. Este trabajo está dirigido para clientes residenciales. Para esto, se utilizó el software ES-SELECT para seleccionar las principales tecnologías de batería utilizadas actualmente. Las tecnologías evaluadas en este trabajo fueron: ácido de plomo e iones de litio. Se implementaron dos casos de estudios en MATLAB / Simulink con datos reales de temperatura, irradiación y comportamiento de carga residencial de Puerto Rico, en un escenario de un sistema fotovoltaico residencial con baterías conectado a la red. Primero, comparamos el rendimiento de ambas tecnologías de batería durante un apagón real. Luego, analizamos el comportamiento de diferentes bancos de baterías cuando el sistema está conectado a la red. Presentamos una lista de características deseadas para una nueva tecnología de batería que combina los mejores atributos de cada tecnología. A continuación, comparamos el rendimiento del sistema utilizando una tecnología de batería y un banco de baterías híbrido. Finalmente, determinamos el costo asociado del sistema utilizando el almacenamiento de batería híbrido y lo comparamos con el sistema utilizando una tecnología de batería.

To my beloved husband Sergio, my mother Olga, my father Victor, my siblings Brian and Jonathan and my niece Rocio Marina, who inspire me every day to be the best version of myself and without whom none of my success could be possible.

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Chapter 1

INTRODUCTION

Alongside with current technological advances, worldwide energy consumption continues to increase [1]. New ways to generate electric energy using alternative resources had been developed to meet this consumption. Besides, with the emerging requirements of environmental compliance and energy conservation, the power grid is evolving from the traditional centralized model to a smart decentralized network with renewable sources and Energy Storage Systems (ESS) [2][3]. This transition is marked by the intermittent behavior of several renewable sources, cost reduction of energy storage technologies and the necessity of communications infrastructure from the grid transmission level down to the distribution level [4][5][6].

Most renewable energy generation technologies will benefit from efficient and affordable energy storage. Renewable generation as solar and wind have been growing their capacity into the power system making energy storage an essential part of their functionality [7]. Energy storage, as batteries, provides the ability to balance power demand and generation, almost instantaneously, which makes the grid more resilient, efficient, and cleaner than without ESS [8].

ESS deployed at all levels of the grid can add value to the energy network system. However, customer-side deployments can provide the largest number of services to the electric grid [9]. According to [10], the U.S. energy storage market will grow 17^{th} times its current size by 2023 and behind-the-meter deployments will account for 47% of the annual market that year.

On the other hand, there are a large number of ESS technologies including Battery Energy Storage Systems (BESS). Today, the development of different battery chemistries allows BESS to play an important role on the grid [11]. Though, a large number of BESS projects use no more than one battery technology, missing the characteristics that different technologies could offer if they work together in the same system.

The motive of this work is to study the characteristics of different battery technologies, match these with the requirements of energy storage systems for residential customer services and specify the parameters for an ESS which will operate in parallel with a grid. The research questions are: Which characteristics should a battery have to best operate in parallel with the electrical system? How do we combine the characteristics of existing battery technologies to provide for the needs of end-user services?

The hypothesis is that a combination of desired characteristics from existing battery technologies shall improve desired attributes of the ESS (e.g. efficiency, resiliency, and reduce cost). We seek to determine the desired characteristics of a new type of battery that best fulfill the requirements for main customer services.

We have found no other published studies that combine different battery technologies in an ESS to be used in residential power systems. We expect that this work will increase interest and broaden studies in this area.

The rest of this document is organized as follows: Chapter 2 presents a literature review on the characteristics of the main battery technologies used in residential systems and the requirements to be met for customer services applications. Chapter 3 presents previous related studies and the review of the sources of information consulted. Chapter 4 shows the general and specific objectives defined for this work. Chapter 5 presents the methodology employed to obtain the battery technologies to combine in this work. Chapter 6 details the scenario and study cases performed including results of the simulations. In Chapter 7 we discuss the results of the simulations and present the list of desired characteristics for a new battery technology, the set of battery technologies that best fulfill the requirements for main customer services, the energy management system model and the cost calculations. The remaining chapters present the conclusions, contributions, and future work.

Chapter 2

OBJECTIVES

This section describes the objectives that have been formulated for the proposed work. First, the general objective is presented and then the specific objectives.

2.1 General Objective

To determine the parameters for an Energy Storage System (ESS) based on different battery technologies characteristics, which will operate in parallel with a grid.

2.2 Specific Objectives

1. To identify and categorize the characteristics of main battery technologies currently used in energy storage systems for customer services.
2. To identify and categorize the requirements of energy storage systems for proper functioning of its main applications for customer services.
3. To determine the combinations of battery technologies that best fulfills the requirements of customers of energy storage systems.
4. To state a list of desired characteristics for a new battery technology that best fulfill the requirements for main customer services.
5. To develop an Energy Management System (EMS) model for a strategy of charge, discharge and optimum State of Charge (SOC) for each combination of battery technologies.
6. To determine the associated monetary cost of the set of battery technologies that fulfils the requirements of customer services.

Chapter 3

LITERATURE REVIEW

In this chapter, we review Energy Storage Systems (ESS) and the main applications of Battery Storage Systems (BESS) for customer services. The characteristics of different battery technologies and the requirements to be met by the energy storage systems in customer services are explained and categorized.

3.1 Energy Storage Systems (ESS)

Energy storage systems play an important role between energy sources and loads. Decentralized energy production growth introduces greater network load stability problems, making energy storage a convenient solution [12]. Without storage, the generation of energy must equal the consumption [8]. New and evolving batteries chemistries are considered as potential solutions for some challenges that face the electric grid today [13]. Energy storage allows the use of energy at a later time that was generated [14]. Figure 1 shows a schematic representation of a complete ESS with a DC generic storage device is shown.

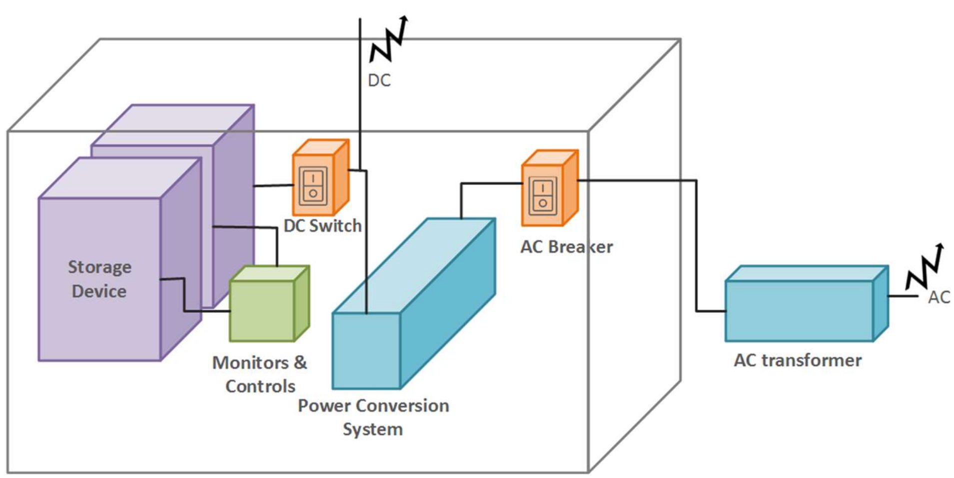

Figure 1. Battery energy storage system schematic, adapted from [14]

Nowadays, power grids face several challenges that could be mitigated by the installation of energy storage technologies [13]. There is a wide range of electricity storage technologies that provide different services to the electric-grid main stakeholders. In order to understand the diverse approaches of ESS deployed around the world, [8] divided the technologies into six main categories:

1) Solid State Batteries – storage solutions that consist in one or more electrochemical cells that convert the chemical energy into electric energy.
2) Flow Batteries – rechargeable batteries where the energy is stored directly in the electrolyte solution.
3) Flywheels – rotating mechanical devices used to store rotational energy that can be used instantly.
4) Compressed Air Energy Storage (CAES) – storage solution that compressed air to store energy that can be used in other time.
5) Thermal – technologies that allows to store energy in the form of heat or cold to use in demand.
6) Pumped Hydro-Power – hydroelectric dams that use water to create electricity to be used on the grid.

Similarly, energy storage technologies can be categorized into their power and energy relationship, that is a comparison between discharge time and power rating. In [14], the authors proposed a comparison for conceptual purposes (many of the technologies could have broader power ratings and longer discharge times than illustrated). It is shown in Figure 2. The significant overlap on the discharge time and power rating comparison for the different battery technologies shown in Figure 2 makes this relationship a trivial factor to select between one technology or another. Other considerations such as lifecycle, performance of the battery (depth of discharge, temperature, efficiency), location, space limitations, and economic costs, are important factors for the battery selection [15].

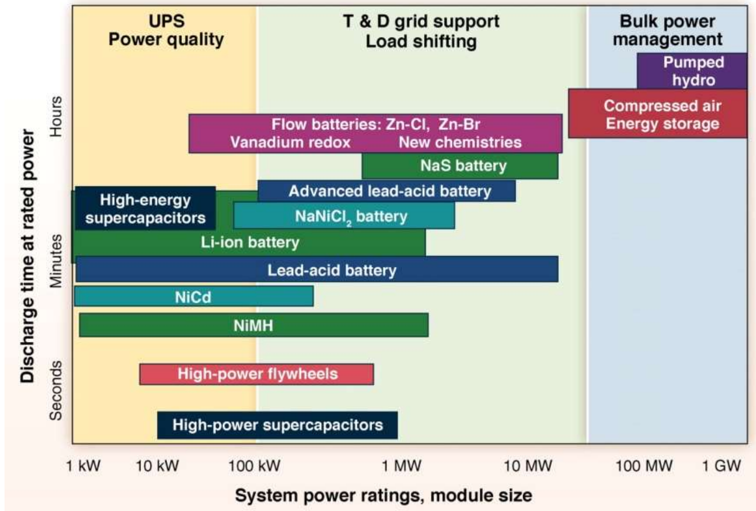

Figure 2. Positioning of Energy Storage Technologies, obtained from [14]

3.1.1 Battery technologies used on ESS: Overview

Energy storage technologies discussed in this work relate to end-user renewable energy integration, specifically PV installations for residential customers. Technologies as CAES and pumped hydro are not used in small-scale energy systems due to their high cost and large size. Therefore, these technologies are deployed mostly in utility scale [16]. On the other hand, due to the facility of use and low costs, the most used technologies today for customer deployments are Solid State Batteries (Lead-Acid and Lithium Ion) [13]. The main characteristics and operating principles of the technologies used in this work are explained in the following sections.

3.1.1.1 Lead-acid Battery

Lead-acid batteries are the first technology of rechargeable battery storage and is still widely used [17]. Since its beginning, several inventors have made chemicals and physical improvements to the design and composition of this battery technology [18]. These batteries are devices which store electrical energy in electrochemical form. The chemical principle of this technology is the same for all lead-acid designs [5]. It consists of two electrode plates, one positive and one negative, placed in an electrolyte material which allows the transference of ions between them. The positive electrode is composed of PbO_2 (lead dioxide), and the negative electrode is composed of Pb (metallic lead). The active material in both electrodes is highly porous to maximize surface area. The electrolyte is a sulfuric acid solution, usually around 37% sulfuric acid by weight when the battery has full charge [14][19]. The chemicals of the battery create pollutants during the production process [20]. However, around the 96% of lead-acid batteries are recycled (surpassing paper and aluminum) [7]. In Figure 3, the chemical principle of lead-acid battery technologies, during discharge operation, is illustrated.

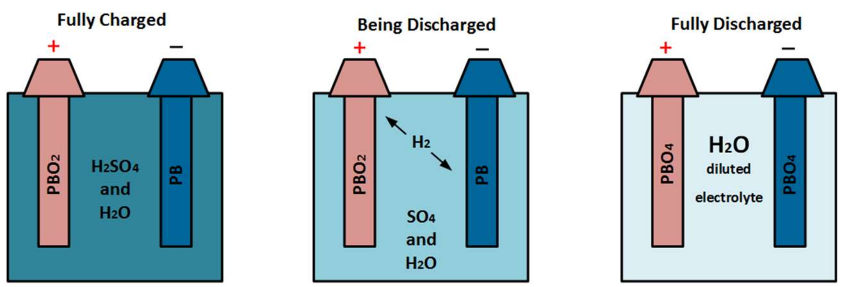

Figure 3. Lead-Acid Battery chemical principle, adapted from [21]

The power output of Lead-acid batteries is non-linear. Also, depending on its application its lifetime varies significantly: due to the discharge rate, and number of deep discharge cycles. Its main characteristics, in contrast with other battery technologies are: low investment costs, lowest self-discharge of rechargeable battery systems, and ease of maintenance. Therefore, it provides a cost-competitive solution to different customer services. Nevertheless, it technology has a limited cycle life, poor performance at extreme ambient temperatures, failure due to deep and continuous cycling, and a large eco-footprint due to its chemical composition [16][22].

Many commercial lead-acid batteries still used have low depth of discharge (<20%), low cycle numbers (<500) and a limited life time of 3-4 years. However, more recent versions can achieve higher cycles and a depth of discharge of 50% [5][15]. Deep discharge increases in lead-acid batteries the ageing mechanisms as corrosion, sulfation and loss of active mass [23]. Some lead-acid technologies have supercapacitor-like features that give them fast response, similar to Li-ion batteries [14].

3.1.1.2 Lithium Ion Battery (Li-ion)

Li-ion battery technology has grown and matured in the past two decades, both from a technical and cost perspective. Today, Li-ion is leading the market as the battery technology for energy-storage applications [14][11]. First li-ion batteries were used in consumer products, but now, due to the technology development, it is highly used in energy-storage systems, ranging from residential systems with PV deployments to different services for the grid [8].

Li-ion batteries store energy trough a chemical reaction. The battery cell contains two reactive materials which have the capacity of transfer electrons when contact electrically, also must have the capacity of exchange ions in order to maintain overall charge neutrality as electrons are transferred [24]. The battery cell is designed in order to keep the materials from a direct contact to each other, but with an external terminal isolated from the other material´s terminal, as shown in Figure 4. Into the cell, the materials are connected ionically to each other through an electrolyte material which conducts ions but no electrons. This is achieved because of a porous insulator membrane, called separator, which is filled with an ionically conductive salt solution, and is located between the reactive materials. When the external terminals are connected electrically trough a load, the electrons are transferred, and a current and voltage is applied to the load [14].

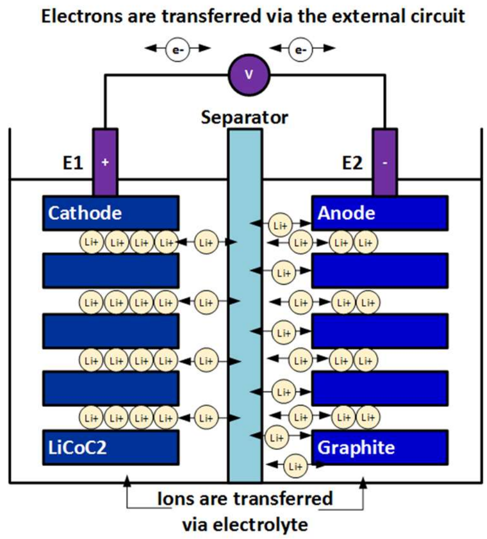

Figure 4. Li-ion chemical principle, adapted from [14]

Li-ion batteries have around 100% of efficiency and the highest energy density compared to Lead-acid. Some of the disadvantages about this battery technology include high investment costs and complicated charge management systems [16][25]. Li-ion batteries are lighter and more compact that lead acid batteries. Also, they have higher depth of discharge (DoD) and longer lifespan [26][27]. Moreover, Li-ion batteries had an almost constant ohmic resistance among all its states of charge [28].

3.1.2 Table of main battery technologies and its characteristics

We analyzed battery technologies reports, datasheets of batteries, and other literature in order to fill the information on Table 1. With this information, we can assess the technologies with real data, and use its features to match the requirements of the customer services stated in Table 2. According to [14], [16], [19], [22], [15], [29]:

Table 1. Technology data sheets

	Lead-acid Battery	**Lithium Ion Battery (Li-ion)**
Maximum Energy or Duration	4 hrs	5 hrs
Response Time	10 – 20 milliseconds	10 – 20 miliseconds

Operating Features:	-	-
Efficiency	0.90	0.92
Depth of Discharge (DoD)	50%	70%
Parasitic Loss	0.1%/day	0.01%/hr
Lifetime/Replacement	5 yrs	10 yrs
Size	residential	residential
Siting Issues:	-	-
Environmental	Lead disposal	Chemical disposal
Safety	Lead Disposal	Chemical

3.2 Main applications of ESS for customer services

Energy storage can be deployed at three different levels on a system: at transmission level, at distribution level, or behind the meter. However, customer-sited systems, deployed behind-the-meter, provide the largest number of services to the grid. There are three stakeholders which receive the benefits from an energy storage system: independent system operators (ISOs) and regional transmission organizations (RTOs), utilities, and customers [9]. The main services, according to different reports, that energy storage can provide to the electricity grid to each stakeholder are shown in Figure 5.

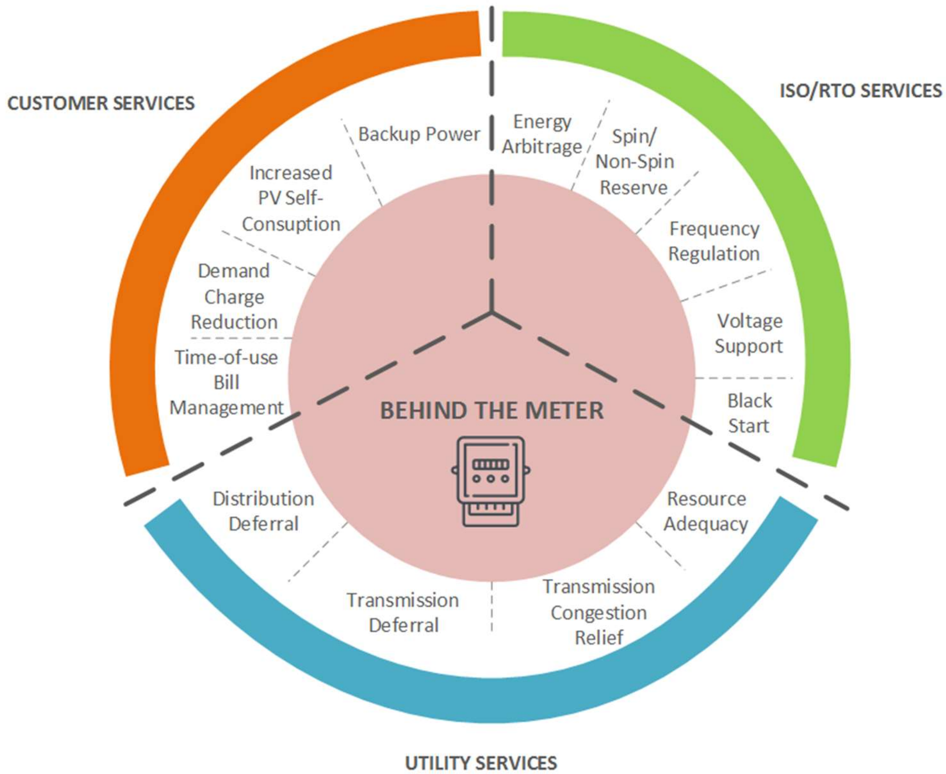

Figure 5. Services batteries can provide, adapted from [9]

In this work, we will study the services that energy storage systems provide to residential end-users, the customer services in Figure 6.

3.2.1 End-User Bill Management

Battery energy storage systems can reduce the cost for the electric service. This reduction can be significant. There are two variants in end-user bill management: time-of-use (TOU) and for commercial and industrial end-users that use a significant amount of electricity, demand charges. Since the focus of our project is residential customers, the benefit involves electricity residential end-users that pay TOU electric energy prices [8].

End-users who are subject of TOU electric pricing can use energy storage to reduce their bill's cost by retail energy time-shift. The energy time-shift involves the storage of energy when demand of energy and price are low. Then, that energy is used when demand and price are high, instead of purchasing high priced energy [9]. The maximum discharge duration for this application is determined based on the relevant tariff. That is, tariff during on-peak [30].

The benefit is the difference between on-peak (times when the demand of energy is higher) and off-peak (periods of lower demand) less the cost for energy losses during the storage charge-discharge cycle [8]. The benefit is internalized as profit [31].

An example of a hypothetical TOU tariff, adapted from [14] is shown in Figure 6. Summer on-peak (12:00 pm to 6:00 pm) the energy prices are $32\ ¢/_{kWh}$. During partial-peak (8:30 a.m. to 12:00 p.m. and 6:00 p.m. to 9:30 p.m.) the prices are $15\ ¢/_{kWh}$, and during off-peak (9:30 p.m. to 8:30 a.m.) prices are $10\ ¢/_{kWh}$.

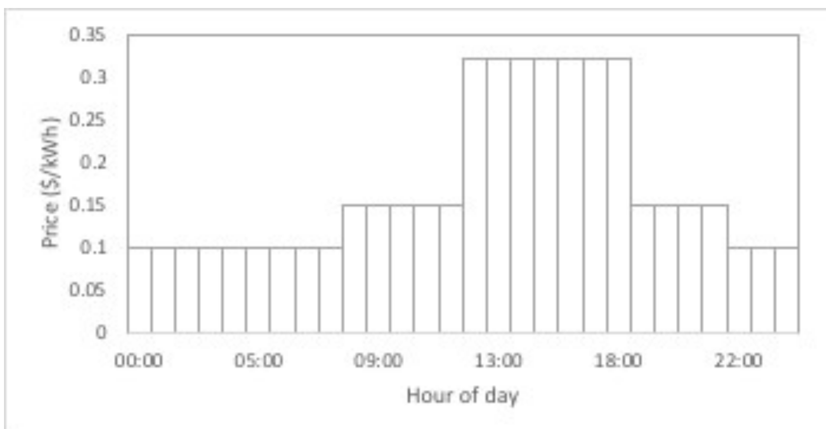

Figure 6. TOU energy prices example, adapted from [14]

To estimate the benefits of energy storage systems for TOU, consider a residence of 1 kW for 30 days on summer and a storage with 6-hours of discharge duration to avoid annual on-peak energy charges (180 kWh),

$$0.32\ \$/_{kWh} \times 180\ kWh = \$57.6$$

Now, consider an energy storage system with an efficiency of 90% and a depth of discharge of 50%. To discharge for 180 hours (180 kWh), the storage system has to be charged with,

$$180\ hours\ \times \frac{1\ kW}{0.9} = 200\ kWh$$

It is, in order to use 6-hours per day during on-peak periods, we have to charge the battery system almost 7 hours per day (6 hours/0.9) during off-peak periods.

The charging energy cost using off-peak price at $10\ {}^{¢}/_{kWh}$ is,

$$ {}^{\$0.10}/_{kWh} \times 200\ kWh = \$20 $$

Then, the cost reduction realized for 30 days in summer with this tariff structure is,

$$ \$57.6 \quad - \quad \$20 \quad = \quad \$37.6 $$

Now, if the battery system is used just for this service (TOU in summer), the maximum price we should pay for it, in order to have a return on the investment in 3 years is,

$$ {}^{\$37.6}/_{3\ years} = \$12.53 $$

Or,

$$ {}^{\$37.6}/_{200\ kWh} = {}^{\$0.19}/_{kWh} $$

3.2.2 Distributed Grid-Connected PV Integration

Distributed grid-connected PV integration is currently increasing as an electric supply resource into the electrical grid [32]. However, PV deployments present challenges such as: rapid output variations (ramping), daily variability of the output, effects on power quality, voltage and current harmonics, current “backflow” and differences between generation output and demand [8][11]. ESS provides a solution to manage those challenges used as renewables firming and peak shaving [33][34].

Due to PV intermittence, energy storage can be used to match the generation output with the load during the demand cycles when they do not coincide [19]. For this service, the batteries are charged when the load demand is less than the generation input and is used when the generation drop due to it intermittence nature [30]. One of the main reasons of the intermittence is due to the clouds passing overhead, an example of its nature is shown in Figure 7.

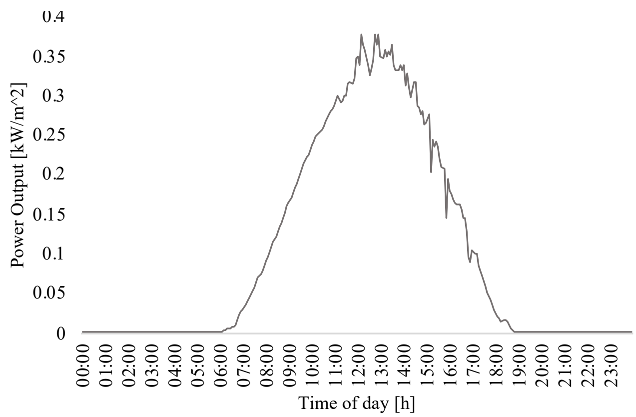

Figure 7. PV intermittence [1]

3.2.3 Demand Charge Management

ESS could be used by customers in order to obtain a reduction in their overall costs for electric service by reducing their demand during peak periods specified by the utility. Customers must avoid using power during peak demand periods, when demand charges apply, to avoid demand charges, which is associated with a given kW of peak load. To avoid the demand charge, the load must be reduced during all peak hours, usually a specified period of time and on specified days. In many cases, the demand charge is assessed if load is presented during just a 15 minute period [14][30].

To reduce load during peak periods, batteries are charged when there are no or low demand charges. Then, the stored energy is discharged during periods when demand charges apply. Typically, energy storage may discharge during five to six hours, depending on the tariff structure [31].

An example of an hypothetical load adapted from [31] is shown Figure 8. During mornings and evenings, the customer's net-demand is 1 p.u. At nights, when the energy price is low, the customer's net-demand doubles because it is stored at a rate of 1 p.u. while the normal load requires another p.u. of power. During peak demand periods (12:00

[1] Data obtained from University of Puerto Rico - 18.21 degrees N, 67.14 degrees O

p.m. to 5:00 p.m.), storage discharge (at a rate of 1 p.u.) to serve the user`s load of 1 p.u., avoiding demand charges.

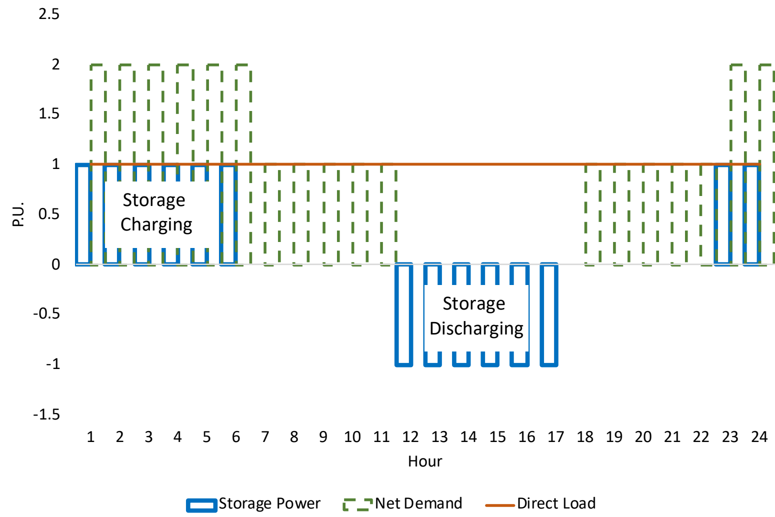

Figure 8. On-peak demand reduction using energy storage, adapted from [31]

Another example of a hypothetical applicable tariff, adapted from [14] is shown at Figure 9. This example shows a week of power demand for a customer, where the peak loads exceed the threshold set by the first peak of the month on Monday afternoon. This event set the level of power for the remaining month. The customer's loads must remain below that threshold to avoid demand charge penalties.

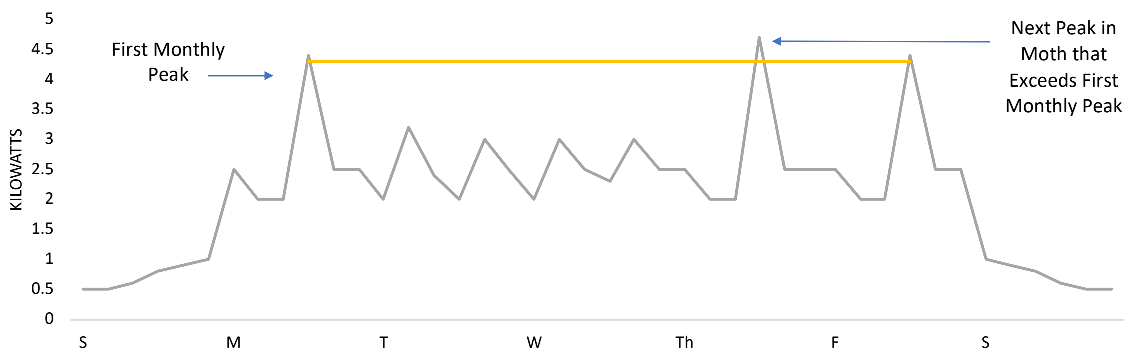

Figure 9. Storage for customer-side demand management, adapted from [14]

3.2.4 Uninterruptible Power System (UPS)

ESS can provide backup power to customers in the case of grid failure [9]. During blackouts, the energy from the batteries is used to maintain power according to the end-user's load. UPSs can also offset power quality anomalies [8]. This service requires the ESS and customer loads to island during the outage and resynchronizes with the utility when power is restored. The capacity of the storage system depends on the time duration that the storage must serve the load that is protecting [14].

The discharge duration required depends on the situation-specific criteria. It depends on the objective of the power backup: ride through outages of extended duration (several hours), or to complete an orderly shutdown of processes (> 1 hour), or transfer to on-site generation resources (few minutes) [30].

3.2.5 Table of main applications of energy storage systems for customer services and its requirements

We use reports and other literature about applications' characteristics of battery technologies for customer services to fill the information of Table 2. According to [14], [19], [22], [30]:

Table 2. Energy storage application for customer services and their characteristics

Application	Duration	Power	Storage Time	Energy [kWh]	Minimum cycles/year	Response Time
End-User Bill Management	Short duration	< 5kW	1 – 6 hrs	5	50 - 250	< 1 min
Distributed Grid-Connected PV Integration	Short duration, continued	< 5 kW	6 hrs <	< 5 k	3000 <	< 1 cycle
Reduction of Peak AC Demand	Short duration	50 kW <	1 – 4 hrs	5	50 - 500	< 1 min

Uninterruptible Power System	Short duration, continued	2 – 5 kW	< 1 hr	1 - 4	150 - 400	secs

Chapter 4

PREVIOUS RELATED STUDIES

In this section we describe briefly the sources of information consulted. Also, we further discuss previous work done by others which are particularly related to our inquiry. Finally, we contrast the investigations addressed with our work.

4.1 Background

There are some reports and articles that study the performance characteristics of different energy storage technologies, their classification and main applications into the power grids. In [19], a report made in 2001 by Schoenung at Sandia National Laboratories, the author characterized stationary applications and technologies of short and long-term storage. The technologies evaluated include: batteries (lead-acid and advanced), flywheels (low and high speed), supercapacitors, superconducting magnetic energy storage, compressed air energy storage, pumped hydro, and hydrogen. In the report the author matches application's storage times with storage technologies' characteristics by examining both performance characteristics and cost. In contrast we aim to study specifically the applications for end-users and the characteristics of two battery technologies. Furthermore, the author specifies the technologies for each application, but we propose to find a combination of battery technologies which will increase the efficiency of the system and reduce the cost associated.

In [14], a report made in 2013 by Abbas et. al. at Sandia National Laboratories, the authors write a handbook to guide utility and rural cooperative engineers, planners, and decision makers to plan and implement energy storage projects. The handbook provides the latest developments in technologies and tools, and a database of the cost of current storage systems in a wide variety of electric utility and customer services. The report is similar to our work due to their interest in the requirements of the services that energy storage systems could offer to the grid, and also the study of the technologies characteristics. The handbook is a tool that allows the correct development of energy storage projects because it addresses the requirements to be met by the ESS for each application. Also, they perform a cost analysis. We aim to take a step further and use this information in order to design a solution which increase efficiency, cost and reliability for customer services by combining different battery technologies.

In [16], an article published in 2010 in ”Energy and Buildings”, Nirmal-Kumar et. al. made an assessment for small-scale renewable energy integration using battery energy storage systems. They outline the benefits of the use of energy storage in the renewable energy integration, provide an overview of the battery technologies characteristics used in small-scale renewable systems and use software as Simulink and National Renewable Energy Laboratory’s HOMER to assess technical and economic feasibility of the battery technologies selected respectively. It is related to our work due to how they assess the different battery technologies. Similar to them, we aim to assess our battery solutions technically and economically using simulations with real data. However, it differs from our work since we propose to study first the requirements of the services, and then match the right combination of technologies that works better at each case and finally, assess the result.

In addition to the performance analysis featured in the previous inquiries, there are some reports that develop a cost analysis similar to our work. In [35], the authors consider PV-systems with storage deployments behind-the-meter and analyzed the cost of customer-installed systems in California and Tennessee. They consider dispatch strategies such as manual scheduling and peak-shaving to increase the system value and reduce demand charges. They use the software SAM to this study. This model is similar to our work due to the cost analysis combining different combinations of factors into the system. However, it differs to our work since we study a grid-tied PV system with different battery bank technologies but with the same sizes and control strategies. Also, we perform the calculations based in real data processed into a MATLAB/Simulink simulation.

Reports as [36] develop a cost benchmark and study deployment barriers for residential solar photovoltaics with energy storage. They analyze three cases: PV only, PV with small battery bank and PV with large battery bank. Also, they analyze AC coupling vs DC coupling of PV plus storage system for residential use. They compare different cost reports as [35] and [37]. We aim to use this information in order perform a cost analysis of a PV-system with different battery technologies bank.

4.2 Previous Work

There are some previous works which combine different technologies of storage systems to improve a specific performance feature. In [38], the authors presents a simulation tool for optimizing an off-grid hybrid PV-wind-diesel system with the combination of three battery technologies: lead-acid, lithium-ion, and vanadium redox-flow to supply the electricity to a telecommunication base station. The management strategy operates each battery under consideration of the respective aging characteristics in order to increase the overall economics of the system. Their EMS affects the choice of the suitable combination of battery technologies made by the optimization algorithm (Genetic Algorithm) to find the best solution with the minimal costs. They found that the use of VRB technology without any other battery technology is the optimal solution. Similarly, we aim to find the optimal combination of different battery technologies, yet we address different customer services for a distribution system.

In the preliminary work [39], the authors expose that there is no single type of energy storage system that can achieve high energy, high power, and high life cycle all at the same time. They propose to combine different types of energy storage systems into a hybrid energy storage system (HESS) for electrified vehicles, in order to use the inherent strengths of each individual system to optimize efficiency, life cycle, and simplicity. They combine batteries, ultracapacitors (UC), fuel cells, and internal combustion engine-generator set, by arranging them into series, parallel, and series-parallel configurations to satisfy the load requirements. Their focus is to combine a lithium battery and UC with a third ESS of choice. The authors propose to perform a detailed analysis, case studies, experimental design, setup, and verifications to be presented in the future. This proposal is similar with our work because we aim to combine different technologies of batteries in order to combine their characteristics in one system and obtain a better performance. However, we are focused in distribution systems and they are focused in electrified vehicles.

The authors in [40] presented a case study of standalone photovoltaic-based micro-grid with HESS to demonstrate the effectiveness of EMS in mitigating battery stress. They review and discuss the technological advancements and developments of battery-supercapacitor based HESS in standalone micro-grid system. They also review the characteristics, strengths, weakness and applications of passive HESS, semi-active HESS, and full-active HESS. They found that battery stress can be reduced with some HESS topologies while maintaining high level of power quality and reliability. Similarly, we aim to describe an EMS model which stablish the work principle of the different types of battery technologies obtained. However, our research not include the study of supercapacitors.

Chapter 5

BATTERY ASSESSMENT: ES-SELECT

This chapter presents the method employed to obtain the battery technologies to combine in this thesis. To achieve this, we used the software ES-Select. In the first part of this chapter we make a brief software description. Then, in the second part, we explain the process followed to obtain the battery technologies that best fulfill the customer-services requirements.

5.1 Software Description

ES-Select is a decision-support tool developed by Sandia National Laboratories in collaboration with DNV KEMA and the U.S. Department of Energy. Its main purpose is to find feasible storage options for grid-connected systems according to a specific location and a group of applications to be met. The software has three main components: data bases (storage applications and storage technologies), comparative analysis (storage options and cost and benefits) and special features (bundle multiple applications and feasibility scores). Figure 10 shows ES-Select design and functionalities.

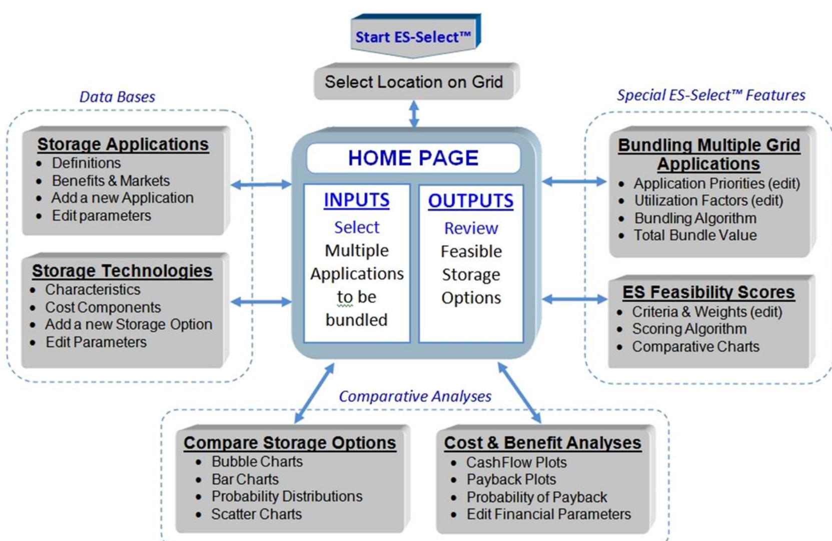

Figure 10. ES-Select Design and Functionalities, obtained from [41]

5.2 Selection of Battery Technologies

As a first step to the selection of the battery technologies that best fulfill the customer-services requirements using ES-Select, we have to specify the location where we will deploy the ESS. The possible locations that ES-Select allows are shown in Figure 11. Each location imposes restrictions on both the number of applications for that location as well as the ES technologies appropriate for the site. As we are developing an inquiry about residential customers, we selected the residential/small commercial location which allows systems up to 100kW.

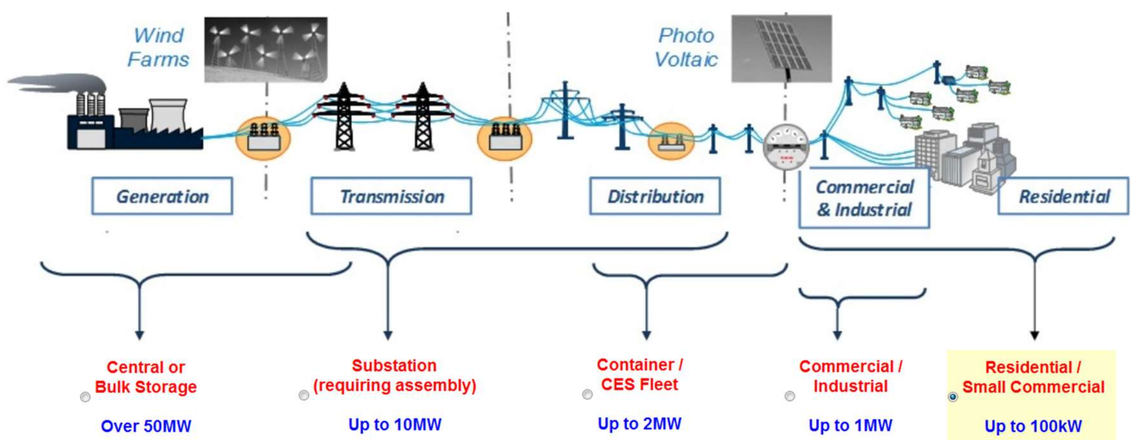

Figure 11. Possible Locations for Grid-Connected Energy Storage, obtained from [41]

Into the database of storage applications available in ES-Select for residential locations, we review the definitions of the applications to match with the ones we are studying in this work. The applications to use for ES-Select input are in Table 3.

Table 3. ES-Select Customer Applications, obtained from [41]

Application	ES-Select Tittle	ES-Select Definition
End-User Bill Management	Application 12 – Retail TOU Energy Charges	Energy storage could be used by end users (utility customers) to shift or reduce energy consumption at peak hours to reduce their overall cost for electricity. Energy is purchased at off-peak hours when electricity

		price is low, and then released at the on-peak hours when electricity price is high.
Distributed Grid-Connected PV Integration	Application 20 – Renewables Capacity Firming	The objective of renewable capacity firming is to make the generation output somewhat constant. Storage could be used to store wind and solar power during hours of peak production regardless of demand, and discharge to supplement traditional generation when renewable output reduces during expected generation time.
Reduction of Peak AC Demand	Application 13 – Retail Demand Charges	Energy storage could be used by end users (utility customers) to reduce power consumption when demand charge is high to reduce their overall cost for electricity. Energy is purchased when demand charge do not apply or low, and then discharged when the demand charge do apply or high.
Uninterruptible Power System	Application 15 – Service Reliability (Consumer Backup)	This electric service reliability application focuses on the need for back-up power systems at Commercial and Industrial facilities. Usually, the facilities use a combination of batteries for ride-though of momentary outages and then have a diesel generator for longer duration outages.

The application’s characteristics in the database are customizable, however, we use the default values since the applications characteristics match with the values presented in the reports and articles shown in Table 2 (See *Appendix A.1*). Also, ES-Select divided the grid applications into four groups based on its requirements such as discharge duration, depth of discharge, frequency of use and compatibility with other applications. The four groups arranged as four quadrants with the discharge duration and frequency of use as axes are shown in Figure 12.

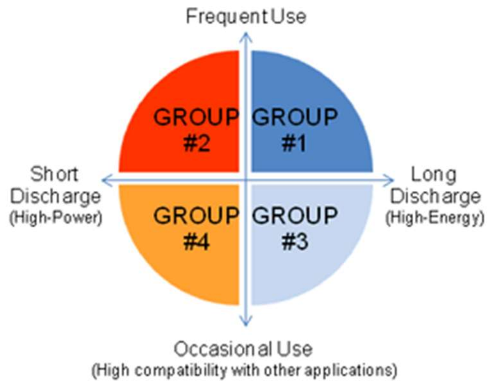

Figure 12. ES-Select Groups for Grid Applications, obtained from [41]

Table 4 shows the groups and characteristics of the applications used in this work according with ES-Select.

Table 4. ES-Select Groups and Characteristics, obtained from [41]

Application	ES-Select Tittle	Group and Characteristics
End-User Bill Management	Application 12 – Retail TOU Energy Charges	Group 1: Discharge of duration (hours), Frequency of usage (frequent), Typical discharge depth (deep)
Distributed Grid-Connected PV Integration	Application 20 – Renewables Capacity Firming	Group 1: Discharge of duration (hours), Frequency of usage (frequent), Typical discharge depth (deep)
Reduction of Peak AC Demand	Application 13 – Retail Demand Charges	Group 1: Discharge of duration (hours), Frequency of usage (frequent), Typical discharge depth (deep)
Uninterruptible Power System	Application 15 – Service Reliability (Consumer Backup)	Group 3: Discharge of duration (hours), Frequency of usage (occasional), Typical discharge depth (deep)

In order to quantify the application value or present worth of each application, that is the value on a given date of a future payment or series of future payments, discounted to reflect the time value of money [42], the software uses the following economic assumptions:

- Escalation of benefits (%) is the percentage at which an annual change in the value of benefits is expected to occur: 2.5.

- Discount rate (%) is the rate as a percentage used to calculate the multiplier that converts the anticipated future value (return) to the present value: 10.
- Electricity price escalation (%/yr) is the rate of increase of the electricity cost used for calculating the cost of operational losses through the life of a project: 2.5.
- Cost of Energy for charge ($/MWh) is what needs to be paid at off-peak time to charge an energy storage device. This is used to calculate the annual cost of operational losses: low (30), high (50).
- Project life defines the length of the period for which the cash flow and payback values are calculated: 15 years.

The applications discharge duration plotted with the application values after 10 years are shown in Figure 13. This graph provides information to determine whether energy storage is a feasible option for specific requirement, and an estimation of the expected economic cost of the system with 10 years of usage, according to the discharge duration (energy stored).

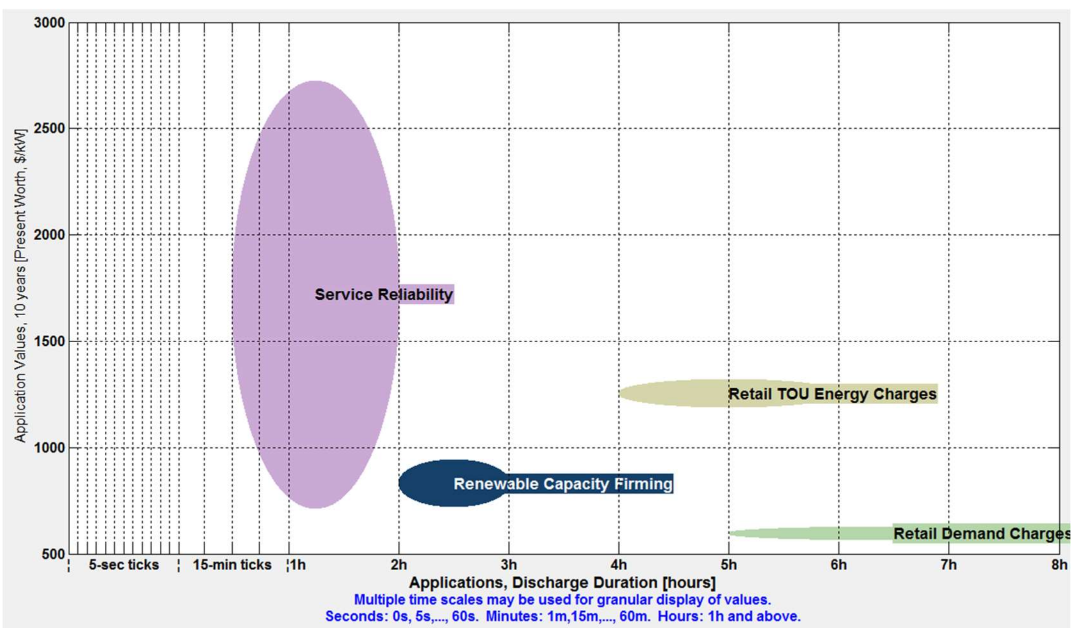

Figure 13. Application Values ($/kW) vs. Required Discharge Durations (hr)

Similar to the application's characteristics database, the characteristics of the storage technologies are customizable, however, we use the default values since the characteristics match with the values presented in the reports and articles shown in Table 1 (See *Appendix A.2*).

ES-Select identifies and compares the storage technologies using feasibility scores of storage options for grid applications into one feasibility equation, according to the following criteria:

- Maturity or readiness for commercial deployment.
- Appropriateness for the selected grid location (availability, mobility, size, weight, scalability, etc.)
- Meeting application requirements (discharge duration, cycle life, efficiency, etc.)
- Installed cost in either $/kW or $/kWh basis (user's choice)

However, the installed cost will be calculated afterwards based on the combined battery sets, we use all the criteria listed above in order to obtain an accurate feasibility score for each application. Then, each criterion has a weight of one in the feasibility equation.

ES-Select calculates a feasibility percent for each technology that fit the application selected based on the criteria explained above. Since we are studying a residential system with a PV system and connected to the grid, we combine the application of distributed grid-connected PV integration with the other applications. Figure 14 shows the ES-Select output for end-user bill management, demand charge management and uninterruptible power supply combined with distributed grid connected PV integration. We only show battery technologies with high feasibility percent.

1	**Valve Regulated Lead Acid**	**VRLA**	61%
2	**Lithium Ion - High Energy**	**LIB-e**	60%
3	Advanced Lead Acid	LA-adv	58%

A. Feasibility percentage for end-user bill management and distributed grid connected PV integration

1	**Valve Regulated Lead Acid**	**VRLA**	61%
2	**Lithium Ion - High Energy**	**LIB-e**	60%
3	Advanced Lead Acid	LA-adv	58%

B. Feasibility percentage for demand charge management and distributed grid connected PV integration

1	**Valve Regulated Lead Acid**	**VRLA**	62%
2	**Lithium Ion - High Energy**	**LIB-e**	59%
3	Advanced Lead Acid	LA-adv	59%

C. Feasibility percentage for uninterruptible power supply and distributed grid connected PV integration

Figure 14. Feasibility percentage per application

Therefore, the technologies to combine in the system are Lithium Ion and Lead Acid. Figure 15 shows the energy efficiency and the discharge duration of the feasible technologies for the applications.

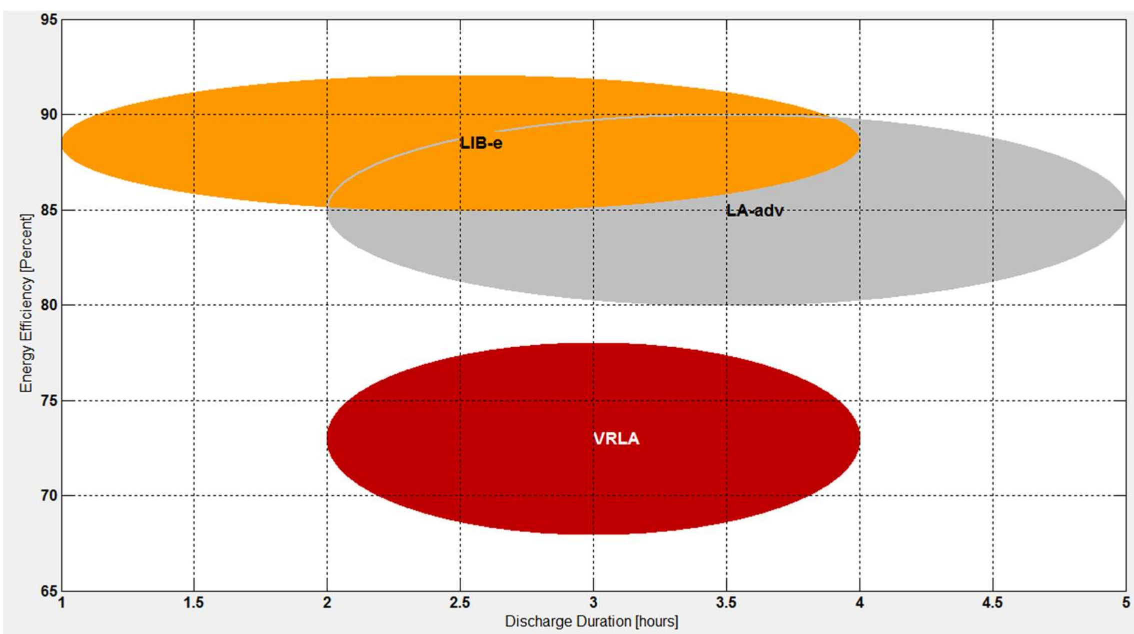

Figure 15. Technologies Discharge Duration and Energy Efficiency

Chapter 6

CASE STUDIES

This chapter presents the case studies used in this thesis. The first part of this chapter consists on a scenario overview, where we explain the model and data used. A description of the case studies follows. Finally, we show the results of the case studies simulations carried out in MATLAB/Simulink.

6.1 PV Grid-Connected Microgrid

Our study scenario is a grid-connected microgrid composed by a photovoltaic (PV) generator, a battery energy storage system (BESS), and one residential house. Figure 16 shows the functional diagram of the components in the scenario described. The microgrid on the scenario is located in Puerto Rico (PR).

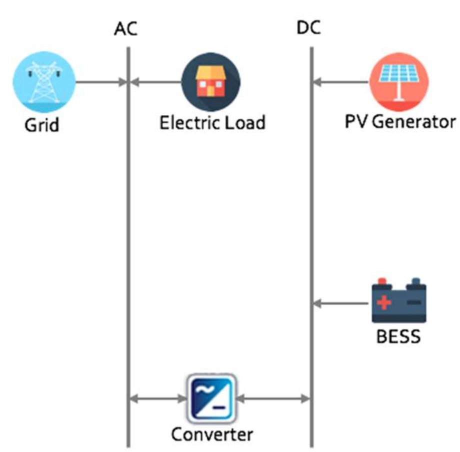

Figure 16. Functional Diagram of the Scenario

6.1.1 PV Array Model

In our simulations we use the photovoltaic (PV) block of Simulink [43]. The PV array block implements an array of PV modules. The array consists on strings of modules connected in series and then those strings are connected in parallel. The block includes a database of preset PV modules from the National Renewable Energy Laboratory (NREL)

System Advisor Model (January 2014) and also allows the user to customize a PV module. The NREL database includes manufacturer datasheets measured under standard test conditions (STC)

$(Irradiance = 1000\, {}^{W}/_{m^2}, temperature = 25\ degrees\ C)$.

The PV Array block uses a five-parameter model: current source (I_L), diode (I_d and $_nI$), series resistance (R_s) and shunt resistance (R_{sh}) to represent the irradiance and temperature dependent I-V characteristics of the module. The model is shown in Figure 17.

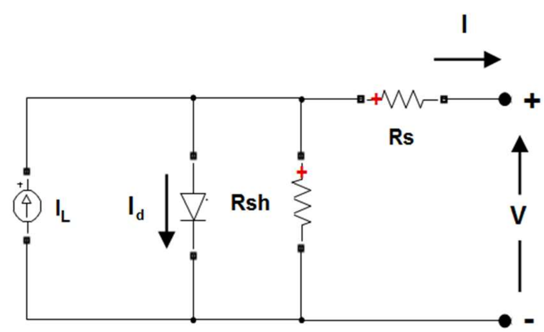

Figure 17. PV five-parameter model

The diode I-V characteristics for a single module are defined by the equations

$$I_d = I_0 \left[e^{\left(\frac{V_d}{V_T}\right)} - 1 \right] \quad (1)$$

$$V_T = \frac{kT}{q} \times nI \times N_{cell} \quad (2)$$

Where:

- I_d is the diode current (A)
- V_d is the diode voltage (V)
- I_0 is the diode saturation current (A)
- nI is the diode ideality factor, number close to 1.0
- k is the Boltzmann constant $= 1.3806e^{-23}J.K - 1$
- q is the electron charge $= 1.6022e^{-19}C$

- T is the cell temperature (K)
- N_{cell} is the number of cells connected in series in a module

The PV Array block has three ports: two inputs and one output:

- I_r: Input signal representing varying sun irradiance in $\frac{W}{m^2}$
- T: Input signal representing varying cell temperature in degrees C.
- m: Output vector containing five signals:
  - V_PV: PV array voltage (V)
  - I_PV: PV array current (A)
  - I_diode: diode current (A)
  - Irradiance ($\frac{W}{m^2}$)
  - Temperature (deg C)

6.1.2 Load Data

We use real data collected from different customer residences in Puerto Rico. The data was collected using an energy meter, WattNode Pulse WNB-3Y-480-P, to record power (W) consumption and energy consumed (Wh) in a specific period of time. Data was measured continuously and recorded every minute. The data is recorded in a HOBO State Data Logger UX90-001. The energy meter is connected in a Single-Phase Three-Wire topology.

6.1.3 Battery Simulations

The scenario uses the generic battery model block of Simulink [44]. The battery block implements a generic dynamic model parameterized to represent most popular types of rechargeable batteries. The battery equivalent circuit model is shown in *Appendix B*.

The battery block of Simulink uses a discharge curve that consists of three sections as shown in Figure 18. The first section represents the exponential voltage drop when the battery is charged (efficiency). The width of the drop depends on the battery type. The second section represents the charge that can be extracted from the battery until the voltage drops below the battery nominal voltage. Finally, the third section represents the total discharge of the battery, when the voltage drops rapidly [44].

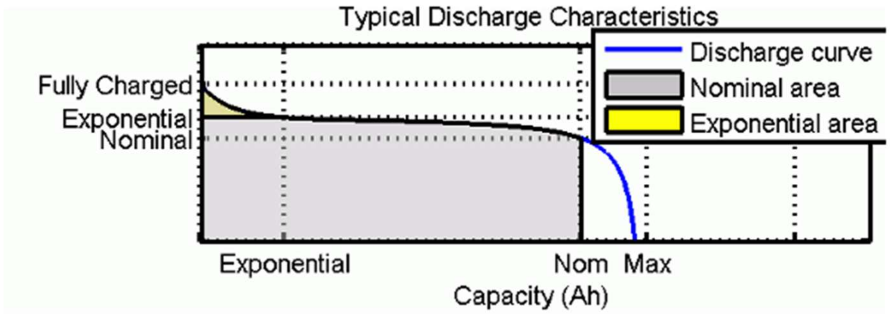

Figure 18. Battery Discharge Curve, obtained from [44]

Figure 19 shows the typical charge characteristics for Lead-Acid and Li-Ion battery types.

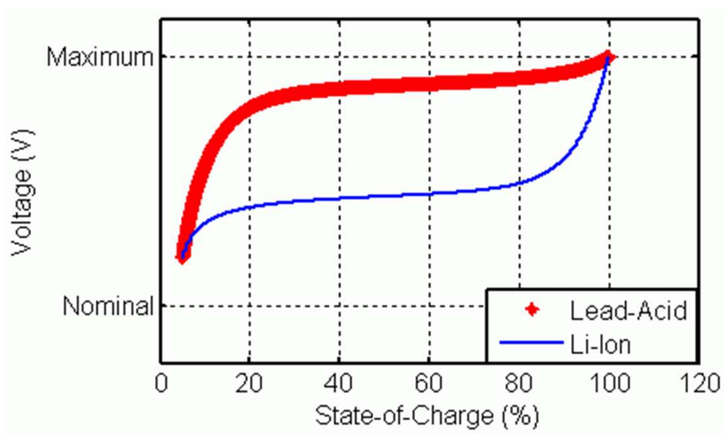

Figure 19. Typical Charge Characteristics, obtained from [44]

The output of the battery block is a vector named (m) containing seven signals:

- Ambient Temperature (C): when enabled (only available for lithium-ion batteries).
- Cell Temperature (C): when enabled (only available for lithium-ion Batteries).

- SOC (%): the battery state-of-charge. For a fully charged battery the SOC is 100% and for an empty battery is 0%. The SOC is calculated as:

$$SOC = 100\left(1 - \frac{1}{Q}\int_0^t i(t)dt\right) \quad (3)$$

- Current (A): the battery current.
- Voltage (V): the battery voltage.
- Age (equivalent full cycles): when enabled (only available for lithium-ion batteries).
- Maximum Capacity (Ah): when enabled (only available for lithium-ion batteries).

The battery function block in this model is considered to operate under ideal conditions and hence losses relating to ambient temperature are assumed to be minimal [16]. However, we add a large resistance in parallel with the battery terminals to represent the self-discharge of the battery, as indicated in the model assumptions in [44].

6.1.4 Scenario MATLAB/Simulink

The system components are arranged as shown in Figure 20. The PV block receives real, unprocessed, data of temperature and irradiance collected on a minute-by-minute basis at the University of Puerto Rico Mayagüez- 18.21 degrees N, 67.14 degrees W.

The load behavior comes from a vector of real demand data as discussed before. It is expressed as power (kW); thus, we calculate the current demanded from the load.

The battery block has two controlled current sources connected in parallel. One receives the current from the PV block. The other one represents the load. The battery has a charge controller that disconnects the PV module when the battery SOC reaches 100% to avoid over-charging. Also, it disconnects the load when the battery SOC drops to 20% to avoid deep-discharge.

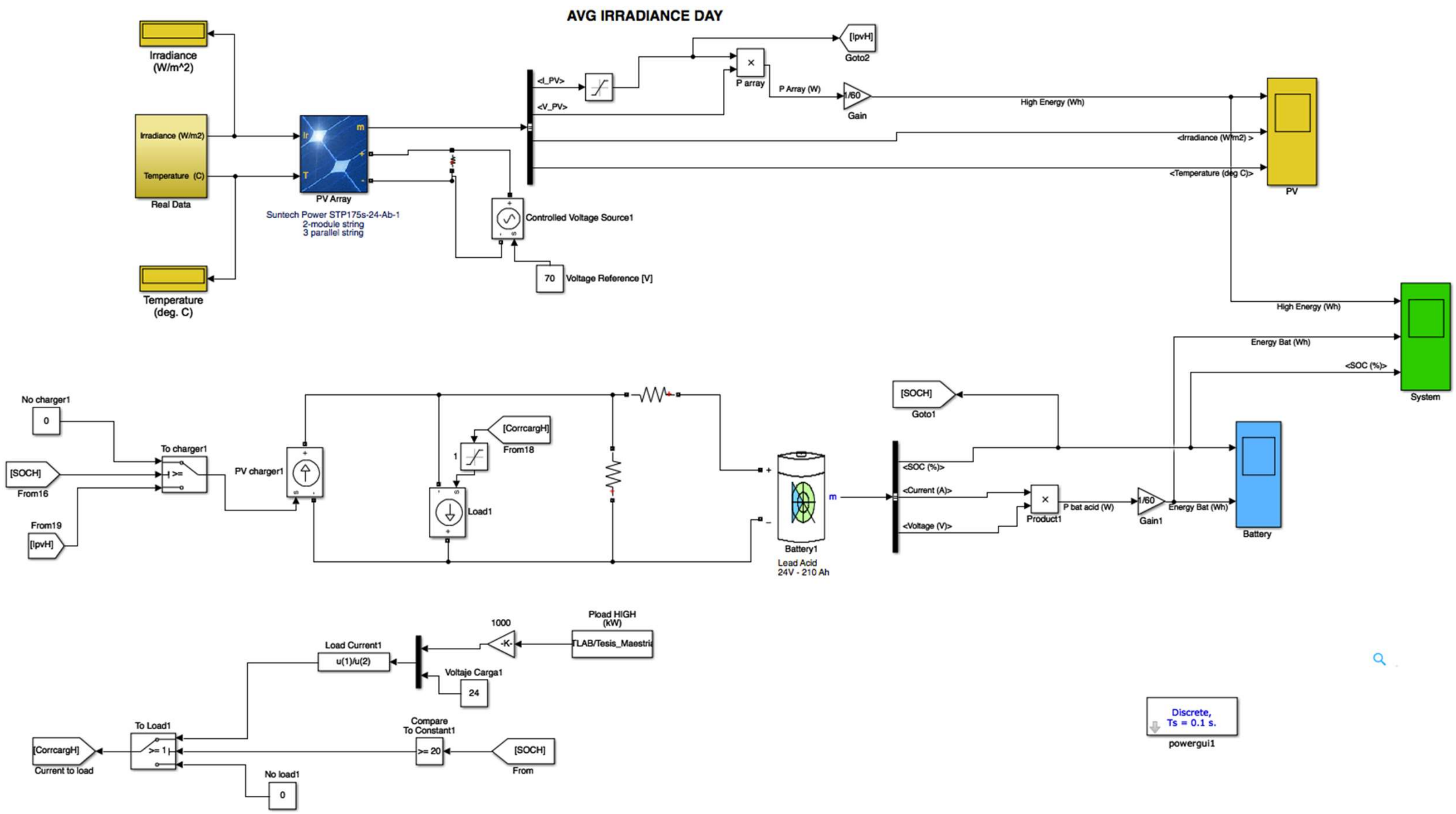

Figure 20. MATLAB/Simulink Scenario

A controlled voltage source with a fix voltage value is connected in parallel with the PV block in order to simulate a MPPT controller. We use this method instead of a precise model for the MPPT controller to diminish the computational requirements of the simulation. As shown in Figure 21, the MPPT power has a small change in the points around the optimal voltage value. In this case, the curve above with an irradiance of $1\ kW/m^2$, the MPPT voltage point is 70.4 V and the power output is 1045 W. The middle curve with an irradiance of $0.5\ kW/m^2$, the MPPT voltage point is 71.14 V with a power output of 528.6 W, however, the controlled voltage source has a fix value of 70 V that produces a power output of 527.3 W, a difference of 1.3 W compared with the MPPT power value. Finally, the curve below with an irradiance of $0.1\ kW/m^2$, the power output difference between the MPPT value and the fixed value is 0.9 W.

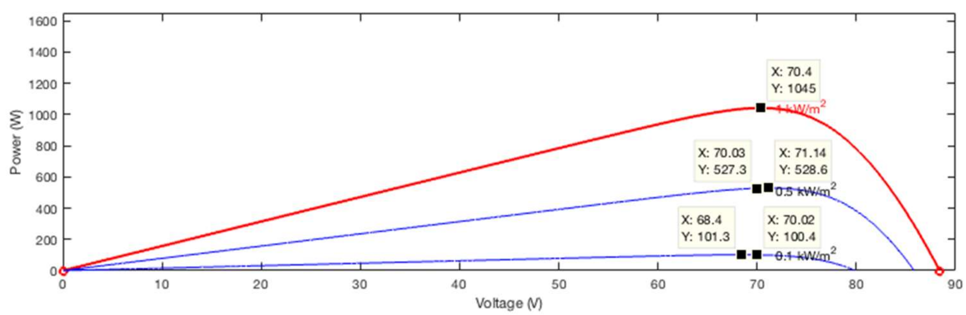

Figure 21. V-P curve for a PV system

6.2 Case Study 1: Customer Back-Up [45], [46]

The dwelling under study is at 18.16° N, 67.08° W, has 202 square meters of livable space and it is inhabited by a family of 5: two female ages 47 and 20 and three male ages 52, 18 and 12 (ages at 20 September 2017). It is a two stories house made of concrete.

In 2009 a grid tied rooftop photovoltaic system, with no batteries, was added to the dwelling, see Figure 22. The system has twelve (12) 175 W monocrystalline solar panels with open circuit DC voltage of 44.2 V and short circuit DC current of 5.2 A. The solar panels were connected in series, a single string, and into a 3-kW grid tied inverter. The 2.1 kW system generates, on average, 8 kWh per day. This is the annual average daily generation calculated using measurements over the course of one year. This energy production is in close agreement with published estimates for this region [47][48].

Figure 22. Rooftop solar photovoltaic system on the dwelling under study.

The grid tied rooftop photovoltaic system operates under a net-metering agreement between the residence owner and the electric utility. The net metering agreement allows the excess power generated by the photovoltaic system to be exported into the distribution grid. At night the dwelling consumes electric energy from the electric grid. At the end of each billing period the electric energy exported into the grid is subtracted from the energy demanded from the grid and the customer receives a bill for the net energy consumption.

In September 2017, Hurricane Maria hit Puerto Rico. The rooftop solar photovoltaic system did not suffer damage during the Hurricane. Since the damage to the electric network was extensive the need to adapt the existing solar photovoltaic system to supply the dwelling with electricity was evident. A local market search was conducted, by foot since there was no Internet or phone service, to obtain batteries, charge controllers and a suitable inverter plus electric wire, circuit breakers, boxes, etc.

The available charge controllers, MPPT with a maximum input power of 1,200 W and PV array open circuit voltage range from 37 to 105 V DC (for 24 V DC battery bank) defined the system adaptation. The solar panels were re-wired in series per group of two for 88.4 V DC open circuit. Three groups of two panels each were combined in parallel for a total short circuit current of 15.6 A. A maximum input power of 1,050 W was obtained from this arrangement.

These six solar panels were connected to one charge controller. The charge controller output was connected to four (4) deep cycle, flooded, lead acid 6 V DC batteries connected in series to obtain 24 V DC. Each battery has a 210 Ah capacity, a 1.26 kWh of maximum storage per battery. A 2 kW pure sine inverter was connected in parallel to the 24 V DC battery bank, as shown in Figure 23. The output of the inverter is 120 V AC thus a "jumper" was used to provide the dwelling with 120 V AC service.

A second MPPT charge controller, identical to the first, was used to connect the remaining six solar panels, with the same parallel series arrangement, to a second set of four (4) deep cycle , flooded, lead acid 6 V DC batteries connected in series to obtain 24 V DC. The same 2 kW pure sine inverter was also connected in parallel to the second 24 V DC battery bank. Thus the total storage capacity of the two 24 V DC battery banks is 10.08 kWh and all 12 solar panels are in use.

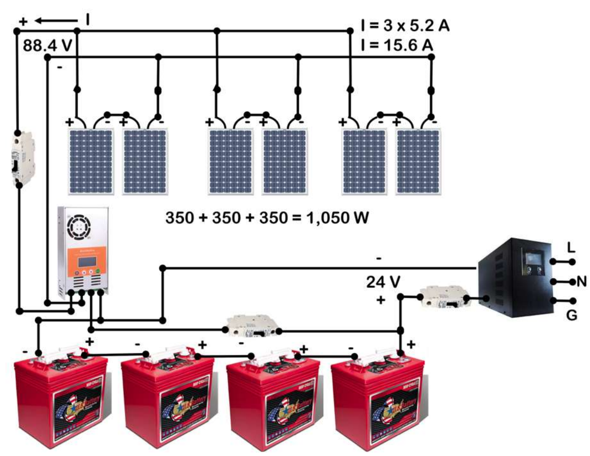

Figure 23. "Half" grid-tied residential photovoltaic system.

6.2.1 Load Information: Case 1

Figure 24 shows the monthly electric energy exported into the distribution grid (accredited) and the net electric energy billed to the customer in the seven (7) billing periods prior to a blackout due to the hurricane Maria (Feb-March 2017 to Aug-Sept 2017). There is no accredited electric energy in the Jun-July and July-Aug 2017 billing periods due to a malfunction in the PV system, a blown fuse between the solar panels and the grid tie inverter, a unique occurrence since the system was installed.

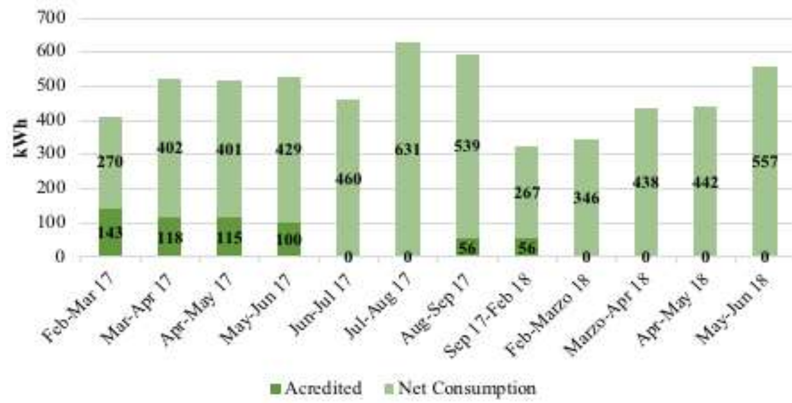

Figure 24. Power Consumption: Grid/Generated

The data in Figure 24 is based on the electric bill from the electric utility. Figure 25 shows the average daily electric energy demand from the electric bill. Notice that the actual demand is higher than shown since the energy used from the photovoltaic system prior to injecting the excess energy generated into the distribution grid is not accounted for in this graph.

Figure 25. Average daily electric energy demand in kWh

Notice the lower average daily energy demand, 13.8 kWh, during the Feb-March 2017 period, a cooler than average period of the year. March-April, April May, and May-June 2017 have similar average daily demand. June-July 2017 was unusually cool, with 139% of normal rainfall observed across Puerto Rico [49]. The average daily demand from

March thru July was 16.4 kWh. The average daily demand from July-Aug thru Aug-Sept 2017 was 21.1 kWh, August being the hottest month of the year at the location.

6.2.2 Uninterruptible Power System (UPS): Customer Back-Up

Due to Hurricane Maria, the electric service from the grid stopped 20 September 2017 and was restored 132 days later, on 30 January 2018 thus the irregular billing periods from Sept 2017 thru Feb 2018 in Figure 24 and Figure 25. From February thru June the photovoltaic system was used as a stand-by emergency generator and was disconnected from the grid (no net metering).

After the conversion from a grid tied to a standalone photovoltaic system was completed, the electric energy consumption at the dwelling resumed but was diminished. The electric loads were: a 19 cubic feet refrigerator in continuous use, a clothes washing machine, illumination and an assortment of electronic devices such as: five (5) cellphones, three (3) laptops, one (1) television, and three (3) videogame consoles although only one videogame console was in use at any given time. Illumination consisted of 12 light bulbs: 8 LED 10 W and 4 CFL 14 W.

Figure 26 shows the average daily energy demand during 10 days of blackout. The minimum energy demand occurs on a Tuesday, 2.42 kWh, the maximum energy demand occurs on a Sunday, 3.84 kWh. On weekdays, the daily average energy demand is 2.68 kWh. On weekend days it is 3.35 kWh, an increment of 25% as compared to weekdays. This is consistent with the inhabitants spending more time in the house during weekend days.

Figure 26. Average daily energy demand during 10 days of blackout

Notice the significant change between in daily average energy consumption prior and during the blackout. The average daily energy consumption during blackout was 2.95 kWh while the lowest average daily consumption prior to the blackout was 13.8 kWh in the Feb-Mar 2017 period (Figure 25), 4.7 times more energy. The highest average daily consumption prior to the blackout was 21.8 kWh in the Jul-Aug 2017 period (Figure 25), 7.4 times more energy than the energy consumption during the blackout.

The measured energy demand suggests that the basic energy needs of the inhabitants of the dwelling under study could have been satisfied with the system shown in Figure 23: six (6) solar panels, one MPPT charge controller and a battery bank of four (4) deep cycle, flooded, lead acid 6 V DC batteries connected in series to obtain 24 V DC. But the actual photovoltaic system under use had twice as many solar panels and batteries. This apparent overdesign offers the advantage of increased days of autonomy.

6.2.2.1 Simulation Results

To determine under which conditions, we can meet the energy demand with the 1.05 kW, 5 kWh PV system, we use Matlab/Simulink to simulate various combinations of weather conditions and electricity demand.

Table 5 shows the three weather conditions used in the simulation: mostly sunny, partly sunny and cloudy.

Table 5. Weather conditions, average daily irradiance (6 AM to 6 PM) and electricity generated by the 1.05 kW PV system

Weather conditions	**Average daily irradiance [kW/m2]**	**Electricity generated [kWh/day]**
Mostly sunny	0.683	5.86
Partly sunny	0.425	3.63
Cloudy	0.136	1.16

Figure 27 shows ambient temperature and irradiance for the three weather conditions. The temperature and irradiance measurements are from 18.21° N, 67.14° W, a location close to the dwelling under study, with very similar weather conditions and correspond to the same season of the year.

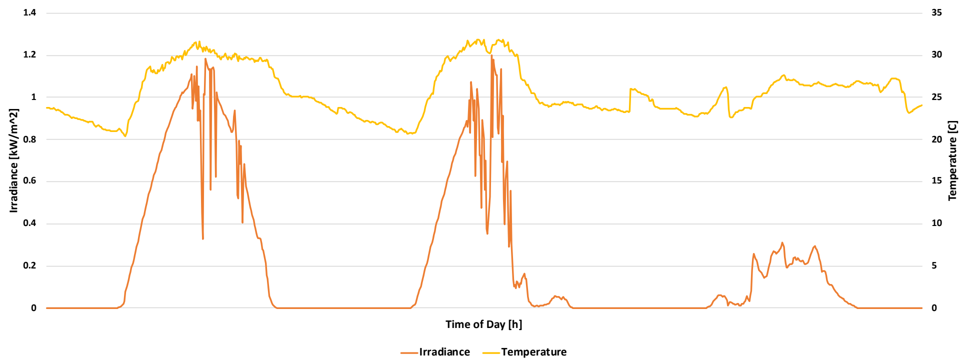

Figure 27. Ambient temperature in C (top curve) and irradiance in kW/m2 for (from left to right) mostly sunny, partly sunny and cloudy weather conditions.

Under these weather conditions the 1.05 kW PV system generates the amount of electricity shown in Table 5. For the purpose of simulation, it is defined three demand scenarios: low, average and high demand. From Figure 26 we identify Tuesday as low demand, Wednesday as average demand and the last Sunday as high demand.

Table 6. Electricity demand conditions

Electricity demand	Cumulative daily demand [kWh]
High	3.84
Average	2.98
Low	2.42

Figure 28, shows the five (5) minutes energy demand curve for the high and low demand scenarios in our simulations.

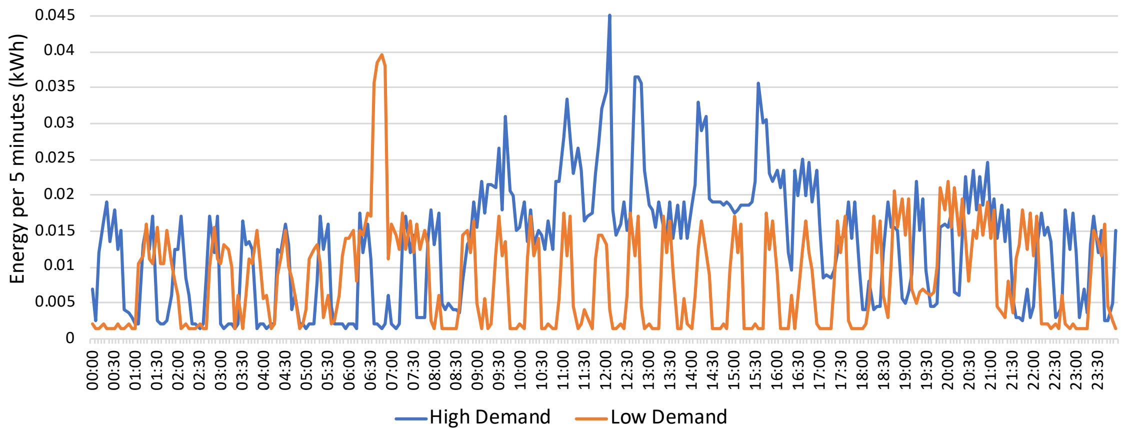

Figure 28. 5-minute daily energy (kWh) demand for low demand and high demand.

In all simulations the battery bank is charged until it reaches 100% state of charge (SOC), provided the energy is available, and we stop draining the battery bank at 20% SOC. The dark blue lines represent the voltage and SOC of the lithium-ion battery type. Likewise, the red lines represent the voltage and SOC of the lead-acid battery type.

- **Mostly Sunny – High Demand (Initial SOC 80%)**

With an initial SOC of 80%, as shown in Figure 29, both battery technologies successfully supply the high energy demand of the residence when mostly sunny weather condition. However, because of the exponential voltage drop of each technology, there is an initial difference of less than 2% of the SOC. Both technologies describe a very similar behavior in the given conditions.

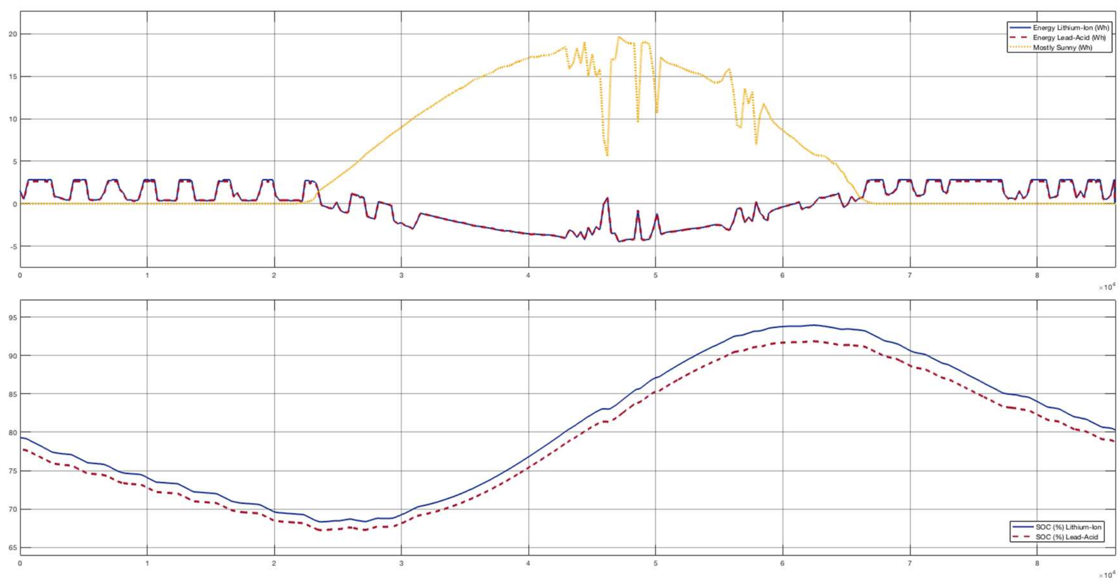

Figure 29. UPS, Mostly Sunny - High Demand (initial SOC 80%)

- **Mostly Sunny – Average Demand (Initial SOC 80%)**

As expected from the previous case, both battery technologies supply the average demand when mostly sunny weather condition. In Figure 30 is noticeably the difference in the slope when each technology is near the full charge condition (SOC = 100%). When the batteries are charging, in the case of the lithium-ion technology, the slope become stepper than the slope of the lead-acid technology. When the lithium-ion battery system reaches a SOC of 100%, the battery system is disconnected from the PV supply to avoid overcharging. The lead-acid battery never reaches the SOC of 100%. Similarly, when both batteries are discharging from the full charge condition, the lithium-battery system discharges quicker than the lead-acid technology. At the end of the simulation, both technologies reach the same SOC (86.6%).

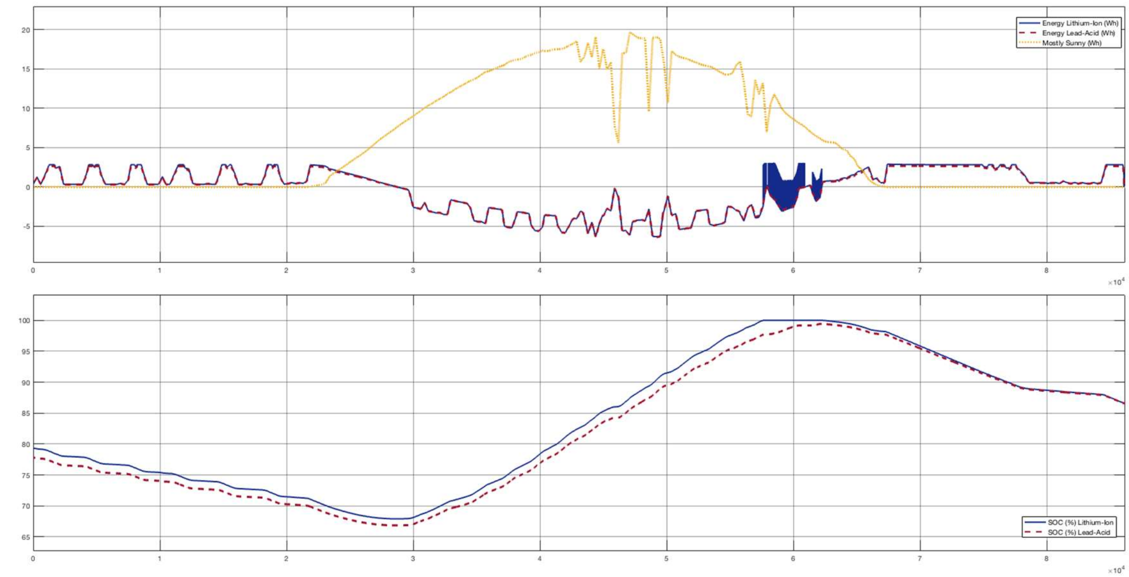

Figure 30. UPS, Mostly Sunny - Average Demand (initial SOC 80%)

- **Mostly Sunny – Low Demand (Initial SOC 80%)**

As shown in Figure 31, with the conditions given, both technologies reach a SOC of 100%. As the previous case, when both batteries are discharging from the full charge condition, the lithium-ion technology discharges quicker than the lead-acid technology. In this case, besides both technologies started with an SOC of 80% and both reaches the fully charged condition, the lead-acid technology finishes the simulation with higher SOC.

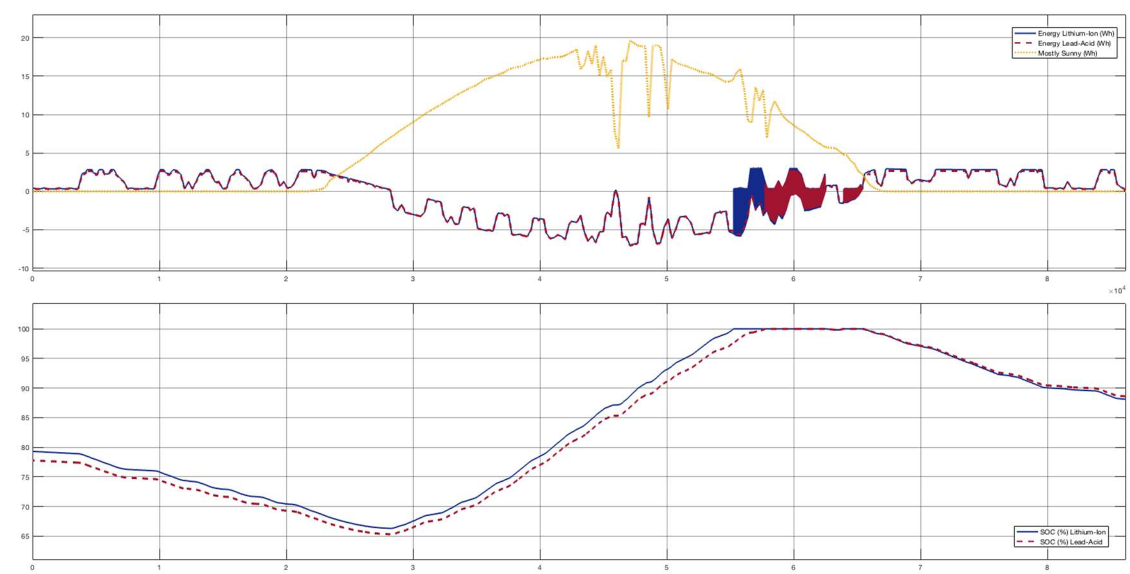

Figure 31. UPS, Mostly Sunny - Low Demand (initial SOC 80%)

- **Mostly Sunny – High Demand (Initial SOC 60%)**

With an initial SOC of 60%, as shown in Figure 32, both battery technologies successfully supply the high energy demand of the residence when mostly sunny weather condition. Apart from this, the initial SOC difference between the two technologies is 3%; a higher value than the previous difference when the initial SOC was 80%. Also, it can be seen that the exponential voltage-drop of both technologies increases with a lower SOC [higher drop than with an initial SOC of 80% (Figure 29)].

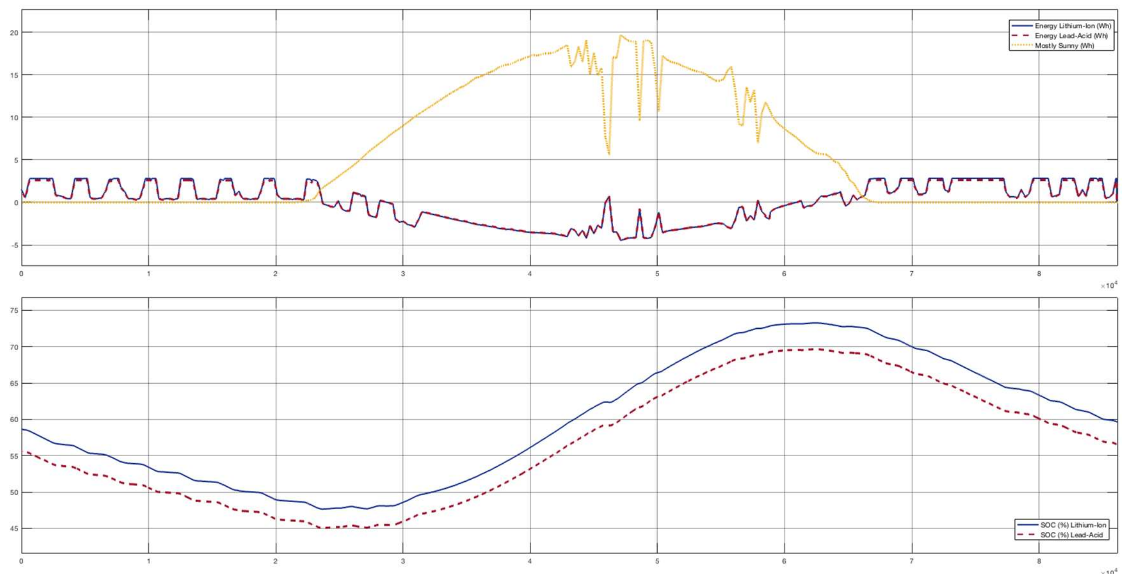

Figure 32. UPS, Mostly Sunny - High Demand (initial SOC 60%)

- **Mostly Sunny – Low Demand (Initial SOC 60%)**

As shown in Figure 33, neither of the battery technologies reaches the fully charged condition. When the batteries are charging, in the case of the lithium-ion technology, the slope become stepper than the slope of the lead-acid technology. In the highest point of both SOC curves, the difference is of 4.26%. Nevertheless, the final SOC difference between both technologies reduces to 3.6%. Also, it can be seen that the difference between the highest point and the final SOC (when the batteries are discharging) is low for lead-acid technology, that is, the lithium-ion technology discharges quicker.

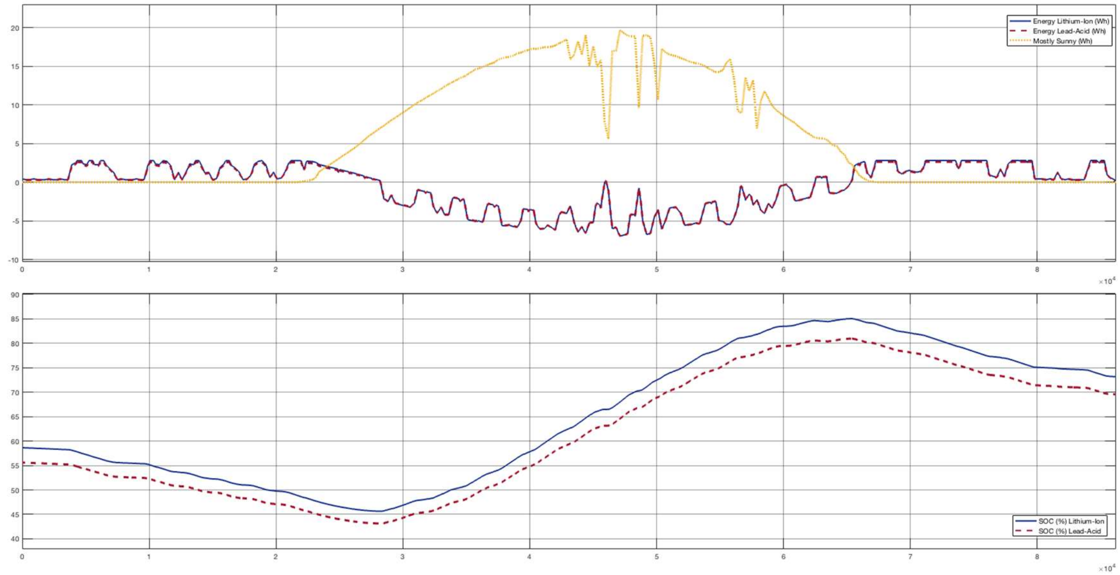

Figure 33. UPS, Mostly Sunny - Low Demand (initial SOC 60%)

- **Partly Sunny – High Demand (Initial SOC 80%)**

As shown in Figure 34, due to the exponential voltage drop, the difference between the SOC curves at the beginning is 1.55%. When the SOC curves reaches the highest point, the difference is 1.62%. Finally, at the end of the simulation, the final SOC difference is 0.68%. It can be seen also, that the lithium-ion battery discharges quicker than the lead-acid battery.

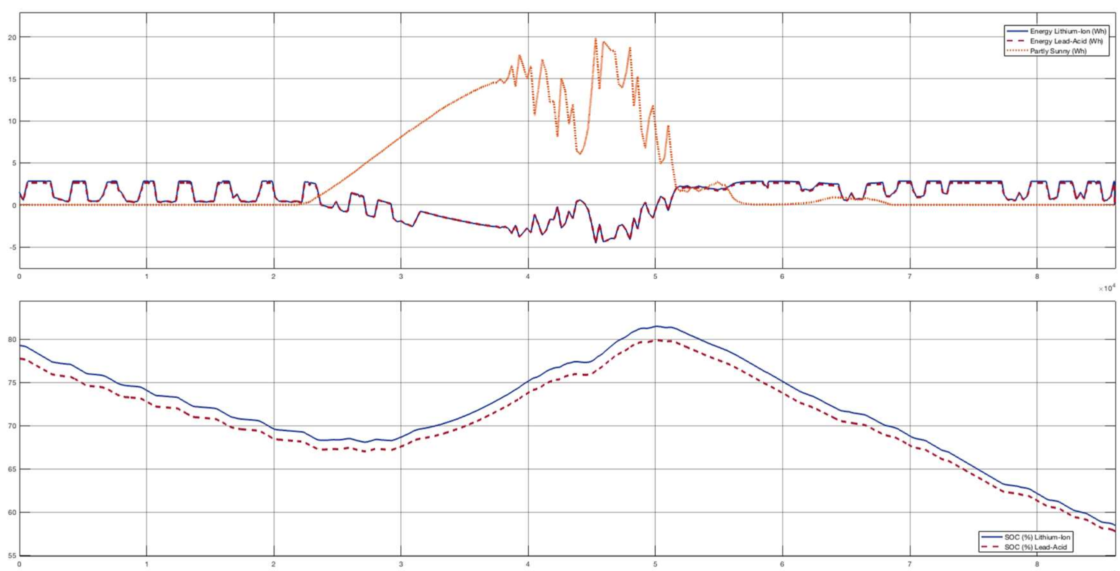

Figure 34. UPS, Partly Sunny - High Demand (initial SOC 80%)

- **Partly Sunny – Average Demand (Initial SOC 80%)**

In Figure 35 can be easily appreciated that lithium-ion battery technology discharges and charges quicker than the lead-acid technology. Hence, when both technologies reach the highest SOC value, the percentage difference tends to be greater than when both technologies are discharging to the lowest point.

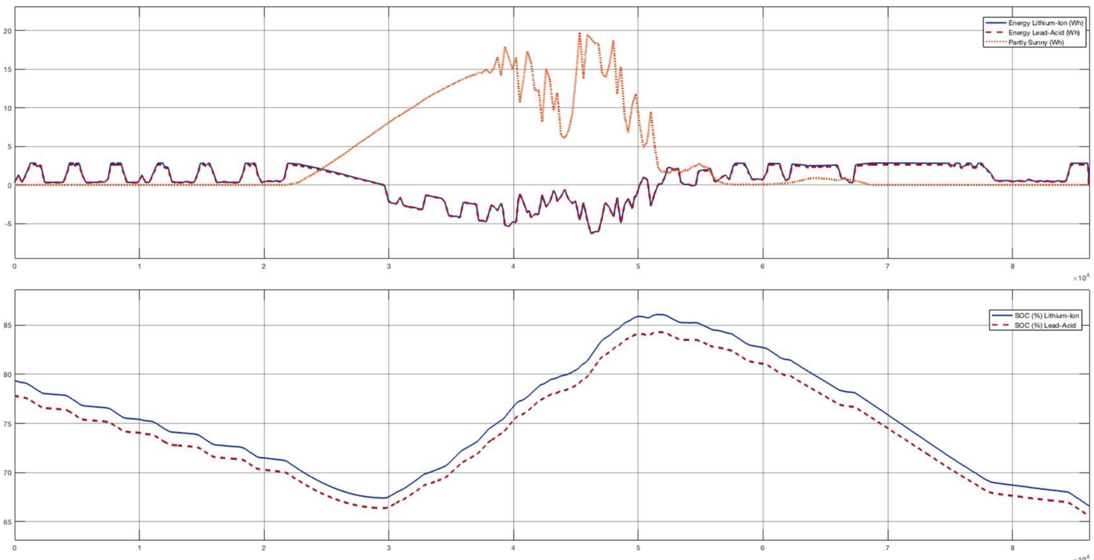

Figure 35. UPS, Partly Sunny - Average Demand (initial SOC 80%)

- **Partly Sunny – Low Demand (Initial SOC 80%)**

Figure 36 describes a similar behavior that the case explained above.

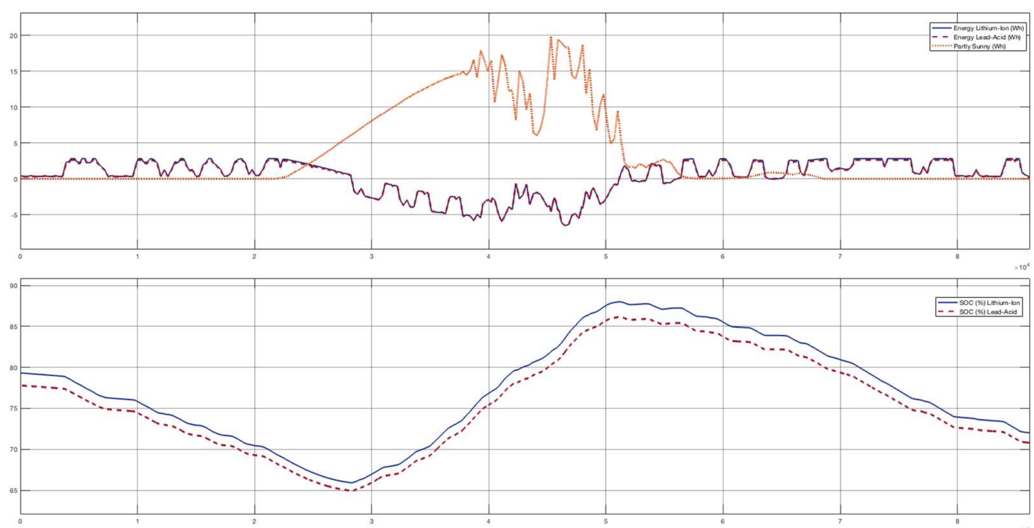

Figure 36. UPS, Partly Sunny - Low Demand (initial SOC 80%)

- **Partly Sunny – High Demand (Initial SOC 60%)**

As shown in Figure 37, with an initial SOC of 60%, both battery technologies successfully supply the high energy demand of the residence when partly sunny weather condition. Nevertheless, the final SOC for both technologies are around 36% at 00:00 (time simulation is based in 24 hours/day). The system disconnects the load when the SOC drops to 20% and the irradiance energy starts around 6:00 am, consequently, it is likely that the system will have to disconnect the load in the morning before the PV system starts to charge the batteries.

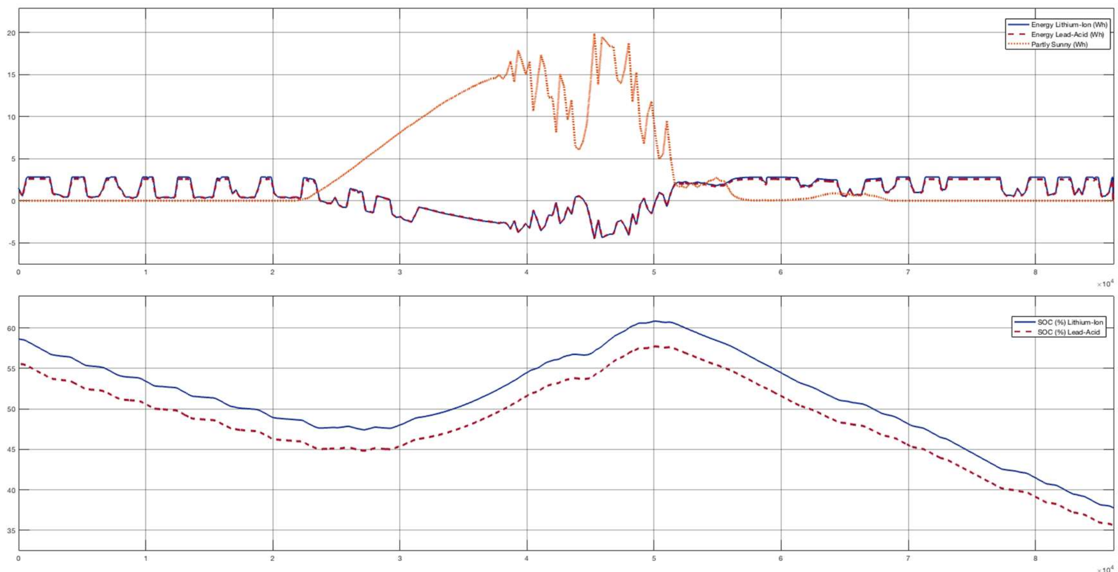

Figure 37. UPS, Partly Sunny - High Demand (initial SOC 60%)

- **Partly Sunny – Low Demand (Initial SOC 60%)**

As shown in Figure 38, the SOC curve for both technologies describes a similar behavior than the case explained above. Nevertheless, the final SOC difference in this case is 2.84% and in the previous case was 1.48%. This difference might be expected due to the reduction in the load demand. As we explained before, the lithium battery tends to discharge quicker than the lead-acid resulting in a progressive reduction of the original difference caused by the initial exponential voltage drop.

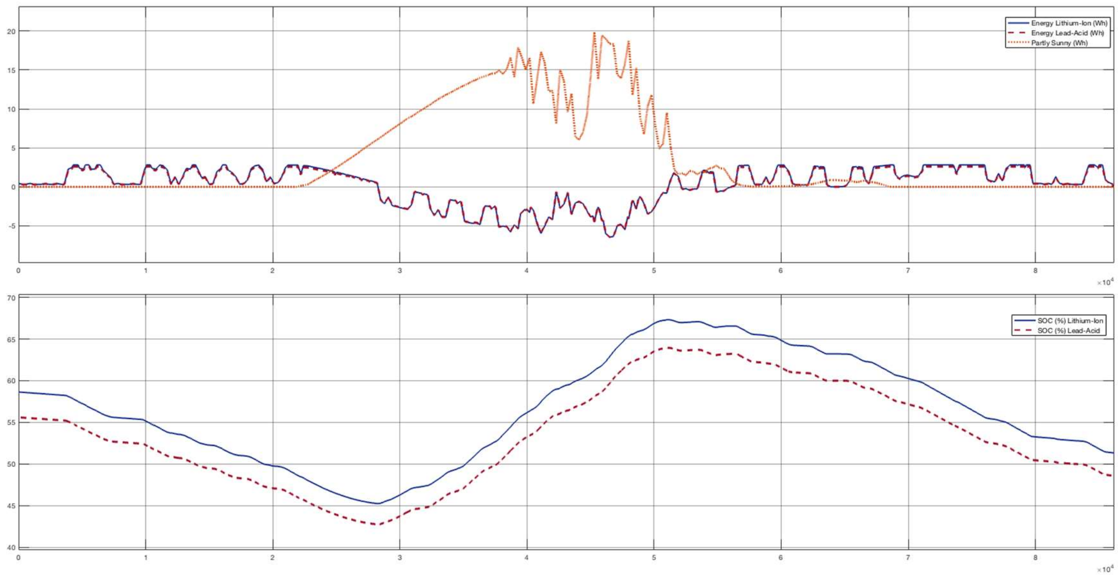

Figure 38. UPS, Partly Sunny - Low Demand (initial SOC 60%)

- **Cloudy – High Demand (Initial SOC 80%)**

As shown in Figure 39, with an initial SOC of 80% both battery technologies successfully supply the high energy demand of the residence when cloudy weather condition. The final SOC for both technologies is around 34% at 00:00 (time simulation is based in 24 hours/day). The battery control system is set to disconnect the load when the SOC drops to 20% and the irradiance energy starts around 6:00 am, consequently, it is likely that the system will have to disconnect the load in the morning before the PV system starts to charge the batteries.

Even though the exponential voltage drop makes the lithium-ion battery SOC higher at the beginning of the simulation, the fact that it drops below the lead-acid SOC at the end of the simulation confirms that the lithium-ion technology discharges quicker. In fact, we could see in the energy behavior, how the lead-acid battery provides less energy to the load demand (red line) than the lithium-ion battery (dark-blue line).

Finally, due to the SOC slope of both technologies, we can infer that with an irradiance below of $400W/m^2$, as in the present case, and with a high demand, the batteries were not charging. Therefore, in a cloudy week, it is highly possible that the system presented would not be enough to satisfy the load demand of the system.

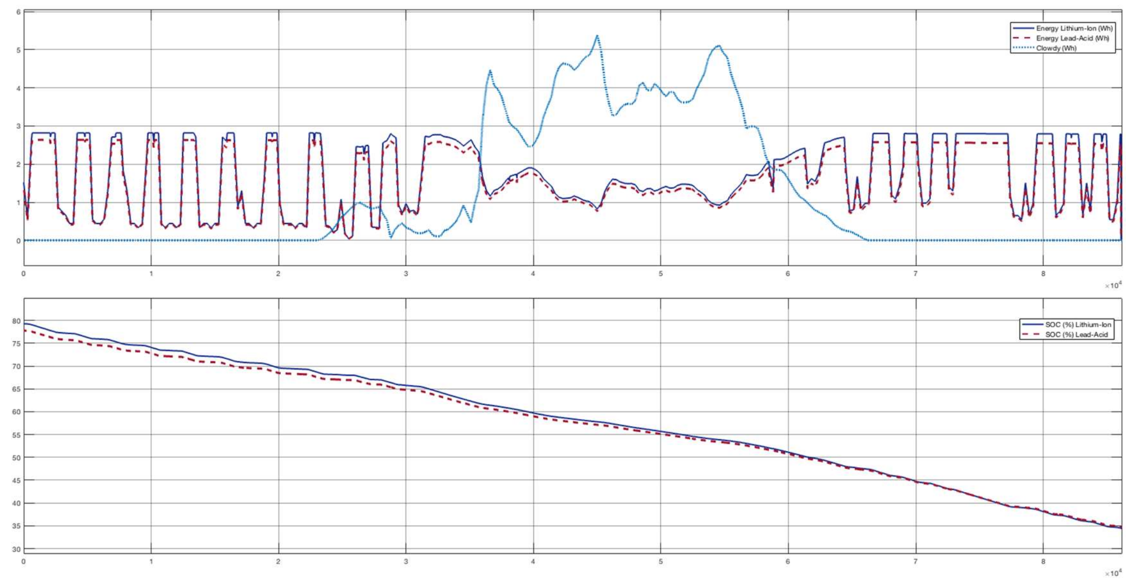

Figure 39. UPS, Cloudy - High Demand (initial SOC 80%)

- **Cloudy – Average Demand (Initial SOC 80%)**

As shown in Figure 40, with a reduction of the load demand, although the PV system charges the batteries during the sun hours, the energy is not enough to increase the SOC, just to hold it near the same value. Besides, the decrease of the SOC indicates that the system needs at least a partially sunny weather condition in order to work as a stand-alone system.

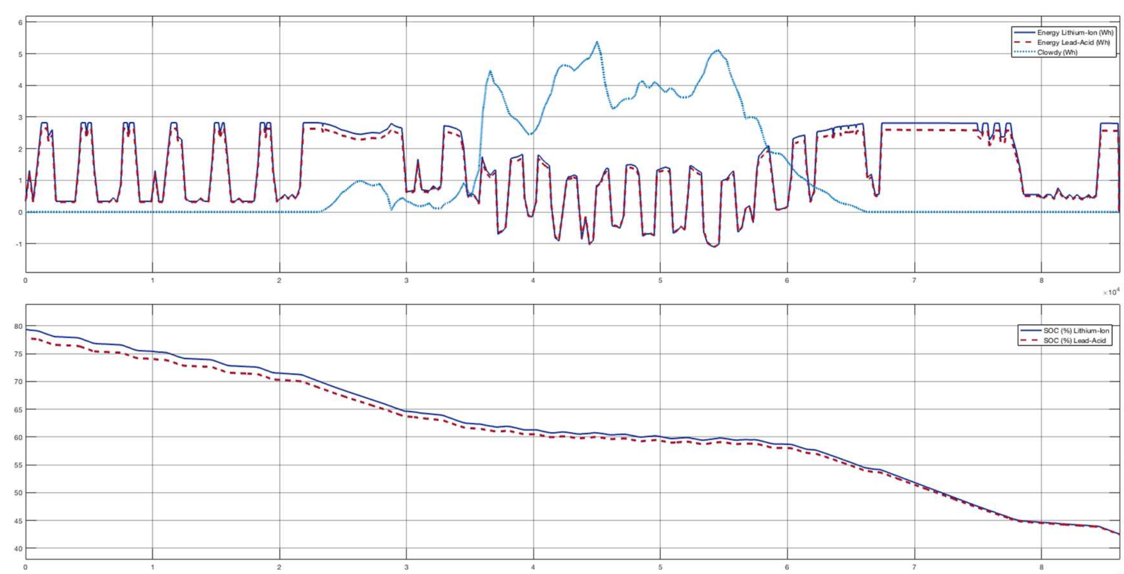

Figure 40. UPS, Cloudy - Average Demand (initial SOC 80%)

- **Cloudy – Low Demand (Initial SOC 80%)**

As shown in Figure 41, with cloudy weather, when the demand is reduced, and during sunny hours, the batteries hold around the same SOC. Also, the lithium-ion battery discharges until reaching a similar SOC than the lead-acid battery. The final SOC did not show a significant variation between the low demand condition and the average demand condition. This small system needs at least a partly sunny condition in order to work as a stand-alone system.

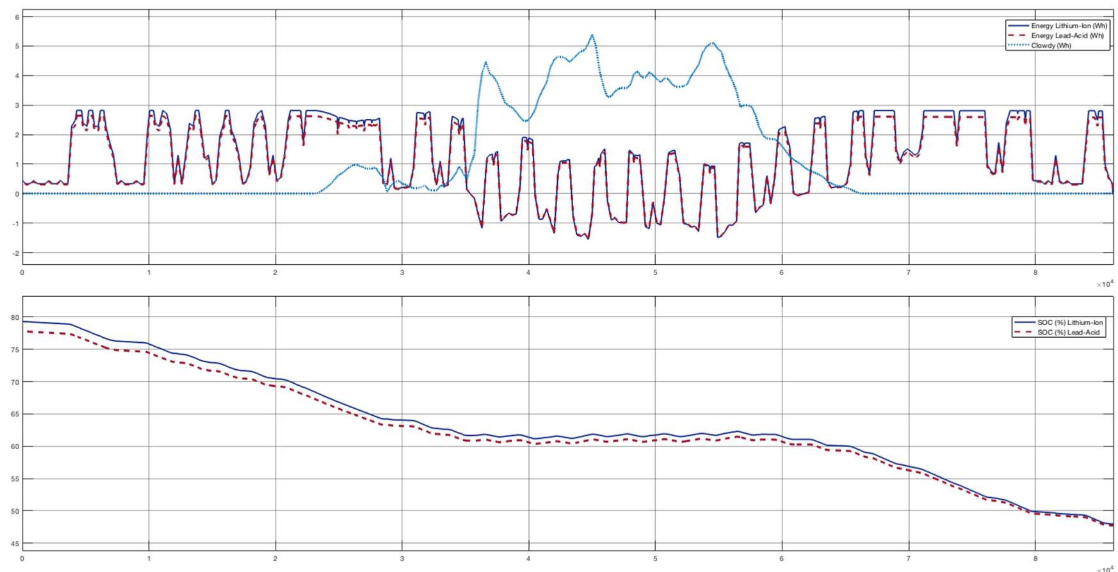

Figure 41. UPS, Cloudy - Low Demand (initial SOC 80%)

- **Cloudy – High Demand (Initial SOC 60%)**

Figure 42 shows the lead-acid battery provides less energy to the system than the lithium-ion battery under cloudy and high demand conditions. This behavior becomes more evident as the lead-acid SOC decreases.

Although the lithium-ion battery discharges quicker, the system with the lead-acid battery disconnects the load first to avoid over discharge.

The previous case starts with a SOC of 80% and ends with a SOC less than 48%. This case starts with a SOC of 60%, and the system had to disconnect the load with either of the battery technologies. We could conclude that with cloudy weather condition this PV-system cannot work as a stand-alone system.

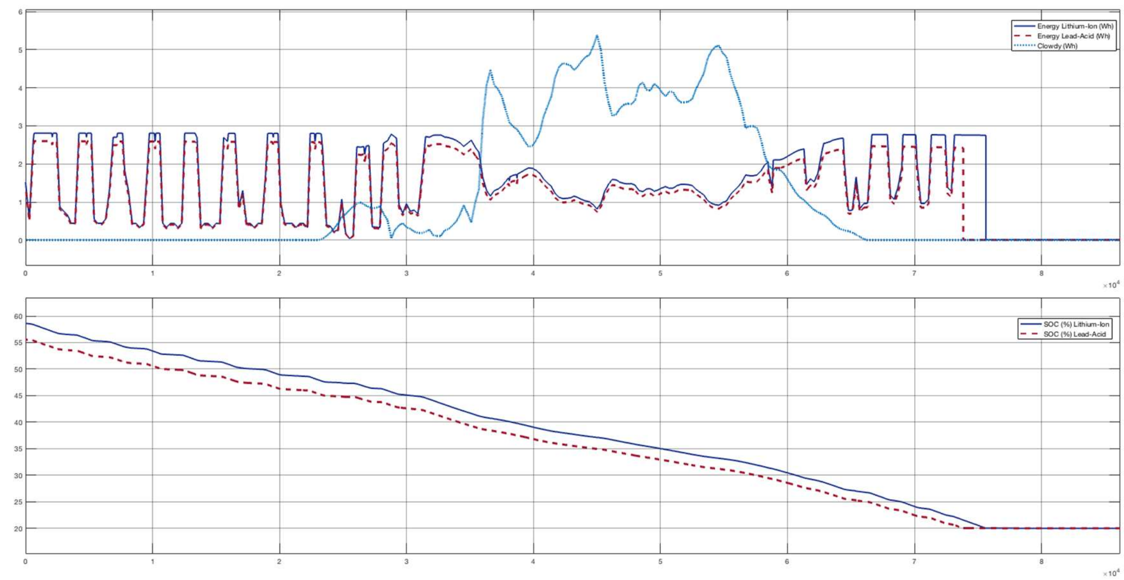

Figure 42. UPS, Cloudy - High Demand (initial SOC 60%)

- **Cloudy – Low Demand (Initial SOC 60%)**

Figure 43 shows low demand and 60% initial SOC. The lithium-ion battery discharges quicker and the initial exponential voltage drop causes a difference between the SOC of both technologies. Both technologies had a similar SOC's behavior, however, due to the difference in the voltage drop, they have an almost constant difference during all the simulation.

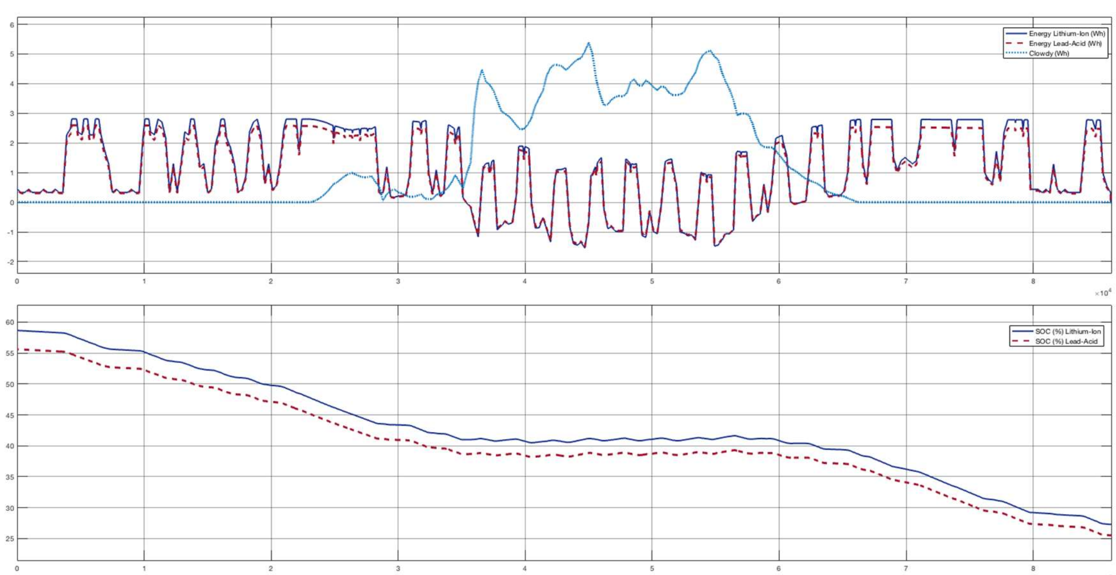

Figure 43. UPS, Cloudy - Low Demand (initial SOC 60%)

6.2.3 Comparison between both battery technologies during a real blackout

Table 7 summarizes the final SOC of the battery bank for a simulation with an initial SOC of 80%. With an initial SOC of 80% the 1.05 kW 5 kWh PV system successfully supply the energy demand of the dwelling under the most severe simulated conditions: high demand with cloudy weather conditions.

Table 7. UPS, Final SOC for 80% initial SOC

	Electricity demand					
Weather conditions	**High**		**Average**		**Low**	
	Lead-Acid	**Lithium-Ion**	**Lead-Acid**	**Lithium-Ion**	**Lead-Acid**	**Lithium-Ion**
Mostly sunny	78.8%	80.3%	86.6%	86.6%	88.6%	88.1%
Partly sunny	57.8%	58.5%	65.6%	66.7%	70.8%	72.0%
Cloudy	34.7%	34.4%	42.6%	42.6%	47.7%	48%

Table 8 shows the final SOC of the battery bank for a simulation with an initial SOC of 60%. With an initial SOC of 60% the PV system fails to supply the energy demand of the dwelling under the most severe simulated conditions: high demand with cloudy weather conditions. The PV system does supply the energy demand for the remaining conditions.

Table 8.UPS, Final SOC for 60% initial SOC

	Electricity demand			
Weather conditions	**High**		**Low**	
	Lead-Acid	**Lithium-Ion**	**Lead-Acid**	**Lithium-Ion**
Mostly sunny	56.6%	59.6%	69.6%	73.2%
Partly sunny	35.6%	37.1%	48.6%	51.5%
Cloudy	<20%	<20%	25.5%	27.3%

Finally, Table 9 summarizes the simulation results obtained from case 1.

Table 9. Summary of Results: Case 1

Lead-Acid Battery	**Lithium-Ion Battery**
Discharges slower	
	Charges quicker
	Lower exponential voltage drop zone
Exponential voltage-drop increases with a lower SOC	Exponential voltage-drop increases with a lower SOC
Supply the energy needed when good weather condition ($> 400W/m^2$)	Supply the energy needed when all weather conditions

6.3 Case Study 2: Net-Metering Agreement

Figure 44 shows the daily electric energy consumption and the average daily power demand during 30 days for a residence in Puerto Rico. The maximum energy demand occurs on August 27, 2017, 8.7 kWh. The minimum energy demand occurs on August 22, 2017, 6.8 kWh. On weekdays, the daily average energy demand is 7.82 kWh. On weekend days it is 7.78 kWh. The lack of measurements from September 6, 2017 to September 8, 2017 corresponds to the lack of energy for damages caused by Hurricane Irma [50].

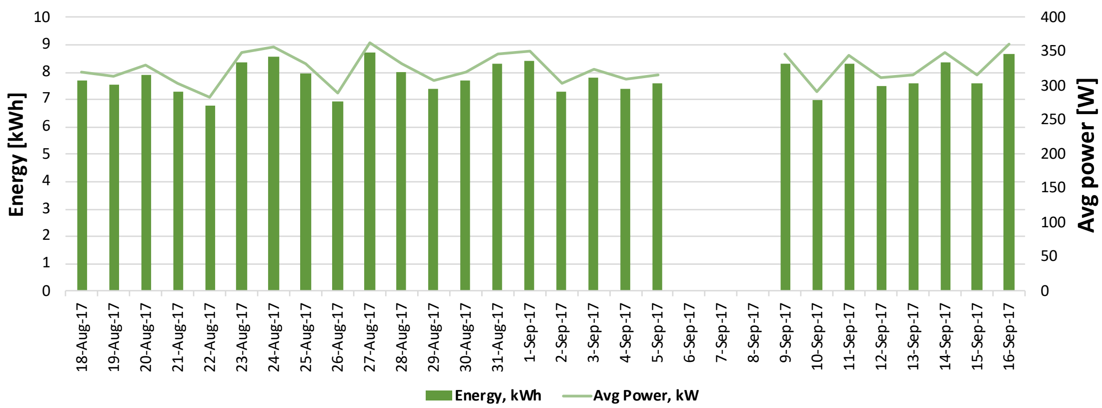

Figure 44. Average Daily Energy Consumption in kWh; Average Daily Power Demand in W

Table 10 shows the day and time of the larger power demand during the 30 days of measurements. The highest demand is 5.3 kW.

Table 10. Day and time of higher power demand

Day/time	Power Demand (kW)
August 23, 2017 / 11:23	5.3
August 28, 2017/ 11:00	5.2
August 24, 2017/ 09:42	5.1

From Figure 44 we identify the week from August 23 to August 29 as the average demand week for the residence. Figure 45, shows the one-minute power demand curve for this average demand week. We will use this demand in our simulation.

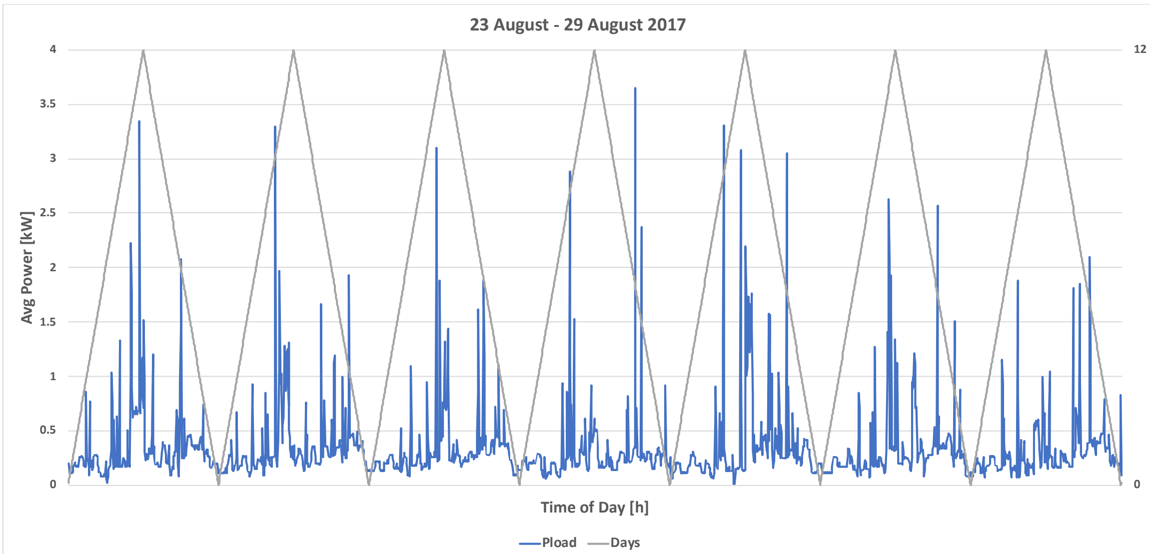

Figure 45. 1-minute average daily power (kW) demand for the average demand week

6.3.1 Grid-Tied PV System with Batteries

In this scenario, we study a grid-tied PV system with batteries operating under a net-metering agreement between the residence owner and the electric utility. To allow a comparison with our previous scenario, we use the same PV module and battery characteristics than in Case 1.

For the PV generator module, we use the solar panels Suntech Power STP175S-24-Ab-1. The maximum energy demand occurs on August 27, 2017, 8.7 kWh. Estimating an average of 4 hours of sun daily [48], we need a capacity of,

$$PV capacity = \frac{8.7\ kWh}{4h} = 2.175\ kW$$

Leaving around a 30% of capacity, it would be needed 16 solar panels for a maximum input power of 2.8 kW. Due to the simulation shown in Figure 20 uses a controlled current source to charge the battery system, and assuming a 120 A inverter, the panels are combined in parallel for a total nominal current of 79.2 A and nominal voltage of 35 V.

For the battery system we use 12 deep cycle, 6 V DC batteries. Each group of four (4) batteries are connected in series to obtain 24V DC, then, the three (3) groups are connected in parallel. Each battery has a 210 Ah capacity, then system has a total of 630 Ah, a 15.12 kWh of maximum storage.

For this battery bank with a nominal voltage of 24 V and with the maximum energy demand of 8.7 kWh. Then, the system has a discharge rate with maximum energy consumption and with maximum depth of discharge of 80%,

$$Discharge\ Rate\ (hours) = \frac{15.12\ kWh}{8.7\ kWh} \times 24\ hours = 41.74\ hour$$

6.3.2 Customer Services Simulations: Case 2

The simulation used in Case 2 is shown in Figure 48. The purpose of the simulation is to determine if there is a difference in energy injected into the grid, for net-metering, when we use different battery technology. In the simulation we add the block shown in Figure 46. The block has three (3) inputs and one (1) output. The inputs are: energy demanded by the load, energy into the battery and energy from the PV-System. The output is the energy from/to the grid. The relationship between the inputs and outputs is,

$$Energy_{load} - Energy_{PV} - Energy_{Battery} = Energy_{Grid} \qquad (4)$$

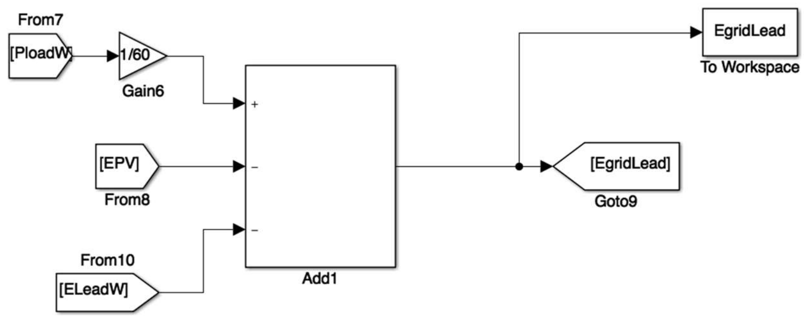

Figure 46. Energy from/to the Grid Module

For weather conditions, we use measured data representing a week of average irradiance and temperature, as shown in Figure 47. The temperature and irradiance measurements are from 18.21° N, 67.14° W, a location close to the dwelling under study, with very similar weather conditions and corresponding to the same season of the year.

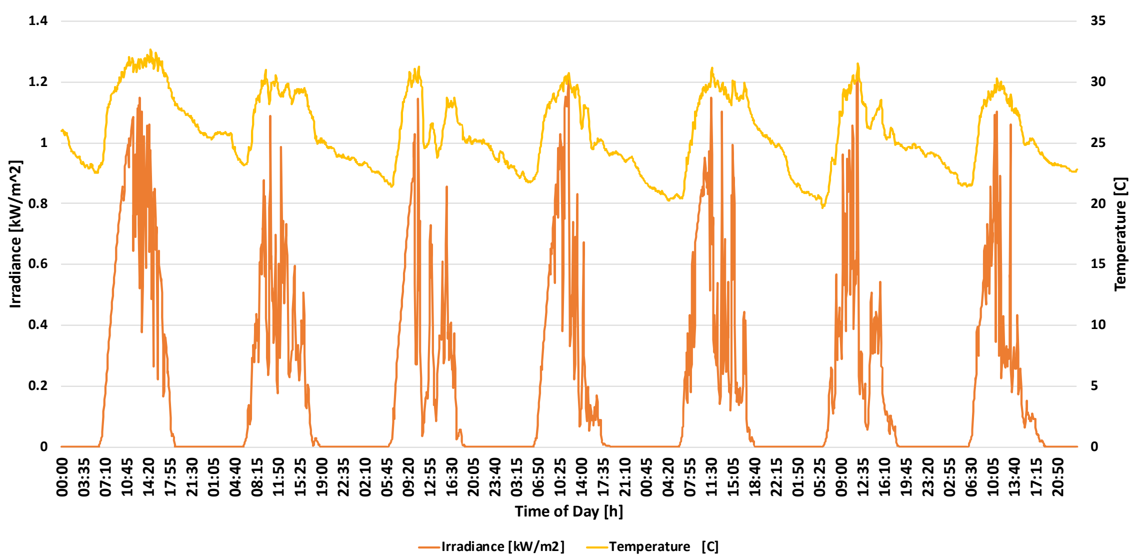

Figure 47. Ambient temperature in C (top curve) and irradiance in kW/m2 for Seven Days

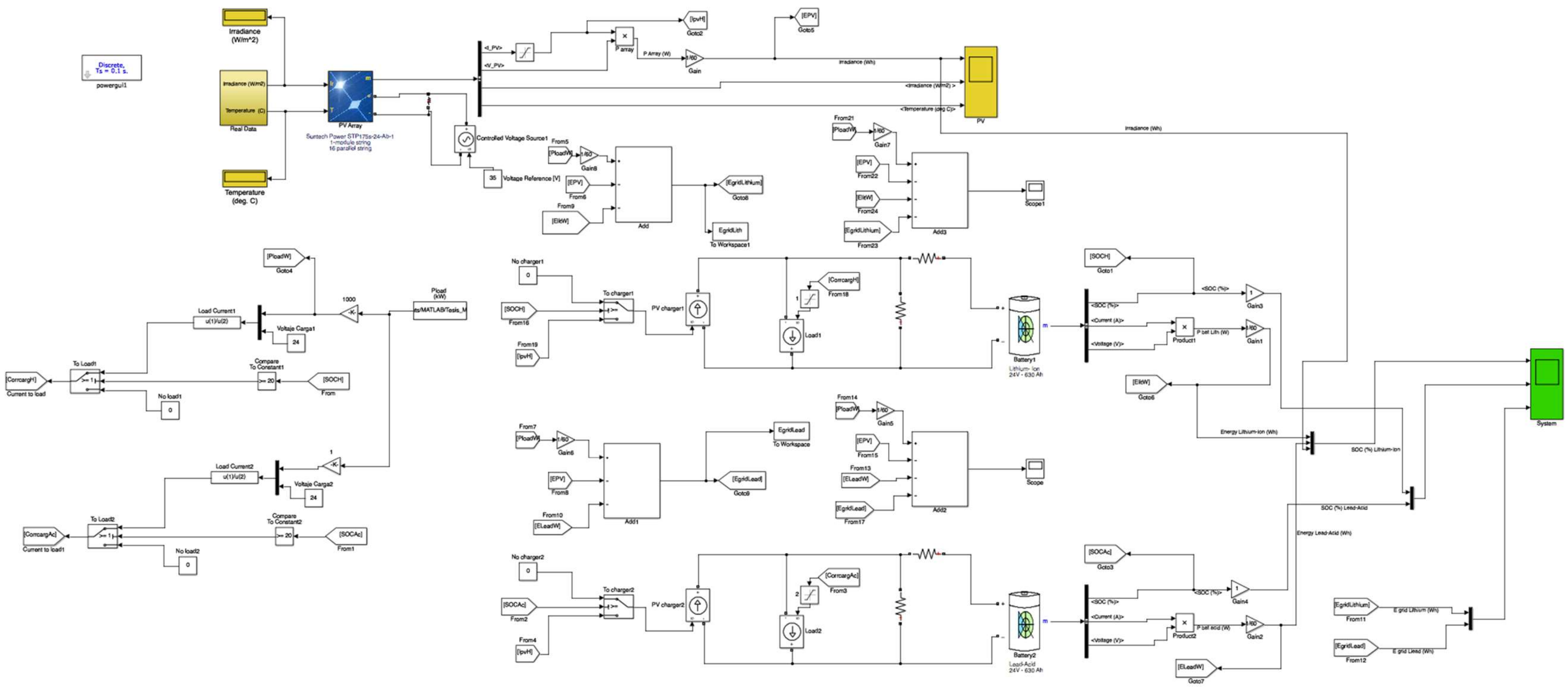

Figure 48. MATLAB/Simulink Scenario Modified for Case 2

6.3.2.1 Simulation Results

With the residential demand shown in Figure 45, an initial SOC of 80% in the battery bank and the system described above, we obtain the behavior shown in Figure 49. In the top graph, we show the energy from the PV system and the energy that goes to and from the battery bank. In the middle graph we show the SOC of the battery banks. Finally, in the third graph, we show the energy injected into the grid (negative values) or consumed from the grid (positive values).

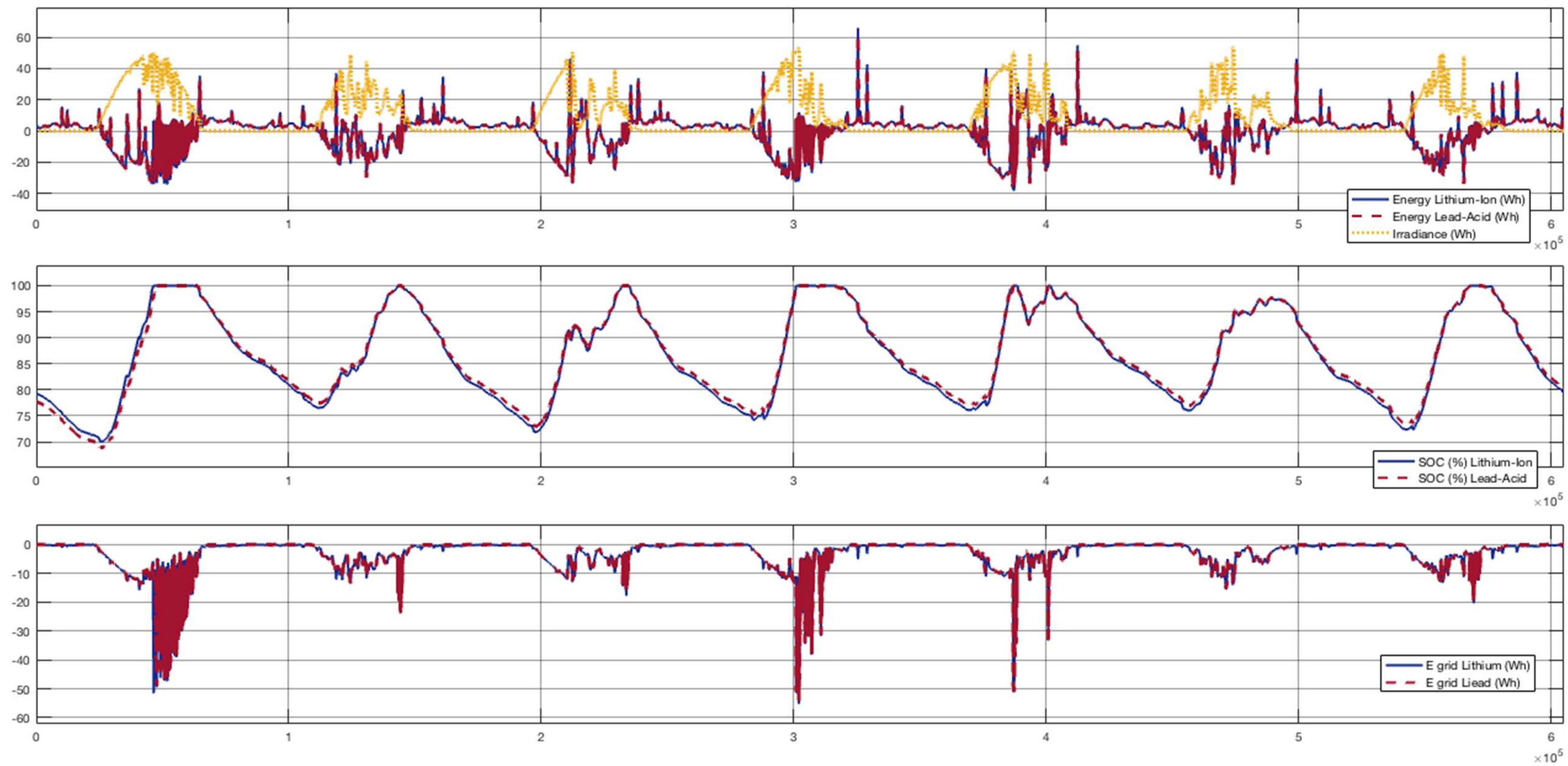

Figure 49. Net-Metering behavior (from up to down): Energy from the PV panels and to/from the batteries, SOC of batteries and Energy to/from the Grid

In the following we discuss the behavior shown in Figure 49.

- First day: The li-ion battery bank starts with a SOC of 79% and the lead acid battery bank start with a SOC of 77.5%. Both battery technologies behave similarly with the Li-ion technology exhibiting a stepper slope of discharge.
- Second day: Both battery banks start charging at the same time, around 6 AM. Due to the SOC difference reached during the discharge stage, both battery banks reach a SOC of 100% at the same time.
- Third day: As shown in Figure 50, although the lithium-ion discharges quicker, it injects more energy to the grid due to the slower peak-response of the lead-acid battery. It can be seen in the third square small peaks of energy injected to the grid with the lithium-ion technology. Also, it can be seen how the lead-acid energy to the grid remains constant during those peaks.

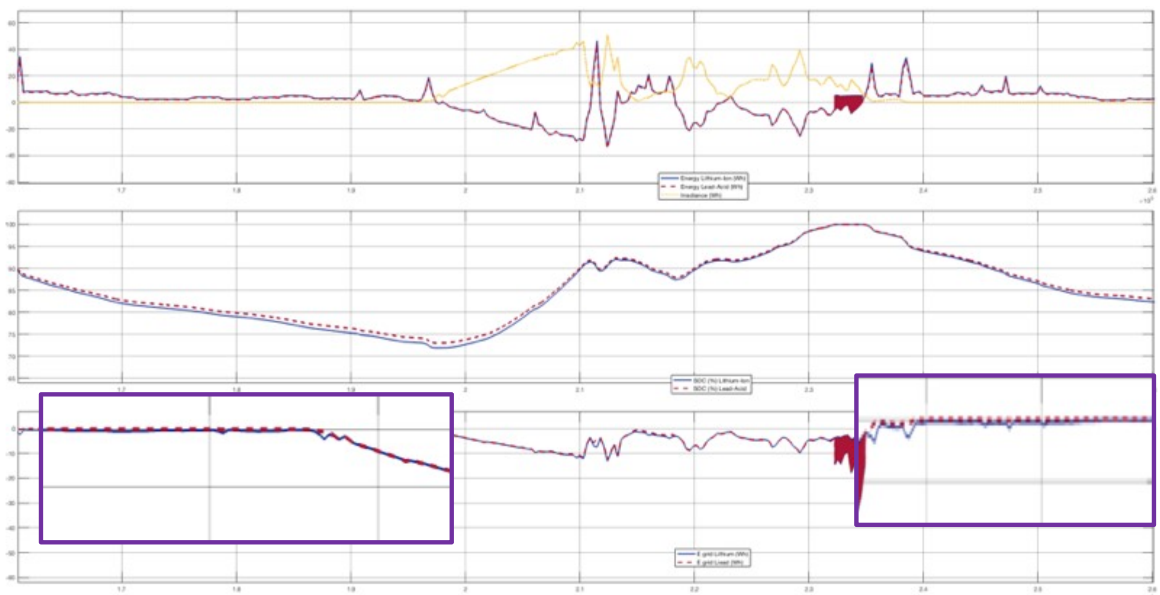

Figure 50. Net-Metering behavior: Third (3) Day Simulation with Zoomed Squares

- Fourth and fifth days: Again, the lithium-ion battery charges and discharges quicker than the lead-acid technology. Also, it can be seen how the slower peak-response of the lead-acid batter affects the energy injected to the grid. Both technologies reach a SOC of 100% around the same time.

- Sixth day: In this day, a partly cloudy day, the amount of energy injected into the grid decreases and neither of the battery banks reach a SOC of 100%.
- Seventh day: Both battery banks reach a SOC of 100% at approximately the same time. The lead-acid battery ends the day with a higher SOC.

Table 11 shows the energy injected into the grid (for net metering) during these seven days. It can be seen in all cases that the lithium-ion battery technology injects more energy to the grid than the lead-acid battery technology. The last column shows the additional energy that the lithium technology injects more than the lead-acid technology. Also, it can be seen that the system injects energy to the grid during the night (6:01 PM to 5:59 AM), it is because the sun does not rise exactly at 6 AM or hide exactly at 6 PM every day.

Table 11. Energy into the Grid (negative)

Time of Day	**Lead-Acid [kWh/week]**	**Lithium-Ion [kWh/week]**	$\lvert \mathbf{Lithium} - \mathbf{Lead} \rvert$ **[kWh/week]**
Day (6AM to 6PM)	-33.35	-35.02	1.56
Night (6:01 PM to 5:59 AM)	-0.45	-2.01	1.67
Total	-33.80	-37.03	3.23

Chapter 7

RESULTS AND ANALYSIS

In this chapter we present our results and analysis. The first section states a list of desired characteristics for a new battery technology. The second section presents results of the set of battery technologies that best fulfill the requirements for main customer services. The third section describes the energy management system model. In the fourth section, the cost calculations and cost comparison between different configurations for the battery storage system is presented. Finally, the process implemented to calculate the hybrid system is presented in section five.

7.1 Desired Characteristics for a New Battery Technology

For residential use a new battery technology that fulfills customer services requirements should have the following characteristics:

1. Low exponential voltage drop: a high voltage drop decreases the available energy when the battery bank is in use.
2. High rate during the charging moments: as lithium-ion battery.
3. Low rate during the discharging moments: as lead-acid battery.
4. High depth of discharge: as lithium-ion battery.
5. Quick response to reduce peak demand: as lithium-ion battery.
6. High discharge duration (storage capacity).
7. Large power rating capacity.
8. High efficiency to avoid self-discharge.
9. High lifecycle.

7.2 Sets of Battery Technologies

For the load behavior in Figure 45 we calculate the energy demand during the day (6 AM to 6 PM) and the energy demand during the night (6:01 PM to 5:59 AM). Figure 51 shows the result.

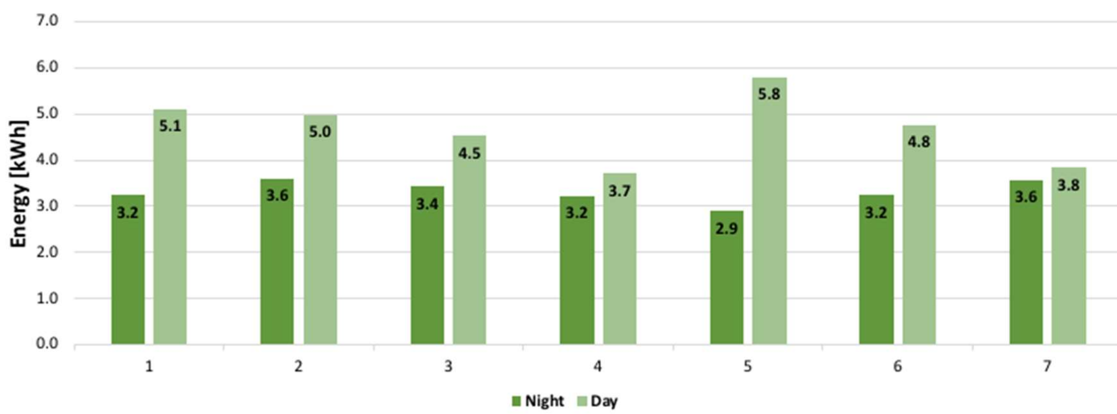

Figure 51. Energy demand during night and day for the week under study.

We now study the behavior of a battery storage system with combined technologies, one storage technology to be used during the day and a different battery storage technology to be used during the night. The PV module remains the same.

- Battery Storage System for 6 AM to 6 PM (day)

The maximum energy demand during the day occurs on day five (5), 5.8 kWh. For the battery system we use 8 deep cycle, 6 V DC batteries. Each group of four (4) batteries are connected in series to obtain 24V DC, then, the two (2) groups are connected in parallel. Each battery has a 210 Ah capacity, then system has a total of 420 Ah, a 10.08 kWh of maximum storage.

- Battery Storage System for 6:01 PM to 5:59 AM (night)

The maximum energy demand during the night occurs on day two (2), 3.60 kWh. For the battery system we use 4 deep cycle, 6 V DC batteries. The four (4) batteries in this group are connected in series to obtain 24V. Each battery has a 210 Ah capacity, then system has a total of 210 Ah, a 5.04 kWh of maximum storage.

Notice that the total battery storage system with both technologies has a maximum storage of a 15.12 kWh, as in the case with just one technology.

Therefore, the new module used to calculate the net-metering energy from/to the grid is shown in Figure 52. Hence, the block has four (4) inputs and one (1) output. The inputs are: the energy of the load, the energy of both battery technologies and the energy from the PV-System. The output is the energy from/to the grid. The relationship between the inputs and outputs is,

$$Energy_{load} - Energy_{PV} - Energy_{Lithi} \quad - Energy_{Lead} = Energy_{Grid} \qquad (5)$$

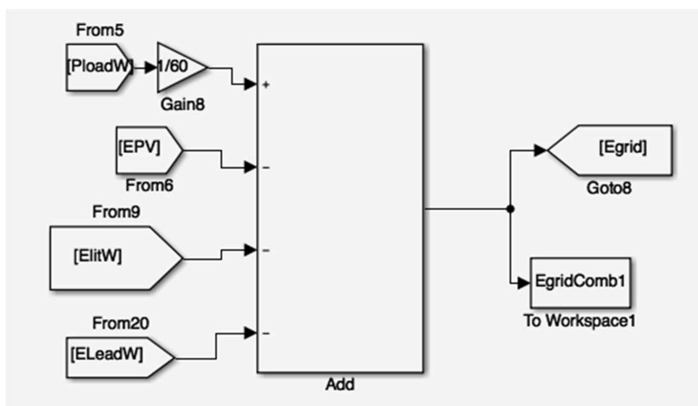

Figure 52. Energy from/to the Grid Module with Combined Battery Technologies

In our simulation we use one battery technology during the night and the other battery technology during the day. To charge the batteries, both battery storage systems receive half of the current from the PV system module. The simulation is set to disconnect the load at SOC of 20% to avoid over-discharge and to disconnect the PV module at 100% to avoid over-charge.

Figure 53 and Figure 54 show the simulation results with an initial SOC of 80% for both technologies, a depth of discharge of 80% for both technologies and the cases when the lithium-ion technology is used during the day (with the size calculated for day requirements) and the lead-acid technology is used during the night (with the size calculated for night requirements), and vice versa.

Table 12 shows the Net-Metering energy for the combination of battery technologies during the seven days of the simulation.

Table 12. Net-Metering – Combination Battery Technologies. DoD 80%

	Net-Metering - DoD 80% for both technologies			
	Lead-Acid	**Lithium-Ion**	**Lithium-Ion**	**Lead-Acid**
Moment of the day	Day	Night	Day	Night
DoD	80%	80%	80%	80%
Net Metering [kWh/week]	-36.34	-1.96	-37.58	-0.22
	-38.30		-37.80	
|Δ|	0.5			
SOC Interval [%]	67.08% - 99.5%	29.75% - 100%	66.43% - 100%	34.3% - 100%

From Table 11, the net-metering energy when the system operates with a battery storage system of lithium-ion was -37.03 kWh/week and with a battery storage system of lead-acid was -33.80 kWh/week. It can be seen an increase of energy injected to the grid with either of the combinations proposed.

- **Day: Lithium-Ion Technology, Night: Lead-Acid Technology. Initial SOC 80%. DoD = 80% for both technologies.**

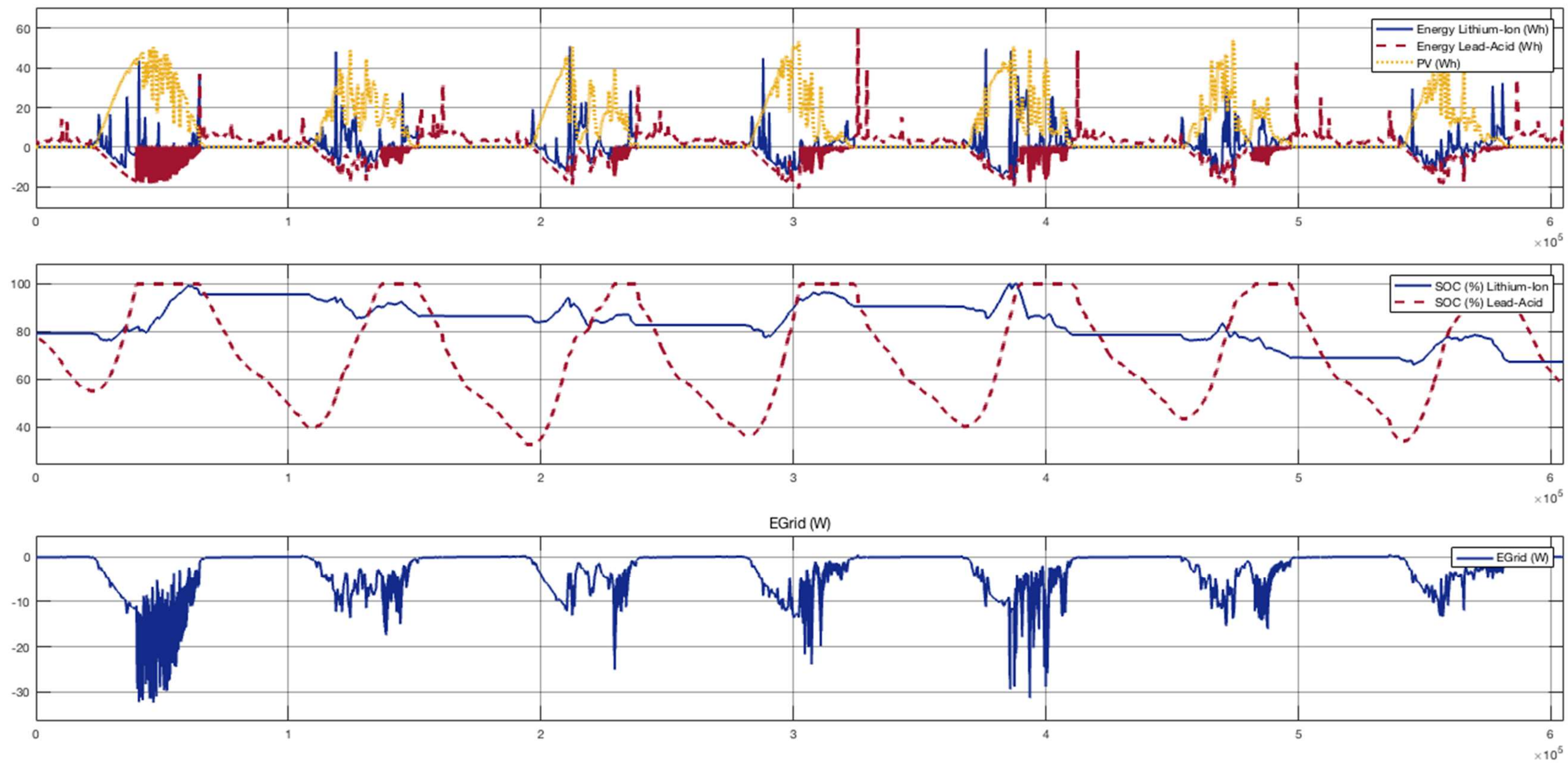

Figure 53. Day: Lithium-Ion DoD 80%. Night: Lead-Acid DoD 80%. Combined Battery Technologies.

- **Day: Lead-Acid Technology, Night: Lithium-Ion Technology. Initial SOC 80%. DoD = 80% for both technologies.**

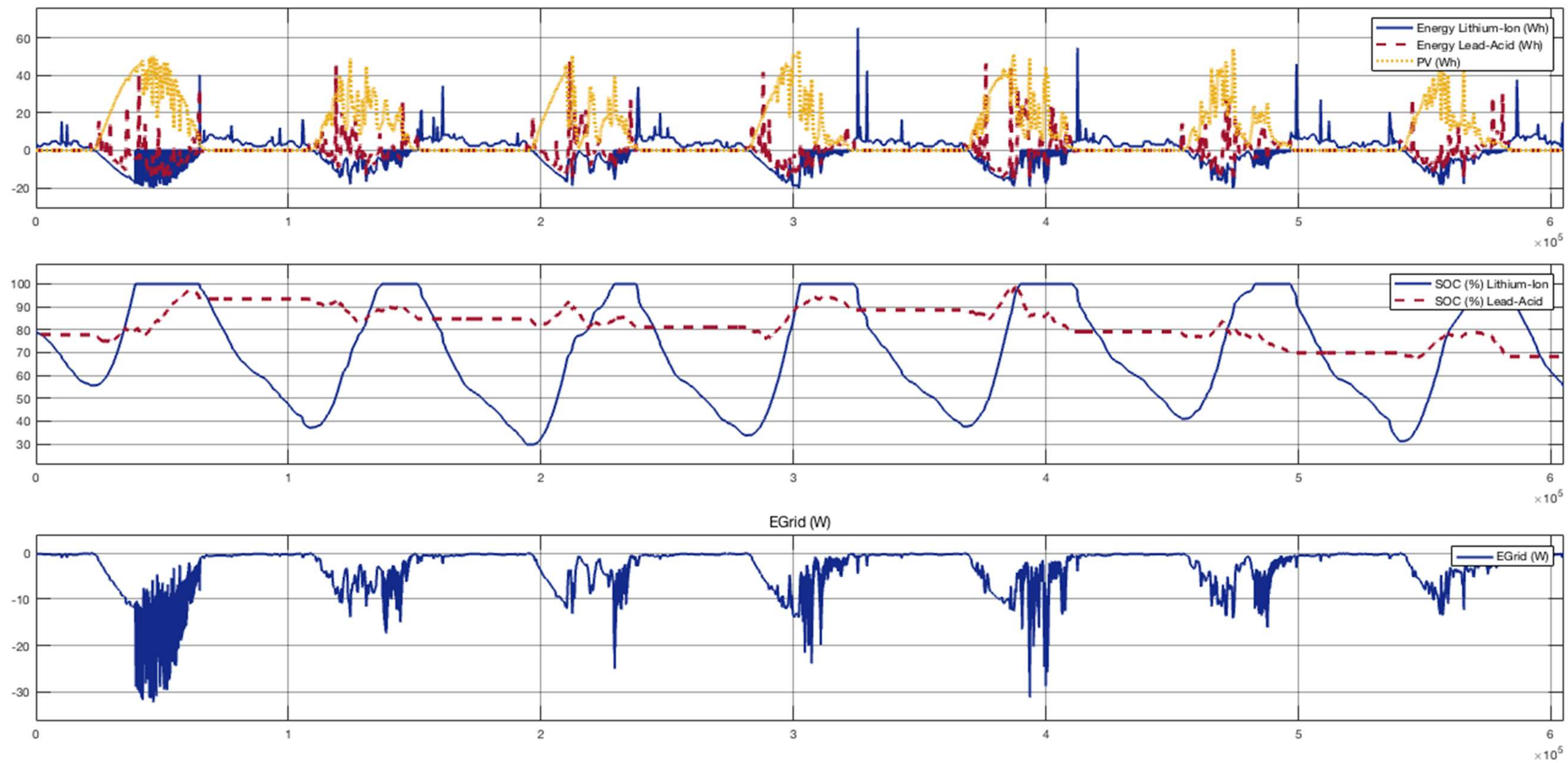

Figure 54. Day: Lead-Acid DoD 80%. Night: Lithium-Ion DoD 80%. Combined Battery Technologies.

From Table 1 can be seen that the Lead-Acid battery technology has an average DoD of 50%. Considering the case when the Lead-Acid technology is used during the night, the DoD drops below this value, then the lifecycle of the battery will be affected. Whereas, the average DoD for a Lithium-Ion battery is about 70%. However, due to technology advances, there are several lithium-ion batteries for residential purpose with a DoD of 80% [51]. For the previous reasons, in addition with a higher injection of energy to the grid and the fact that lead-acid batteries are cheaper, the combination that works better for residential purposes is the one that uses the lead-acid bank during the day (6 AM to 6 PM – bigger bank) and the lithium-ion bank during the night (6:01 PM to 5:59 AM – smaller bank).

Considering a DoD of 50% for the lead-acid battery bank, Figure 55 shows the simulation result of a scenario when the lead-acid battery system is used during the day and the lithium-ion battery system is used during the night with a DoD of 80%. The net-metering is the same than in the case when both technologies had a DoD of 80%, -38.30 kWh/week.

- **Day: Lead-Acid Technology DoD: 50%, Night: Lithium-Ion Technology DoD: 80%. Initial SOC 80%.**

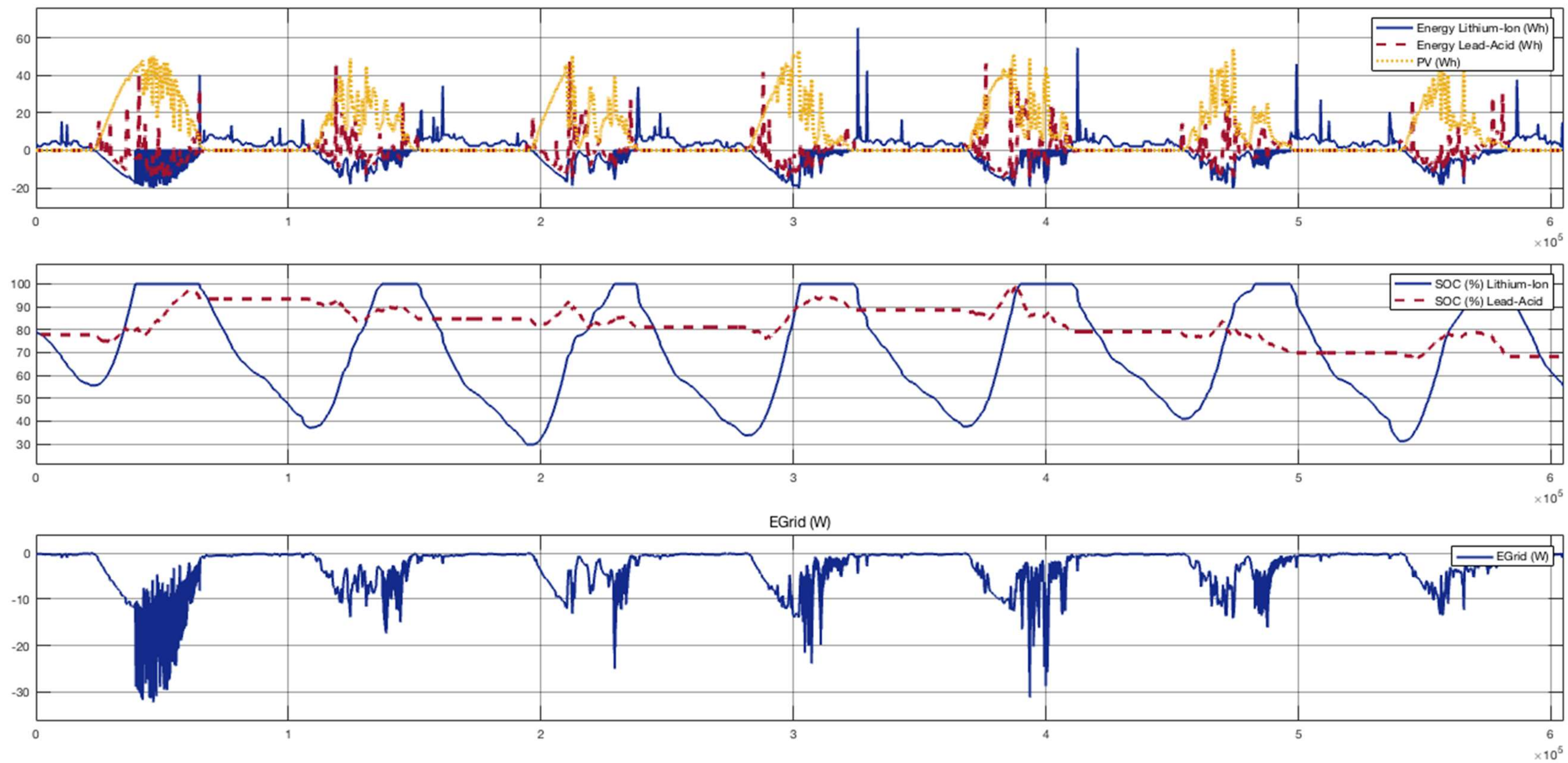

Figure 55. Day: Lead-Acid DoD 50%. Night: Lithium-Ion DoD 80%. Combined Battery Technologies.

7.3 Energy Management System Model

Battery energy storage systems require an energy management system to operate in optimal condition, to maintain the batteries safe and to monitor the full system[52][53]. Also, a well-designed energy management system optimizes in several cases the number of batteries or battery replacements into a system life-cycle [54]. This system, uses the SOC information among with the battery voltage, current and weather data to control the bidirectional power flow between ac grid and dc battery energy storage system [55]. Into better control the DoD for both technologies and to increase their life cycle, we add to the simulation an energy management system model with the logic shown in Table 13. The scenario with all control strategies is shown in Figure 56.

Table 13. Charge Control Logic

Charge Logic			
SOC [%]		**PV Current to Charge**	
Lead-Acid	**Lithium-Ion**	**Lead-Acid**	**Lithium-Ion**
< 70	<50	50%	50%
< 70	>50	75%	25%
> 70	<50	25%	75%
>70	>50	50%	50%

Figure 57 shows the simulation results using this charge control logic and a PV module disconnection at SOC of 100% to avoid over charge. The net-metering obtained is -38.48 kWh/week, an increase of 180Wh/week.

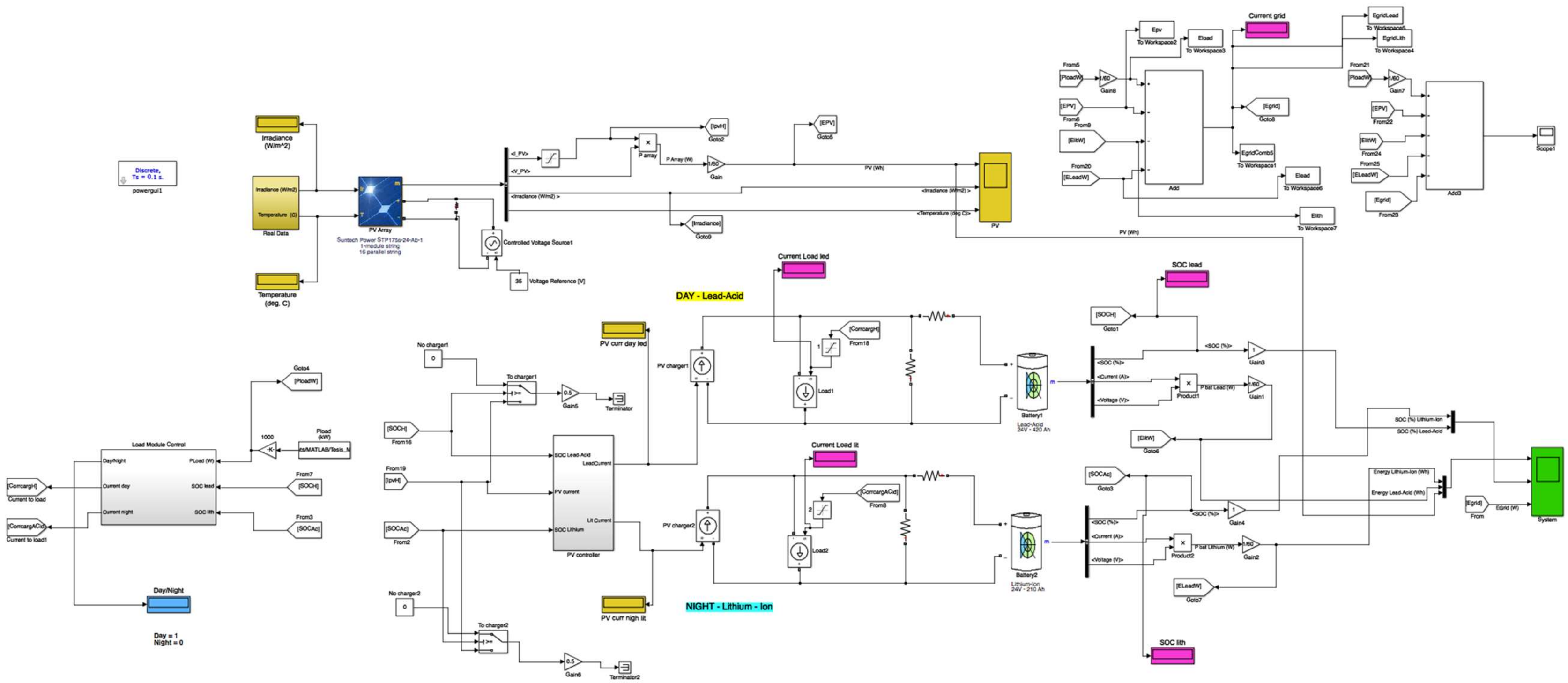

Figure 56. MATLAB/Simulink Scenario Modified with Control Strategies

- **Day: Lead-Acid Technology DoD: 50%, Night: Lithium-Ion Technology DoD: 80%. Initial SOC 80%. Charge Control logic per Table 13.**

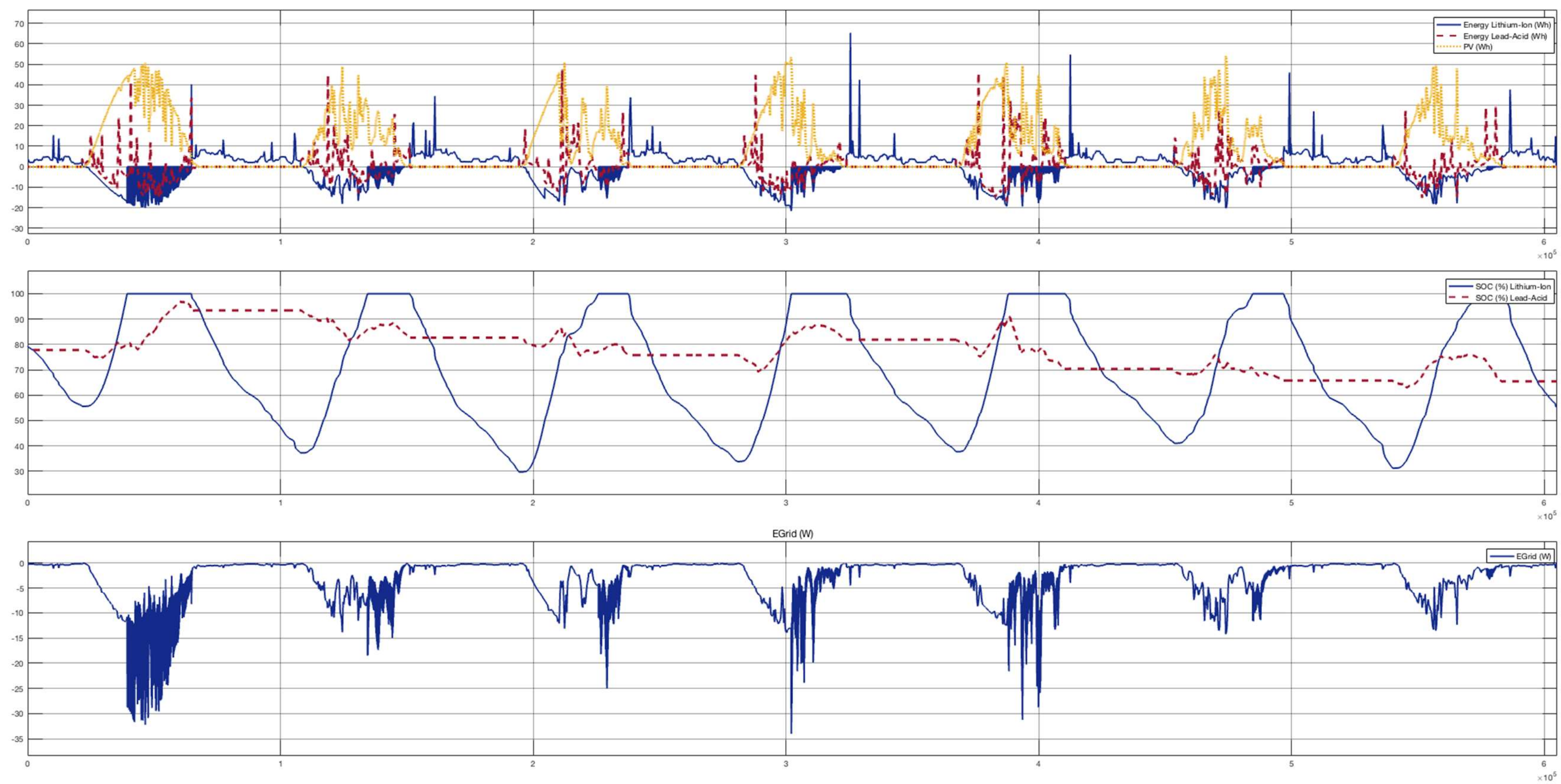

Figure 57. Day: Lead-Acid DoD 50%. Night: Lithium-Ion DoD 80%. Combined Battery Technologies with PV Charge controller

To take advantage of the energy injected to the grid, and to further extend the life of the lithium-ion battery bank, we allow the grid to supply the load at night when the Li-ion battery bank drops to a SOC of 50% (similar to the lead-acid bank). Figure 58 shows the simulation results for this case. With this consideration, the net-metering reduces to 38.05 kWh/week, a reduction of 439 Wh/week.

Although the grid is feeding the load demand during the moments at night when the system disconnects the load (lithium-bank SOC drops to 50%), the net-metering did not suffer a big difference because during the sun hours, the bank's SOC reaches a 100% quicker and then, the system injects more energy to the grid during the day. Table 14 shows the Net-Metering Difference after the additional charge control.

Table 14. Net-Metering Difference After Additional Charge Control

NO Disconnecting the load when Lithium' SOC drops to 50%			**Disconnecting the load when Lithium' SOC drops to 50%**		
Energy Injected to the Grid [kWh/week]	**Energy Consumed from the Grid [kWh/week]**	**Net-Metering [kWh/week]**	**Energy Injected to the Grid [kWh/week]**	**Energy Consumed from the Grid [kWh/week]**	**Net-Metering [kWh/week]**
38. 47	0	38.47	42.57	4.53	38.05

In this case, the load is receiving energy from the grid. It can be seen that it happens during night when the lithium-ion SOC drops to 50%. According to [35], some cities which have TOU charges structures, have the lower cost during the night. With this in mind, a system with these characteristics and in a city with TOU structure would have a significant saving amount. Furthermore, the PV system was designed in order to prevent demand peaks and avoid demand charge.

- **Day: Lead-Acid Technology DoD: 50%, Night: Lithium-Ion Technology DoD: 50%. Initial SOC 80%. With PV Charge Controller.**

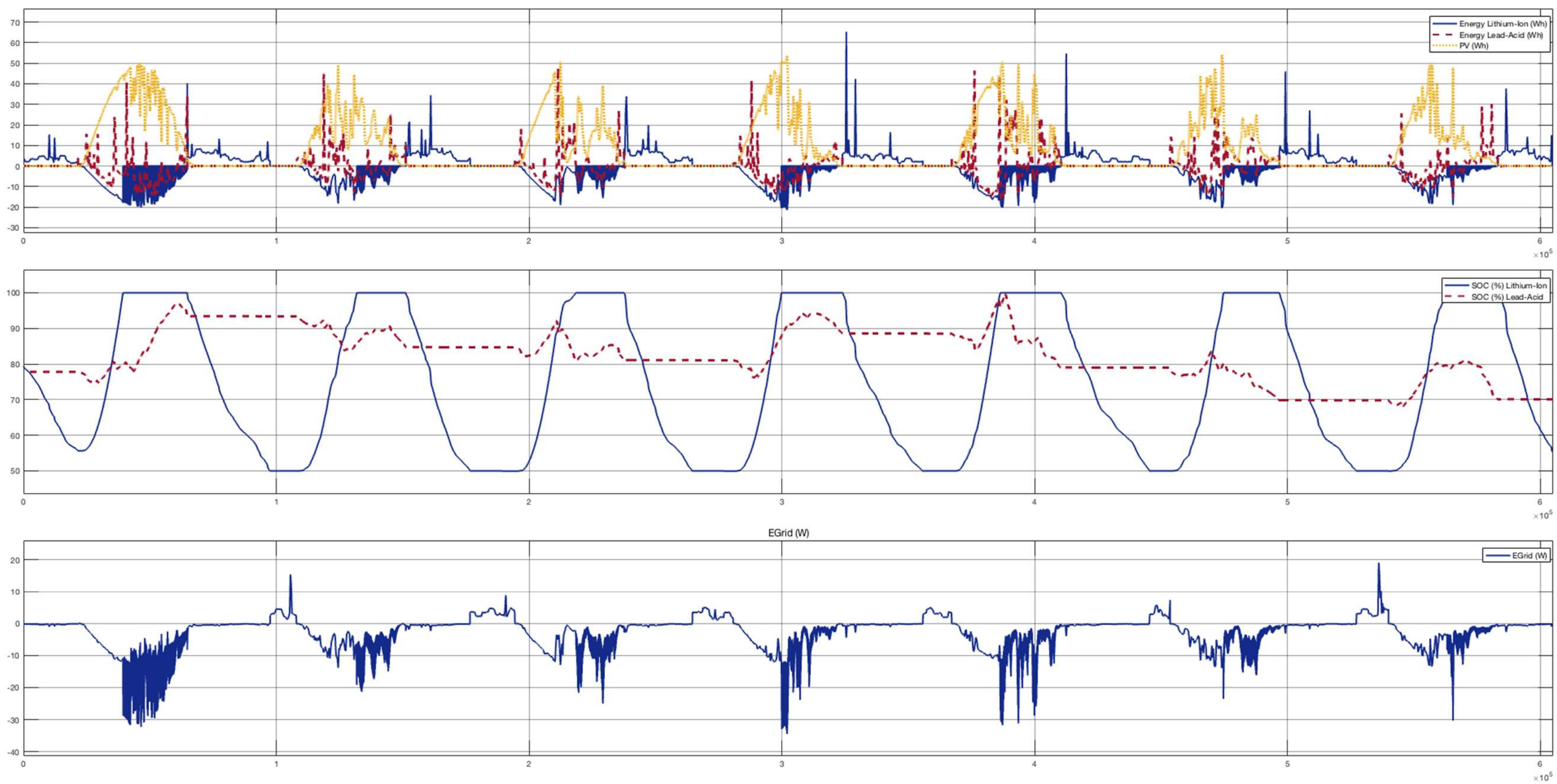

Figure 58. Day: Lead-Acid DoD 50%. Night: Lithium-Ion DoD 50%. Combined Battery Technologies with PV Charge controller

7.4 Cost Calculations

7.4.1 Energy Flow Calculations

To perform an accurate cost comparison between the grid-tied PV system with hybrid battery storage and the PV systems with a single battery technology, it is necessary to measure the flow of energy between all elements of the system. Figure 59 shows the energy flow diagram for the system.

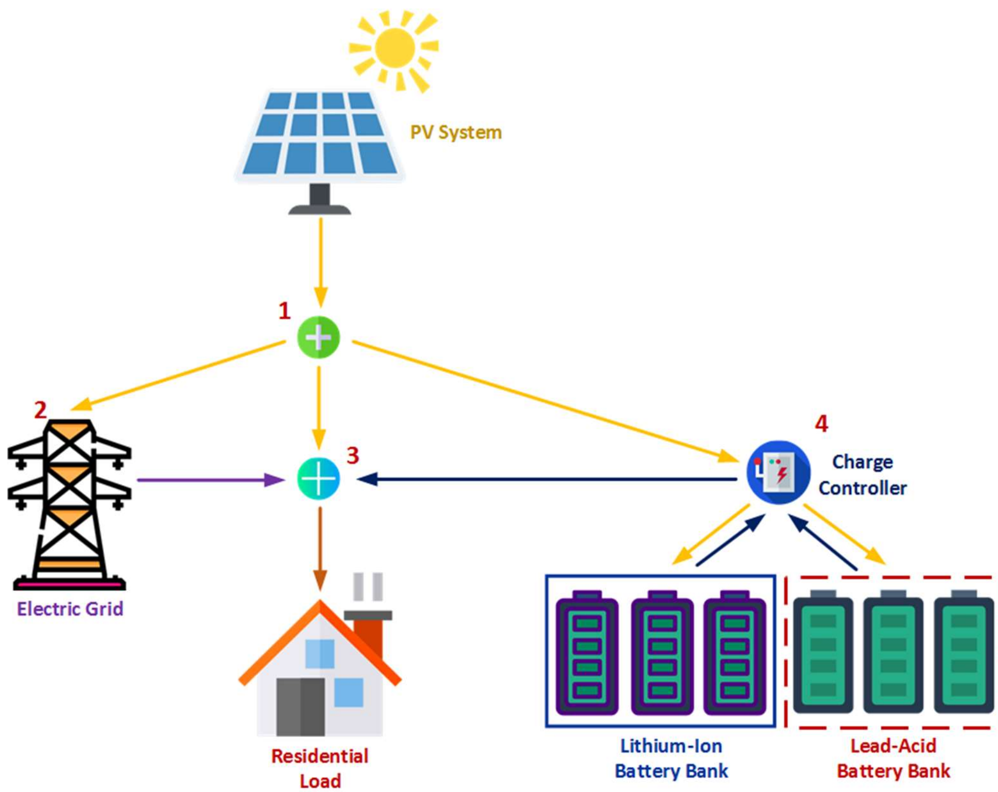

Figure 59. Energy Flow Diagram

Four (4) equations define the energy flow in the system. Each equation corresponds to a numbered node showed in Figure 59. These equations are:

1. The energy produced by the PV panels is equal to the energy into the batteries plus the energy that goes directly from the panels to the load plus the energy that is injected directly from the PV module to the grid.

$$E_{Produced} = E_{Batteries} + E_{Load} + E_{InjectedGrid}$$

2. The energy between the grid and the residence is equal to the energy injected directly from the PV module to the grid minus the energy that the grid supplies to the load.

$$E_{GridNet} = E_{injectedGrid} - E_{GridLoad}$$

3. The energy to the load is equal to the energy that the battery system supplies to the load, the PV module energy that goes to the load and the energy that the grid supplies to the load. That is,

$$E_{Load} = E_{batteries} + E_{PV\_Load} + E_{GridLoad}$$

4. The energy stored in the batteries is equal to the energy from the PV panels minus the energy that the batteries supply to the load. That is,

$$E_{Batteries} = E_{PV\_Batteries} - E_{BatteriesLoad}$$

With the previous equations and the simulation results it is possible to calculate the flow of energy between all elements. Figure 60 shows a diagram with the energy interchange values per week (See *Appendix C*). The cases considered are: lead-acid battery bank with DoD of 50% (Figure 49), lithium-ion battery bank with DoD of 50% (Figure 49), and hybrid battery bank with lead-acid batteries for the day and lithium-ion for the night, both with a DoD of 50% (Figure 58).

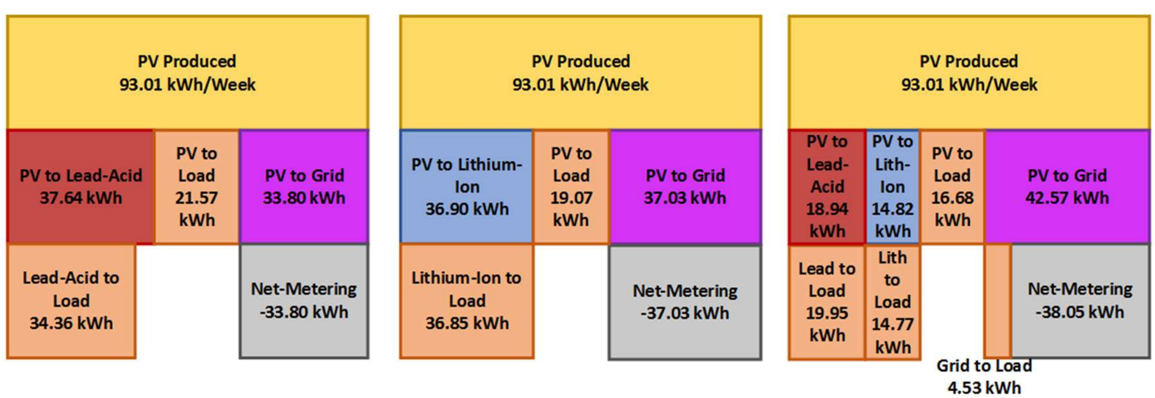

Figure 60. Energy Interchange Diagram Values per Week (from left to right) PV-System with Lead-Acid Battery Bank, PV-System with Lithium-Ion Battery Bank and PV-System with Hybrid Battery Bank

Figure 60 has three (3) diagrams, one for each type of battery storage system. Also, each diagram has three (3) layers. The first layer is the energy produced by the photovoltaic module generator. This energy is independent of the battery bank installed. The second layer represents where the energy from the PV panels is injected, thus the sum of the energy of the second layer corresponds to the PV energy produced in the first layer. Finally, the third layer shows how much electric energy from the batteries goes into the load. It also shows the net-metering energy into the grid.

7.4.2 Life Cycle and Number of Replacements Calculations

Table 15 shows the DoD of each battery bank type per each day of the simulation. The daily SOC information is showed in Figure 49 and Figure 58. With this information, an interval of operation is obtained and showed. It can be seen that all battery banks have a maximum DoD around 30%, except for the lithium-ion batteries inside the hybrid bank, that drops to 50% due to the EMS simulated.

Table 15. Batteries Life Cycle Calculations

Life Cycle Calculations									
Battery System Type		**Depth of Discharge (%)**							
		Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Interval**
Lead-Acid System		31.1	22.5	27.9	24.7	22.9	23.0	26.6	22.5 - 31.1
Lithium-Ion System		29.9	23.4	28.1	25.8	23.9	24.0	27.6	23.4 - 29.9
Hybrid System	**Lead Acid**	25.1	16.1	19.1	23.8	21.0	30.2	32.1	16.1 - 32.1
	Lithium-Ion	44.4	50	50	50	50	50	50	44.38 - 50

With the information from Table 15, and assuming a similar behavior for all weeks during 20 years (useful life), we calculate from Figure 62 and Figure 63 the number of cycles of each bank and the number of replacements necessaries in 20 years.

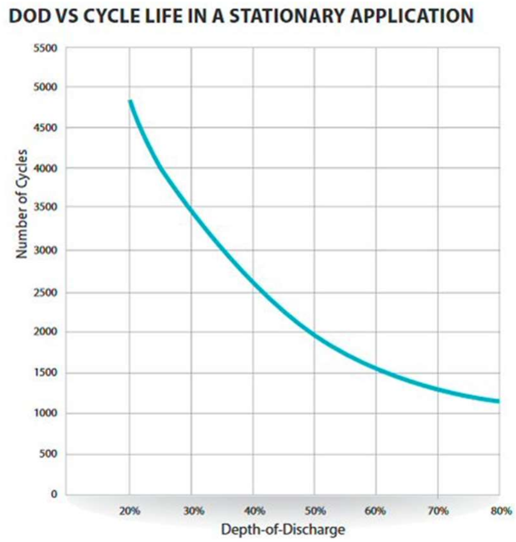

Figure 61. DOD vs Cycle life of Lead-Acid Battery type, obtained from [56]

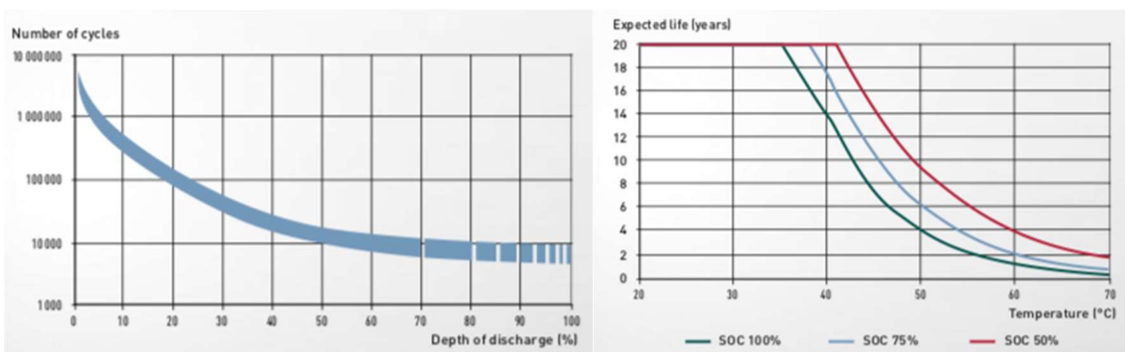

Figure 62. DOD vs Cycle life and Expected life vs SOC of Lithium-Ion Battery type, obtained from [57]

Table 16 shows the number of replacements that each battery bank needs for a useful life of 20 years according to the number of cycles. The replacements are scheduled when the capacity of the battery bank drops to 70%.

Table 16. Batteries 20 Years Replacements Calculations

Replacements Calculations						
Battery System Type		**Cycles Mid-Point**	**70% capacity**	**No. Year Bank**	**Replacement in 20 years**	
Lead-Acid System		3600	2520	6.9	2.9	≅3
Lithium-Ion System		12000	8400	23.0	0.9	≅0
Hybrid System	**Lead Acid**	4300	3010	8.2	2.4	≅3
	Lithium-Ion	11000	7700	21.1	0.9	≅0

7.4.3 Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) measures the lifetime costs divided by energy production. It calculates the present value of the total cost of a system over an assumed lifetime, which allows the comparison of different technologies [58]. To calculate the LCOE of the system with different battery banks, we obtained quotes for the components of the system as October 2018 in Puerto Rico. Reasonable system component costs are shown in Table 17 for the following systems:

- A system with a PV system of 2.8 kW, and lead-acid bank of 15.12 kWh.
- A system with a PV system of 2.8 kW, and lithium-ion bank of 15.12 kWh.
- A system with a PV system of 2.8 kW, lead-acid bank of 10.08 kWh and lithium-ion bank of 5.04 kWh.

Figure 63 shows the materials portion of the initial cost of the previous systems. It can be seen that, for a system with lead-acid battery bank, the portion of the batteries and the PV modules are similar. When lithium-ion batteries are used the percentage cost of batteries increases significantly.

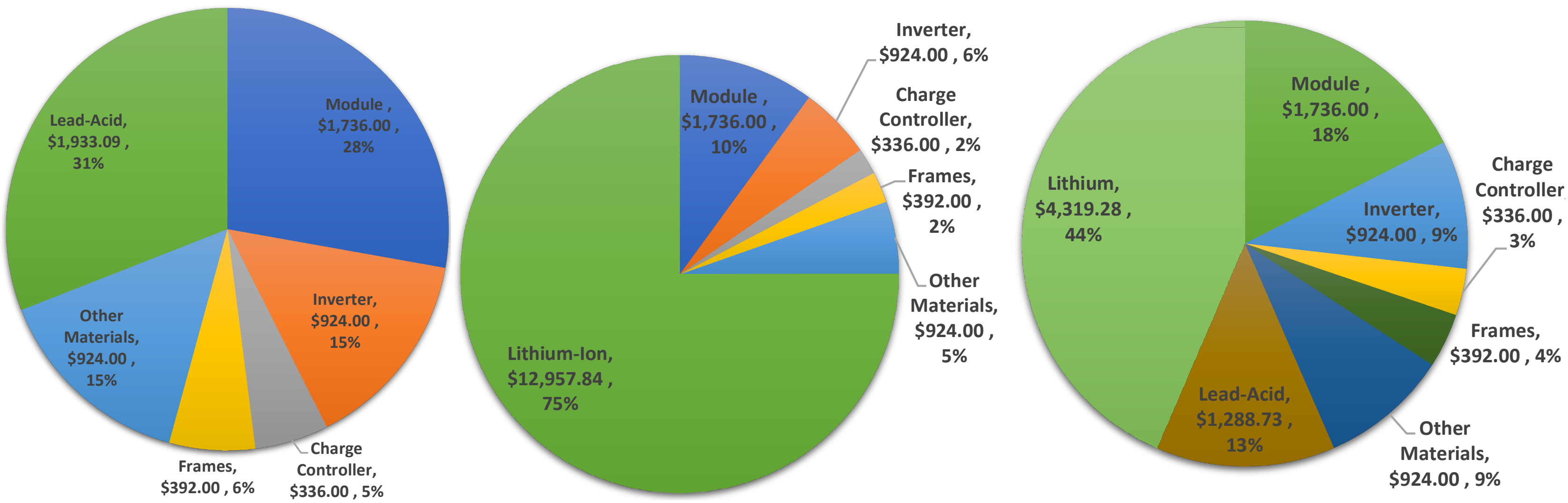

Figure 63. Initial Cost of Materials (from left to right) PV-System with Lead-Acid Battery Bank, PV-System with Lithium-Ion Battery Bank and PV-System with Hybrid Battery Bank

Table 17. Costs Calculations for a Grid-Tied PV-System with Lead-Acid, Lithium-Ion and Hybrid Battery Bank

	Element		Value [$]	Unit
Initial Investment	**PV Modules**		$ 0.62	/W
	Inverter		$ 0.33	/W
	Charge Controller		$ 0.12	/W
	Supporting Frames		$ 0.14	/W
	Other Electrical Materials		$ 0.33	/W
	Battery	**Lead-Acid**	$ 127.85	/kWh
		Lithium-Ion	$ 857.00	/kWh
	Subtotal (Materials)	**Lead-Acid**	$ 6,245.09	
		Lithium-Ion	$ 17,269.84	
		Hybrid	$ 9,920.01	
	Installation (min - max)		$ 1,500.00	$ 2,100.00
	Total with Installation (min - max)	**Lead-Acid**	$ 7,745.09	$ 8,345.09
		Lithium-Ion	$ 18,769.84	$ 19,369.84
		Hybrid	$ 11,420.01	$ 12,020.01
Replacements in 20 years	**Element**		**Value [$]**	**Unit**
	Lead Acid Bank			
	No. Replacements			3
	Cost Replacement 1	$ 124.01	$ 1,875.10	
	Cost Replacement 2	$ 120.29	$ 1,818.85	
	Cost Replacement 3	$ 116.69	$ 1,764.28	
	Subtotal (Materials)		$ 5,458.23	
	Installation UNIT (min - max)		$ 500.00	$ 700.00
	Installation all replacements (min - max)		$ 1,500.00	$ 2,100.00
	Total with Installation (min - max)		$ 6,958.23	$ 7,558.23
	Lithium - Ion Bank			
	No. Replacements			0
	Hybrid Bank			
	Lead Acid			
	No. Replacements			3
	Cost Replacement 1	$ 124.01	$ 1,250.07	
	Cost Replacement 2	$ 120.29	$ 1,212.56	
	Cost Replacement 3	$ 116.69	$ 1,176.19	
	Lithium - Ion			
	No. Replacements			0
	Subtotal (Materials)		$ 3,638.82	
	Installation UNIT (min - max)		$ 500.00	$ 700.00
	Installation all replacements (min - max)		$ 1,500.00	$ 2,100.00
	Total with Installation (min - max)		$ 5,138.82	$ 5,738.82
Total Capital Cost		**Lead-Acid**	$ 14,703.32	$ 15,903.32
		Lithium-Ion	$ 18,769.84	$ 19,369.84
		Hybrid	$ 16,558.83	$ 17,758.83

Considering the weekly energy interchange values from Figure 60 and assuming a similar, average, behavior for all weeks during 20 years, the LCOE of the grid-tied PV system with different battery banks is calculated and shown in Table 20. The procedure for the Lead-Acid System is shown below, for the other two systems the calculations follow the same procedure.

1. The PV produced for one week (Figure 60) is assuming the same for all weeks for 20 years, then,

$$PV_{Produced}\left[{}^{kWh}/_{20\ years}\right]$$
$$= 93.01\,{}^{kWh}/_{week} \times 52\,{}^{weeks}/_{years} \times 20 years$$
$$= 96{,}730\,{}^{kWh}/_{20\ years}$$

2. The PV produced price is calculated considering the panels, inverter, charge controller, frames, other materials and the initial installation price,

Table 18. Costs Calculations for PV Generation Module

Element	Value [$/W]	For 2800 W
Module	$ 0.62	$ 1,736
Inverter	$ 0.33	$ 924
Charge Controller	$ 0.12	$ 336
Frames	$ 0.14	$ 392
Other Materials	$ 0.33	$ 924
Installation	$ 1500	
Total	$ 5,812	

$$PV_{Price}\left[{}^{\$}/_{kWh}\right] = \frac{PV_{totalcost}}{PV_{Produced}} = \frac{\$\ 5{,}812}{96{,}730\ kWh} = \$0.06/kWh$$

3. The energy stored by the lead-acid battery bank for one week (Figure 60) is assuming the same for all weeks for 20 years, then,

$$Energy_{Stored}\left[{}^{kWh}/_{20\ years}\right]$$
$$= 37.64\ {}^{kWh}/_{week} \times 52\ {}^{weeks}/_{years} \times 20 years$$
$$= 39{,}145.6\ {}^{kWh}/_{20\ years}$$

4. The energy round-trip price is calculated considering the initial investment of the battery bank, the replacement costs and the replacements installation prices. We assume a discount of 3% for the battery bank price every time we change it and an installation cost of $500 for each replacement.

Table 19. Costs Calculations for the Lead-Acid Battery Bank

Element	Value [$/kWh]	For 15.12 kWh
Lead-Acid (initial cost)	$ 127.85	$1,933
Cost Replacement 1	$ 124.01	$1,875
Cost Replacement 2	$ 120.29	$1,819
Cost Replacement 3	$ 116.69	$1,764
Installation	$ 500 x 3 times	
Total	$ 8,891.32	

$$Energy\ Stored_{Price}\left[{}^{\$}/_{kWh}\right] = \frac{Energy\ Stored_{totalcost}}{Energy\ Stored} = \frac{\$\ 8{,}891.32}{39{,}145.6\ kWh}$$
$$= \$0.23/kWh$$

5. The net-metering for one week (Figure 60) is assuming the same for all weeks for 20 years, then,

$$Net - Metering\left[{}^{kWh}/_{20\ years}\right]$$
$$= 33.8\ {}^{kWh}/_{week} \times 52\ {}^{weeks}/_{years} \times 20 years$$
$$= 35{,}152\ {}^{kWh}/_{20\ years}$$

6. The kWh cost from the electric Grid, at the time of this study, Puerto Rico is $0.21/kWh [59].

7. The load for one week (Figure 60) is assuming the same for all weeks for 20 years, then,

$$Load\left[{}^{kWh}/_{20\ years}\right] = 55.92\,{}^{kWh}/_{week} \times 52\,{}^{weeks}/_{years} \times 20 years$$
$$= 58{,}156.8\ {}^{kWh}/_{20\ years}$$

8. The LCOE is then,

$$LCOE\left[{}^{\$}/_{kWh}\right]$$
$$= \frac{PV_{totalcost} + Energy\ Stored_{totalcost} - (NetMetering \times \$0.21/kWh)}{Load}$$
$$= \$0.125/kWh$$

Following the same procedure, we obtain the results shown in Table 20.

Table 20. Levelized Cost of Energy Cost (LCOE) Calculations

<table>
<tr><th colspan="8">Cost of Energy Calculations [cent/kWh]</th></tr>
<tr><th colspan="2">Battery System Type</th><th>PV Produced [kWh/20yr]</th><th>PV Price [$/kWh]</th><th>Energy Stored [kWh/20yr]</th><th>Energy Round-Trip Price[$/kWh]</th><th>Net Metering [kWh/20yr]</th><th>LCOE [$/kWh]</th></tr>
<tr><td colspan="2">Lead-Acid System</td><td>96,730.4</td><td>$ 0.06</td><td>39,145.6</td><td>$ 0.23</td><td>(35,152.0)</td><td>$0.125</td></tr>
<tr><td colspan="2">Lithium-Ion System</td><td>96,730.4</td><td>$ 0.06</td><td>38,376.0</td><td>$ 0.34</td><td>(38,511.2)</td><td>$0.182</td></tr>
<tr><td rowspan="2">Hybrid System</td><td>Lead Acid</td><td rowspan="2">96,730.4</td><td rowspan="2">$ 0.06</td><td>20,748.0</td><td>$ 0.31</td><td rowspan="2">(39,572.0)</td><td rowspan="2">$0.140</td></tr>
<tr><td>Lithium-Ion</td><td>15,360.8</td><td>$ 0.28</td></tr>
</table>

Figure 64 shows the LCOE values from Table 20.

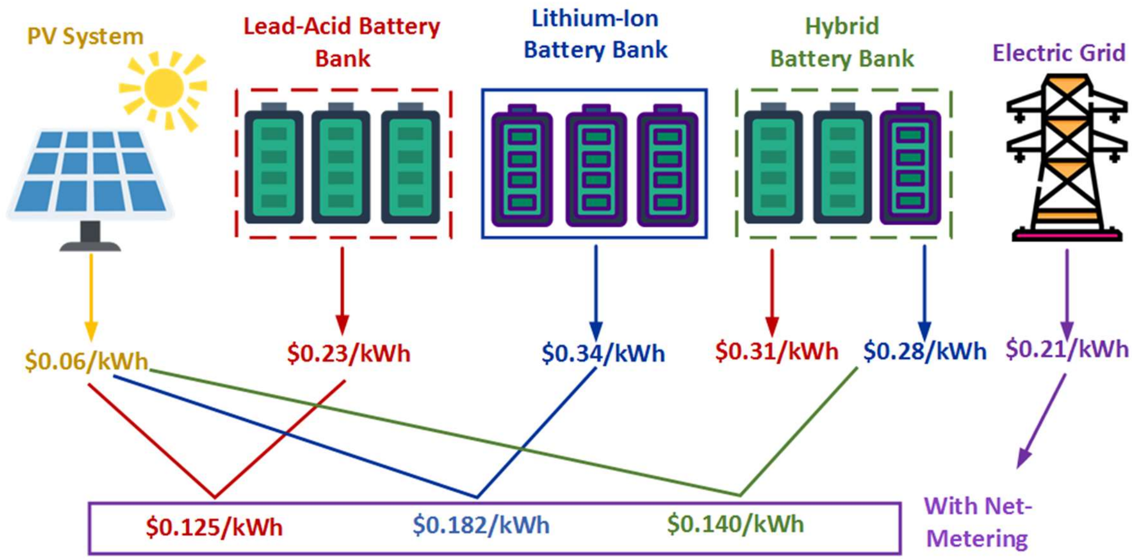

Figure 64. Levelized Cost of Energy Diagram

It is important to compare the cost of produce energy from a PV generator ($0.06/kWh) against the cost of the kWh from the utility in Puerto Rico ($0.21/kWh). With this in mind, it is reasonable to consider an increase of the PV capacity in order to inject more energy to the grid, since for each kWh that is injected that way, the user would have $0.15 of savings. Also, an increase of the PV capacity would mean a lower DoD for the battery bank, that means a larger number of cycles and less replacements could be needed. This savings assume that Energy Commission do not charge for grid services, however, if they decide to allow a charge, it should be less than $0.15/kWh to offer a window for savings.

The systems LCOE shown in Table 21 follows a similar procedure than explained above but without net-metering. It can be seen how in all cases the prize increases due to the lack of net-metering. The higher LCOE is for the system with hybrid battery bank. It led us to conclude that, a hybrid system would be better if the system has net-metering agreement with the utility company, since it has the highest quantity of energy injected to the grid of all ESS considered.

Table 21. Levelized Cost of Energy (LCOE) Calculations without Net-Metering

Cost of Energy Calculations [cent/kWh]						
Battery System Type		**PV Produced [kWh/20yr]**	**PV Produced Price**	**Energy Stored [kWh/20yr]**	**Energy Stored Price**	**LCOE $/kWh**
Lead-Acid System		96,730.4	$ 0.06	39,145.6	$ 0.23	$0.253
Lithium-Ion System		96,730.4	$ 0.06	38,376.0	$ 0.34	$0.323
Hybrid System	**Lead Acid**	96,730.4	$ 0.06	20,748.0	$ 0.31	$0.285
	Lithium-Ion			15,360.8	$ 0.28	

Comparing the results shown in Table 20 and Table 21, it can be seen that the system LCOE in all cases was reduced due to the net-metering agreement with the utility. Due to that reduction, the LCOE with net-metering agreement in all cases is lower than the $/kWh from the utility in Puerto Rico ($0.21/kWh) [59], however, if there is no net-metering agreement, the LCOE in all cases is higher than the $/kWh from the utility.

To study the net-metering value into the hybrid system, a simulation with the same system configuration but with double load demand is carried out and shown in Figure 65. Table 22 shows the LCOE for the system with double load demand with net-metering.

Table 22. Levelized Energy Cost (LEC) Calculations without Net-Metering

Cost of Energy Calculations [cent/kWh]							
Battery System Type		**PV Produced [kWh/20yr]**	**PV Produced Price**	**Energy Stored [kWh/20yr]**	**Energy Stored Price**	**Net Metering [kWh/20yr]**	**LCOE Net-Metering $/kWh**
Hybrid System	**Lead Acid**	96,730.4	$ 0.06	17,960.8	$ 0.36	17,264.0	0.174
	Lithium-Ion			20,332.0	$ 0.21		

Figure 65 shows how the SOC for both battery banks drops quickly to 50% making necessary for the grid to attend the load demand. With this in mind, although the system has a lower LCOE than the utility price, the system cannot disconnect from the grid.

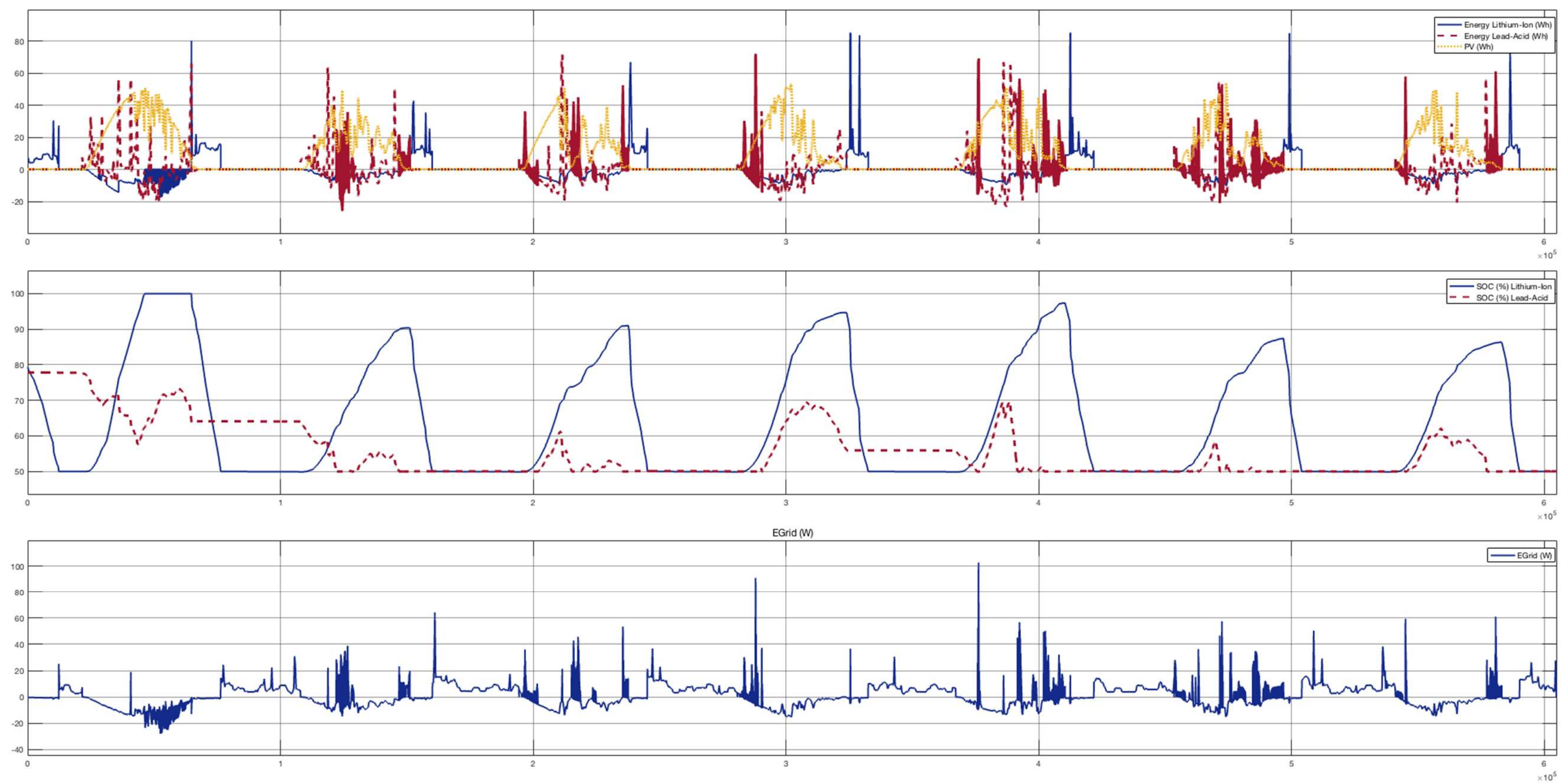

Figure 65. Day: Lead-Acid DoD 50%. Night: Lithium-Ion DoD 50%. Combined Battery Technologies with PV Charge controller and double Load Demand

7.5 Hybrid System Calculation

In this section, a general process to calculate a hybrid system to attend residential customer services is described below:

1. Collect real data of load and irradiance from the customer residence. Calculate the daily energy consumption and the average daily power demand during a considerable period of time.
2. Calculate the energy consumption during the day (6 AM to 6 PM) and during the night (6:01 PM to 5:59 AM) for the period of time measured.
3. Taking into account the number of days of autonomy desired, calculate a lead-acid battery bank to meet the demand during the day. Similarly, calculate a lithium-ion battery bank to meet the demand during the night.
4. Set the parameters for the EMS and the charge controller.

Chapter 8

CONCLUSIONS, CONTRIBUTIONS AND FUTURE WORK

8.1 Conclusions

We have studied a combination of possible storage solutions, using the leading battery technologies, to provide services to residential electric energy customers. To achieve this, first the main battery technologies were identified using the software ES-SELECT. The battery technologies selected were Lead-Acid and Lithium-Ion. Then, a scenario in MATLAB/Simulink of a grid-tied PV system with battery bank was modeled using measured load data and measured solar radiation. Two (2) cases of study were completed to study the performance of the chosen battery technologies. The lead-acid battery bank discharged slower than the lithium-ion battery bank. Also, it has a higher exponential voltage drop zone (less efficiency) than the lithium-ion. The higher exponential voltage drop increases (gets worse) when the battery is operated at a lower state of charge (SOC). Moreover, the lead-acid battery bank performance deteriorates with bad weather condition, and when it is used under a net-metering agreement the system injects less energy to the grid than the lithium-ion.

Thru this comparison we present a list of desired characteristics for a new battery technology. After that, different combinations of the two (2) technologies, lead-acid and lithium-ion, were simulated to find out the best combination based on performance behavior. It was found that a system with a lead-acid bank during the day, with a smaller lithium-ion battery bank during the night and with a well-designed energy management system will inject more energy to the grid and have better performance in terms of SOC.

In addition, a cost analysis was performed with the results obtained. First, the energy flow between all elements of the system was measured. Then, using Depth of Discharge results from the simulations we calculated the life of the battery banks to determine the required replacements over 20 years. Using current costs, from actual quotes, for the system materials we calculated the cost of the system with battery replacements over 20 years.

If there are no charges for net metering an increase on the system PV capacity results in lower price per kWh. Part of this decrease in cost per kWh comes from a lower DoD for the battery bank, that means a larger number of cycles and less replacements could be needed.

The standalone cost of energy for the system with lead-acid battery bank, which is the lower cost of the three system configurations, is 0.253 $/kWh which is 19.2% higher than buying electricity from the grid at its current price of 0.2121 $/kWh.

Finally, through this project it is concluded that the continuous evolution of storage technologies makes it difficult to standardize design processes and cost analysis. Significant differences in performance and costs were found among the sources consulted. These differences were mainly between different research entities and between years of studies.

8.2 Contributions

The main contribution of this work was the finding of a combination of battery technologies that best fulfills the requirements of ESS customers. Also, a main contribution of this work was the comparison between the hybrid battery storage system found and the conventional battery systems with a single technology for residential use. Other contributions of this work include:

1. An EMS model for the combination of battery technologies.
2. A scenario in MATLAB/Simulink of a grid-tied PV system with batteries which model a PV system with real input data, different battery technologies (to use with a single technology or combined technologies) and real load data, as well as, executes the control strategies defined in the EMS model.
3. A MATLAB document which calculates the energy net-metering between the grid-tied PV system with batteries and the grid.

4. A cost calculation of the grid-tied PV system with lead-acid, lithium-ion and hybrid battery bank.
5. A cost comparison between the grid-tied PV system with lead-acid, lithium-ion and hybrid battery bank.
6. Two papers accepted in MEDPOWER 2018. Dubrovnik (Cavtat), Croatia. November 12 to November 15, 2018.

8.3 Future Work

To expand and improve the current state of the presented work, the following future activities were identified:

1. To perform a hardware in the loop simulation including real batteries.
2. Calculate the distribution of PV energy into the battery banks of a hybrid battery system based on SOC (EMS).
3. Analyze the impedance effect when combining both battery technologies into a hybrid system. Design a charge controller which mitigate possible transient effects.

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Appendices

Appendix A: ES-Select Database Configurations

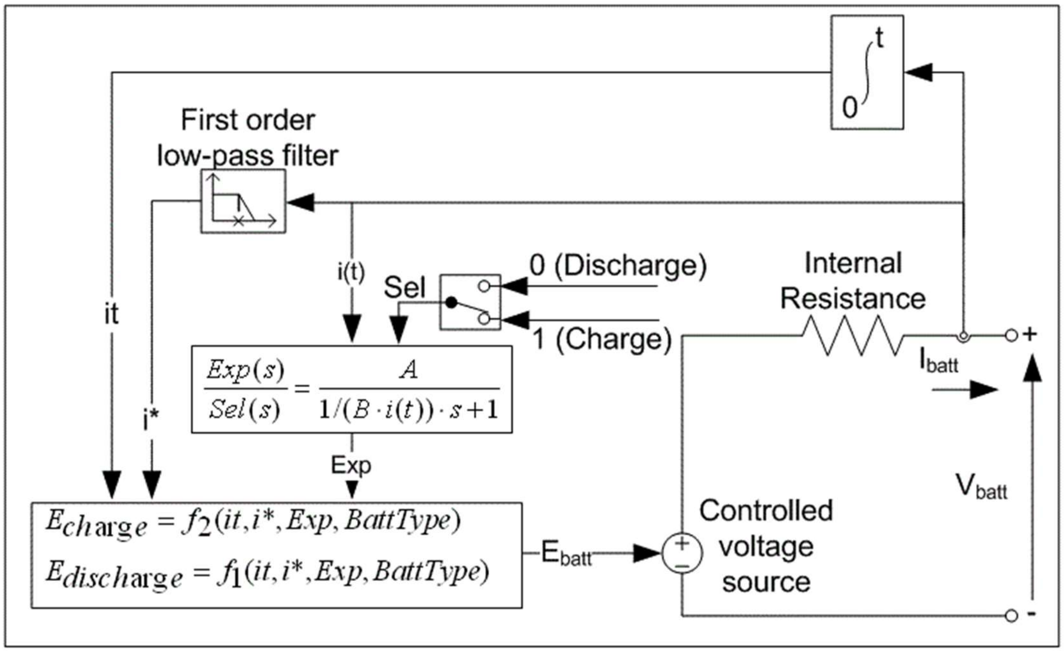
A.1 Applications' Characteristics

	Application Name	Min. Required Discharge Duration @ rated power (hours) LO ALL CELLS EDITABLE min=0.0005 MAX=12	Min. Required Discharge Duration @ rated power (hours) HI ALL CELLS EDITABLE min=0.0005 MAX=12	Annual Benefit ($/kW) LO ALL CELLS EDITABLE min=1 MAX=1000	Annual Benefit ($/kW) HI ALL CELLS EDITABLE min=1 MAX=1000	Total 10-Year Market Potential (Billion USD) LO ALL CELLS EDITABLE min=1 MAX=10000	Total 10-Year Market Potential (Billion USD) HI ALL CELLS EDITABLE min=1 MAX=10000	Minimum Required response time ALL CELLS EDITABLE	Minimum Required Deep Cycles (80% dod) (cycles/year) ALL CELLS EDITABLE min=10 MAX=10000	Minimum Required Shallow Cycles (10% dod) (cycles/year) ALL CELLS EDITABLE min=10 MAX=10000	Requires Electric output? ("x" = yes) ALL CELLS EDITABLE
1	Energy Time Shift (Arbitrage)	3	7	57	100	8.5000	11	hrs	190		
2	Supply Capacity	4	6	51	101	7.6100	12.1000	hrs	100		
3	Load Following	2	4	86	143	22	28.2000	min		1900	
4	Area Regulation	0.3000	0.5000	112	287	2.7000	3.9200	sec	NaN	4000	
5	Fast Regulation	0.3000	0.5000	168	560	0.6800	1.9600	sec	NaN	4000	
6	Supply Spinning Reserve	0.3000	1	12	61	0.5200	2.1000	sec	100		
7	Voltage Support	0.3000	1	55	60	3	4.6800	sec			x
8	Transmission Support	6.0000e...	0.0014	26	29	2.4000	2.5000	sec		1000	
9	Transmission Congestion Relief	3	5	5	20	2.1400	4.1900	min	100		
10	Dist. Upgrade Deferral (top 10%)	3	6	108	320	6.1800	9.4300	min	100		
11	Trans. Upgrade Deferral (top 10%)	3	6	153	540	15.5000	20.3000	min	100		
12	Retail TOU Energy Charges	4	6	166	184	38	54	min	190		
13	Retail Demand Charges	5	8	79	87	10.6000	29	min	190		
14	Service Reliability (Utility Backup)	0.5000	2	80	330	7.3100	9.0100	sec	100		x
15	Service Reliability (Customer Backup)	0.5000	2	100	380	7	8.2000	sec	100		x
16	Power Quality (Utility)	0.0030	0.0200	50	150	4	8.3000	ms		500	x
17	Power Quality (Customer)	0.0030	0.0200	63	170	6	9	ms		500	x
18	Wind Energy Time Shift (Arbitrage)	3	6	14	80	7.8000	13.4000	hrs	190		
19	Solar Energy Time Shift (Arbitrage)	3	5	33	56	8.9000	13.1000	hrs	190		
20	Renewable Capacity Firming	2	3	101	131	24.8000	26.8000	sec	190		x
21	Wind Energy Smoothing	0.3000	0.5000	71	143	1.1500	2.3000	sec		20000	x
22	Solar Energy Smoothing	0.3000	0.5000	71	143	0.1000	0.2000	sec		20000	x
23	Black Start	1.5000	2	4.6000	8.9000	0.0100	0.0120	min	2		x

A.2 Battery Technologies Characteristics

	Storage Technology	Abbreviations	Discharge Duration (hours) LO	Discharge Duration (hours) HI	Specific Energy (kWh/ton-metric) LO	Specific Energy (kWh/ton-metric) HI	Energy Density (kWh/m^3) LO	Energy Density (kWh/m^3) HI	Round Trip AC Energy Efficiency at Rated Power and 80% DoD LO	Round Trip AC Energy Efficiency at Rated Power and 80% DoD HI	Response time to full power	Footprint (m^2/MWh) LO	Footprint (m^2/MWh) HI
1	Lithium-ion - High Power	LIB-p	0.2500	1	60	90	60	90	0.8400	0.9100	ms	40	60
2	Lithium Ion - High Energy	LIB-e	1	4	80	120	90	130	0.8500	0.9200	ms	18	26
3	Ni batt. (NiCd, NiZn, NiMH)	Ni-batt	0.3000	3	50	90	40	210	0.7000	0.8000	ms	26	93
4	Advanced Lead Acid	LA-adv	2	5	18	30	30	70	0.8000	0.9000	ms	33	45
5	Valve Regulated Lead Acid	VRLA	2	4	18	25	30	60	0.6800	0.7800	ms	25	35
6	Vanadium Redox Battery	VRFB	3	5	8	11	15	21	0.5800	0.6800	ms	37	55
7	Adv.Vanadium Red. Flow Batt.	A-VRFB	3	6	17	21	25	30	0.6500	0.7000	ms	17	33
8	Zinc Bromide	ZnBr	2	4	30	50	30	45	0.6200	0.7000	ms	9	19
9	Sodium Sulfur	NaS	6	7	80	140	100	170	0.7300	0.8000	ms	4	5
10	Sodium Nickel Chloride	NaNiCl	2	4	100	150	170	190	0.8200	0.8700	ms	8	11
11	Thermal Storage (Cold)	Ice	4	7	10	20	10	20	0.9000	1	sec	108	135
12	Thermal Storage (Hot)	Heat	4	9	150	160	110	130	0.9100	0.9800	sec	11	13
13	Zinc- Air Battery	ZnAir	5	6	130	170	300	500	0.6500	0.7700	ms	5	6
14	Flywheel	FlyWl	0.0300	1	5	12	5	15	0.8400	0.8600	ms	530	670
15	Double Layer Capacitors	DL-CAP	0.0800	1.2000	2.3000	16	2.1000	15	0.9200	0.9700	ms	100	400
16	Hybrid LA & DL-CAP	Hybrid	0.5000	5	16	28	32	65	0.8200	0.8700	ms	65	150
17	Compressed-Air ES, cavern	CAES-c	8	10	NaN	NaN	NaN	NaN	0.6000	0.7000	min	NaN	NaN
18	Compressed-Air ES, small	CAES-s	3	5	NaN	NaN	NaN	NaN	0.6000	0.7000	sec	NaN	NaN
19	Pumped Hydro	P-Hydro	8	10	NaN	NaN	NaN	NaN	0.7000	0.8000	min	NaN	NaN

Appendix B: SIMULINK Battery Equivalent Circuit Model



For lead-acid battery type, the model uses these equations:

- Discharge Model $(i^* > 0)$

$$f_1(it, i*, i, Exp) = E_0 - K \cdot \frac{Q}{Q-it} \cdot i * -K \cdot \frac{Q}{Q-it} \cdot it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)} \cdot 0\right) \quad (6)$$

- Charge Model $(i^* < 0)$

$$f_2(it, i*, i, Exp) = E_0 - K \cdot \frac{Q}{it+0.1 \cdot Q} \cdot i * -K \cdot \frac{Q}{Q-it} \cdot it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s}\right) \quad (7)$$

For lithium-ion battery type, the model uses these equations:

- Discharge Model $(i^* > 0)$

$$f_1(it, i*, i) = E_0 - K \cdot \frac{Q}{Q-it} \cdot i * -K \cdot \frac{Q}{Q-it} \cdot it + A \cdot exp(-B \cdot it) \quad (8)$$

- Charge Model $(i^* < 0)$

$$f_2(it, i*, i) = E_0 - K \cdot \frac{Q}{it+0.1 \cdot Q} \cdot i * -K \cdot \frac{Q}{Q-it} \cdot it + A \cdot exp(-B \cdot it) \quad (9)$$

In the equations:

- E_{Batt} is nonlinear voltage, in V.
- E_0 is constant voltage, in V.
- *Exp(s)* is exponential zone dynamics, in V.
- *Sel(s)* represents the battery mode. *Sel(s)=0* during battery discharge, *Sel(s)=1* during battery charging.
- *K* is polarization constant, in V/Ah, or polarization resistance, in Ohms.
- *i** is low frequency current dynamics, in A.
- *i* is battery current, in A.
- *it* is extracted capacity, in Ah.
- *Q* is maximum battery capacity, in Ah.
- *A* is exponential voltage, in V.
- *B* is exponential capacity, in Ah^{-1}.

Appendix C: Energy Interchange Values per Week [kWh/week]

Energy Interchange Values per Week			
Battery Bank Type			**Energy [kWh/week]**
Lead-Acid Battery Bank. DoD: 50% Initial SOC 80%.	**1.** $\boldsymbol{E\_PV_{Produced}}$		93.01
	1.1 $E\_PV_{Batteries}$	$EPV_{Lithium}$	0
		EPV_{Lead}	-37.64
	1.2 E_PV_{Load}		21.57
	1.3 $E\_PV_{InjectedGrid}$		-33.80
	2. $\boldsymbol{E_{BatterytoLoad}}$	$E_{Lithium}$	0
		E_{Lead}	34.36
	3. $\boldsymbol{E_{Grid-Load}}$		0
	4. $\boldsymbol{E_{Net-Metering}}$		-33.80
Lithium-Ion Battery Bank. DoD: 50% Initial SOC 80%.	**1.** $\boldsymbol{E\_PV_{Produced}}$		93.01
	1.1 $E\_PV_{Batteries}$	$EPV_{Lithium}$	-36.90
		EPV_{Lead}	0
	1.2 E_PV_{Load}		19.07
	1.3 $E\_PV_{InjectedGrid}$		-37.03
	2. $\boldsymbol{E_{BatterytoLoad}}$	$E_{Lithium}$	36.85
		E_{Lead}	0
	3. $\boldsymbol{E_{Grid-Load}}$		0
	4. $\boldsymbol{E_{Net-Metering}}$		-37.03
Hybrid Battery Bank with PV Charge Controller. Day: Lead-Acid Technology DoD: 50% Night: Lithium-Ion Technology DoD: 50%. Initial SOC 80%.	**1.** $\boldsymbol{E\_PV_{Produced}}$		93.01
	1.1 $E\_PV_{Batteries}$	$EPV_{Lithium}$	-14.82
		EPV_{Lead}	-18.94
	1.2 E_PV_{Load}		16.68
	1.3 $E\_PV_{InjectedGrid}$		-42.57
	2. $\boldsymbol{E_{BatterytoLoad}}$	$E_{Lithium}$	14.77
		E_{Lead}	19.95
	3. $\boldsymbol{E_{Grid-Load}}$		4.53
	4. $\boldsymbol{E_{Net-Metering}}$		-38.05