Study of a Shared Self-Consumption System Applied to Neighborhood Communities in Urban Environments

By

Nour Moussa

Submitted to the Department of Electrical Engineering, Electronics, Computers and Systems
In partial fulfillment of the requirements for the degree of
Erasmus Mundus Joint Master Degree in Sustainable Transportation and Electrical Power Systems
at the
UNIVERSIDAD DE OVIEDO
August 2019

Certified by……………………………………………………………………...
Pablo Arboleya
Associate Professor
Thesis Supervisor

Certified by……………..……………………………………………………….
Javier Izquierdo
Head of emobility EDP España
Thesis Supervisor

Study of a Shared Self-Consumption System Applied to Neighborhood Communities in Urban Environments

By

Nour Moussa

Submitted to the Department of Electrical Engineering, Electronics, Computers and Systems
On August 16, 2019, in partial fulfillment of the requirements for the degree of
Erasmus Mundus Joint Master Degree in Sustainable Transportation and Electrical Power Systems

Abstract

This thesis is a proposal for a coherent model for the implementation of shared self-consumption in neighborhood communities, taking into account both the technical and the economic aspects. As the network's capacity increases, distributed generation gains more popularity due to their added value on both financial and environmental aspects in the society. New systems are proposed frequently in order to adopt more renewable energy resources generation into the grid, this allows citizens to participate in whichever system, according to their preferences. A shared solar system is proposed in this thesis, while studying all factors that might affect the desired output and calculating optimum values for the variables to reach the most economic setup. The study is made by running power flows that are loaded from the ADRES-CONCEPT data matrix. First, a literature review about self-consumption, its impact and its system's components is discussed. Followed by a description of the procedures taken in order to build the proposed model. In chapter four, different tests will be carried out on the proposed system as well as a comparison between different configurations. Last but not least, the thesis will end with proposals for future work to be done while adopting the studied model and enhancing it for usage on a larger scale. In addition to, collaboration with new technologies, such as peer-to-peer energy trading.

Thesis Supervisor: Pablo Arboleya
Title: Associate Professor

Thesis Supervisor: Javier Izquierdo
Title: Head of emobility EDP España

Acknowledgements

I am greatly thankful to Prof. Pablo Arboleya's guidance and support throughout, not only this thesis, but my whole Master studies journey. I would also like to thank Javier Izquierdo and EDP Spain for providing me with such an opportunity to be able to actually put my theoretical knowledge into action. Furthermore, Dr. Islam Elsayed and Dr. Bassam Mohamed, thank you for your great help in this thesis and your outstanding abilities in clarifying all my doubts. Not to mention, all the professors whom I gained my whole knowledge from. Last but not least, the lady behind the scenes, Susana Menéndez Bustillo, who never got tired of all our consistent administrative questions. Most importantly, my family, I would have been nothing without your existence in my life and no words would ever express my gratitude.

On another scale, I would like to thank the Erasmus Mundus Joint Master Degree program for the grants that made me able to perform my studies in three different countries. I would like to end with, the fabulous city Gijón, my home away from home.

Table of Contents

List of Figures

List of Tables

Chapter One

1. Introduction

1.1 Background

The traditional mode of centralized supply has various disadvantages, like its poor technological performance, low efficiency and undesirable environmental impact. This is why the world now is turning towards distributed generation (DG) due to its ability to be more sustainable than conventional electricity generation in means of a flexible demand response and the allowing high installation of renewable generation.

But what is distributed generation exactly? It is electric power generation, within a distributed network, on the demand side of the customer network. Distributed generation refers to any small electric power system independent of the traditional utility grid. It is also known as small scale technologies to produce electricity close to the end users of power. It can be found differently depending on the application. There are two levels of distributed generation technologies; the first one is at local level which includes, often, on-site renewable energy technologies such as wind turbines, geothermal energy production, solar systems (PV & thermal) and some hydro-thermal plants. The second level is the end point level such as conventional fossil fuel generators as a kind of back-up. However, the generation part of the system cannot standalone without energy storage.

Distributed generation tend to have an added value to the grid and various advantages in which it allows it to be commonly used. To begin with, it resolves local supply problems due to its ability to supply energy to remote regions. It can also be used as a backup in high reliability power applications and as a power supply during peak demands for peak shaving purposes. One of the added values to the grid is making it of a better quality in terms of voltage regulation, less power losses and power factor improvement. Last but not least, distributed generation presents the user with economic benefits.

Moreover, some technologies accompanied with the distributed generation are, first, its grid interconnection technologies and control & power quality monitoring. Secondly, as discussed previously, distributed generation are mostly attached to energy storage devices, as a result, it makes the connected load more controllable.

1.2 Motivation

Enhancing grid security and stability is one of the most important features of distributed generation. Unfortunately, many areas worldwide have encountered a blackout and as the network is continuously growing, this requires more security measures to be taken to ensure stable performance. This also improves reliability and continuity of power supply to critical loads in misfortunate events. Not to mention that, distributed generation is environmentally friendly due to the ease of using renewable energy sources.

On the other hand, there are a few drawbacks of such a system, such as that it is hard to control and the power generated fluctuates randomly. Furthermore, high penetration is not recommended regarding grid stability as well as the fact of changeability and uncontrollability of the output power. Therefore, the significance of associating an energy storage system leads to more optimum management.

In such manner, distributed generation based on rooftop photovoltaic systems with battery storage is a promising alternative energy generation technology to reduce global greenhouse gas emissions. Nevertheless, improvement of the distributed energy technologies sector for further enhancing of the advantages of PV systems must include; the use of renewable energy sources more efficiently, minimizing energy supply cost and maximizing grid energy export profit.

1.3 Objectives

The concerns above lead to the objective of the presented thesis; studying of a shared self-consumption system applied to neighborhood communities in urban environments. The present project aims to carry out a detailed study of the possibilities in terms of possible configurations and measurement systems that would allow shared self-consumption at building level. Detailed studies are to be carried out through Matlab Simulink, of the distribution system of a building in which, in addition to the conventional loads, a common photovoltaic generation system will be installed. A shared battery model will also be implemented. All these elements will be accommodated in the distribution network of the building and it will be studied which can be the optimal configuration.

The final objective of the project is to propose a coherent model for the implementation of shared self-consumption in neighborhood communities, taking into account both the technical and the economic aspects.

1.4 Thesis Structure

Towards the previously mentioned objectives, the thesis work was developed, and the structure is organized as follows:

Chapter1: Introduction

This present chapter introduces the motivation for the work carried out in this thesis.

Chapter 2: State of Art

This chapter reviews the research literature for the self-consumption and its new regulations. As well as a discussion of photovoltaic (PV), batteries and electric vehicles' history and evolution.

Chapter 3: Description of Model

This chapter and the next ones describe the developed work in the thesis. In this chapter, a step by step description of how the whole model was built will be reviewed.

Chapter 4: Results and Tests

This chapter compares different modules' results as well as different tests to ensure the successfulness of the model and that it is built up to the required standards.

Chapter 5: Conclusions and Outlook

This chapter indicates the conclusions reached out of the thesis work, and outlooks a future path for research in this field.

Chapter Two

2. State of Art

The chapter is structured as follows.

First, the importance of renewable energy generation, especially from solar energy, will be discussed and the different methods of which the consumer can access the power generated.

Secondly, not all countries adopt the penetration of renewable energy resources in the same way. So in this chapter a few regulations from different countries will be analyzed.

The impact of such penetration is considered third.

Lastly, the main components of the model, which are the PVs, batteries and electric vehicles, have different types and categories. Therefore, they are mentioned to reach the optimum design for the needed application.

2.1 Self-Consumption

Governments' concern now is to reduce buildings' dependency on primary energy and force the integration of energy-efficient technologies and renewable energy utilization. Many prospects as rising energy prices, climate change and technology advancement push citizens to be an active part of the electricity network. They no longer want to only pay for their consumption, but instead they are concerned with the environment and want to participate in the power generation/consumption process.

There is an increasing move towards renewable energy as natural fuel resources are almost being totally consumed as well as their harmful effect on carbon emissions. This brings along self-consumption which is based on PV electricity generation that is consumed locally first and compensates the consumer's energy bill. So, it is safe to say that self-consumption relates to both the energy management and the control of energy expenses while also having a pleasant environmental impact of using renewable energy. As the networks' demand increase, it creates an ideal situation for spreading grid-tied PV generation for self-consumption applications. They help in the penetration of more distributed renewable energy generation, along with environmental benefits and savings for consumers.

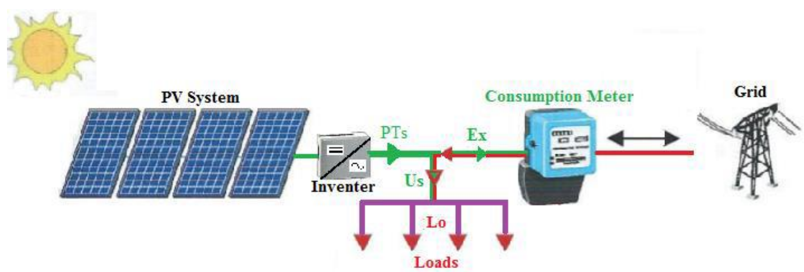


Fig. 2-1 Simple Schema of Self-Consumption [1]

No matter how the connection is implemented, electricity always goes to the nearest point of consumption. In other words, first, it is consumed at the place of the production, and the electricity generated is considered to be of the user in which he can use or export freely with a self-sufficient theoretical percentage that can reach up to 100%. However, it should be known that this percentage is constrained regarding the variations of solar production with the load curve of the consumer

But, what does self-consumption even mean? The term self-consumption, is kind of self-explanatory, it refers to the process by which an individual will suffice their own needs in terms of electrical energy. In which this individual can consume as well as produce energy, also known as prosumer. Regarding the solar energy produced, it should be known that it can either be used instantaneously or stored for future use. Although it is expected that the energy consumed from the sun is free, unfortunately, it is not. The prosumer pays a fee or is charged according to their consumption under the term "Sun Tax". Sun tax covers installation and maintenance costs of the solar panel and other grid charges and taxes.

Self-consumption not only depends on daily consumption patterns, but is also defined as the ratio between the energy consumed and the total PV production. This tends to vary among different consumers as it relies on their load profiles. The role self-consumption play in renewable energy development is inevitable. People are turning towards decentralized energy systems rather than the conventional centralized ones. Therefore, society sectors which were not proactive in the energy market will now have a significant role and impact on the power network. Nowadays, some solar projects developers are encouraged to undergo the self-consumption approach and the lack of it can be a deal breaker according to the technical and economic aspects of the project. The concept is still not 100% agreed upon, however, energy investors are keen on pushing it forward.

Self-consumption emerged to reduce the annual expenditure on electric energy for residential and commercial customers. However, solar panel's power output will always depend on a few factors including the sun's irradiance during the day, the tilt angle …etc. Thus, this requires the system to have an energy storage unit to allow excess energy trading and storage.

Self-consumption can be founded in two ways, either for one house or collective between several buildings on a low voltage grid. Either way, the system requires an onsite energy storage system to improve the rate of the local production, since the strategy to improve self-consumption is to match PV generation and load curves. Another strategy can be through demand side management by using load shifting techniques.

In some self-consumption cases, the outcome turns out to be not economical in terms of PV panel installation due to high load demands. Therefore, for further encouraging of PV panel installation, solutions of solar sharing and collective self-consumption are brought up.

Solar sharing adjusts the electricity bill based on the financial share in a solar project. It can be seen as the creation of a financial product that compromises the drawbacks of self-consumption. It is an agreement between an owner of a PV system and an end consumer. It is done in a way such that it allows the consumer to benefit from deduction on their electricity bill as a return of participating in a renewable energy project.

Collective self-consumption differs, as that the deduction is not made on the individual's bill, but on the overall system's cost. Collective self-consumption is driven by a group of renewable self-consumers joined together. Whatever the scenario is, from apartment owners in the same building with one rooftop PV system to a whole neighborhood connected by a single feeder, the common thing is that it should have one shared renewable source. It works on the concept of transferring excess energy to participating prosumers, allowing the value of the locally generated and used energy to increase along with the revenue from the PV system. In simple words, it is described as a solution to maximize the prosumer's participation while allowing them to avoid the problems associated with the grid and its high distributional costs.

Community solar systems, or what is commonly known as collective solar sharing is now considered to be preferable over separate rooftop PV systems. Shared refers to the investment, development and operations of the facility in a shared manner. Customers invest in a solar installation and are assigned a ratio of PV power generation accordingly. With the assigned ratio, individual residential customers get credit/payment from utility company at a fixed price as per power purchase agreement between utility and residential customers [2]. Not to mention the money savings as result of using less electronic devices and reduced maintenance cost.

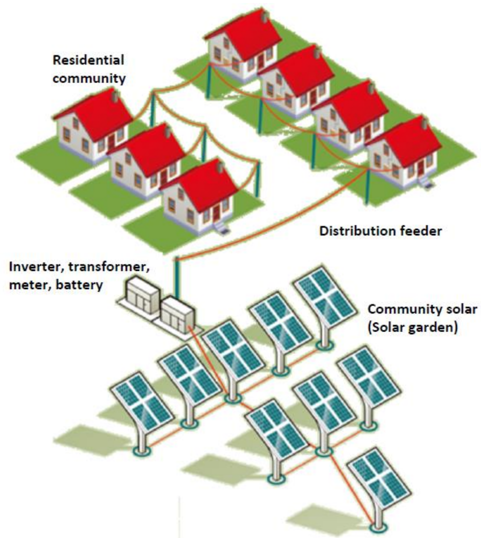


Fig. 2-2 Residential Community Solar [2]

Shared solar is an alternative solution for delivering more accessible and affordable solar power to energy consumers who are either incapable of owning a whole solar panel or do not have the luxury of space for installing one. Not to mention that it overcomes the struggle of providing power access to remote regions. Correspondingly, governments have eased and promoted the new renewable energy framework and regulations, but this of course does not eliminate the presence of limitations.

Simply, shared solar is generally presented as a group of individuals whom purchase together solar panels or shares in a solar power installation. Power generated from this solar setup is either being consumed by the shareholders for their corresponding loads or they get to benefit from reductions on their electricity bills. In this way, consumers benefit from a solar panel installation while sparing themselves the hassle of owning one. These solar installations can be found in several forms such as; offsite solar installations, onsite installations and community group purchasing. Offsite solar installations are where a solar plant is located separately but within the premises of the distribution network. Onsite installations are installed directly upon the building it is servicing such as a commercial building or an apartment block. Lastly, community group purchasing does not depend on the plant’s location, but individuals form groups and purchase shares.

Shared self-consumption describes an energy community sharing local solar production, moreover dealing with surplus according to their preferences. This overcomes drawbacks of individual self-consumption, such as temporary absence of consumption and the burden and responsibility of owning a solar installation. Contrarily, shared self-consumption is beneficial in terms of effectively producing locally consumed energy and selecting best sites for optimum results.

For further proof that shared self-consumption is superior, a study in South France was carried out comparing seven individual residential consumptions versus a production of a single PV plant of the same total power. “While individual self-consumption enables the prosumer to expect using 80% of his solar energy and covering 16% of his electrical needs, the collective operation enables the use of 99% of the solar energy to cover 22% of the participants’ needs” [3]. These energetical and economical results forces the market to invite more solar distributed self-consumption projects to be implemented. Smart meters measure the energy consumption and production at pre-set periods, then according to the previously agreed upon consumption percentage for each individual and the total energy generated by all participants each user is charged. Looking at the community as a whole, the sum of the consumptions equals the sum of solar productions plus the sum of electricity quantities supplied by the different electricity retailers via the public grid [3]. If, at any time period, the total production is superior to the total consumption, then the community can play the role of a producer of energy and sell this energy on the market [3]. In order for these transactions to be adequate, the data needs to be reliable and processed within good security measures.

Most countries consider PV generation connected to a low voltage distribution network is of a passive effect, and as a result, only basic limitations and quality control measures are taken into account. However, some places, like Germany for example, are starting to require active capabilities to the PV generation, in order to contribute to a better control and quality of the main grid [4]. These control actions are taken regarding active and reactive power to maintain a balance of the demand-generation curve and to control the power factor and reduce losses.

Fig. 2-3 Tracker facing east (morning) [4]

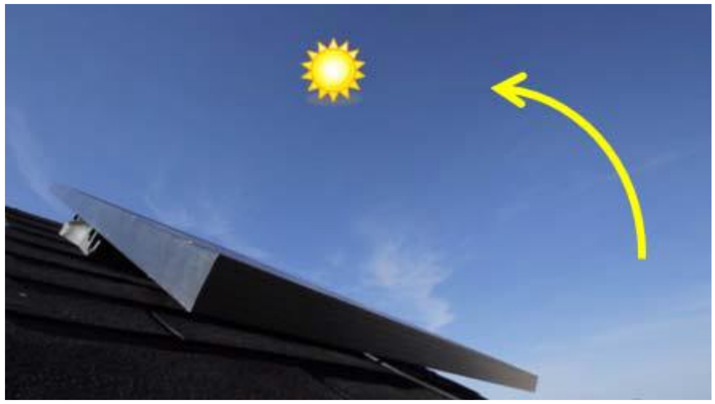


Fig. 2-4 Tracker in flat position (noon) [4]

Fig. 2-5 Tracker facing west (afternoon) [4]

2.2 Regulations

For shared solar systems to be successfully implemented, there is a significant role to be played by government and lawmakers in developing a supportive legal framework.

New regulations for the Spanish market encourage citizens for further self-consumption systems' installations. The new regulation implies that there are two modes of self-consumption depending on whether or not there is a physical device that prevents the injection of excess energy into the network. Previously, the law obliged the user to have a contracted power of an amount more than or equal to the connected devices, even if it is unnecessary due to PV panels installation. This amount was impossible to reduce as the contacted power charges were fixed and cannot be reduced. The user was charged with this fixed amount in addition to variable charges that depend on the energy demanded by the user. However, the situation now is that users can contract the needed power independently from the installed generation capacity.

As for Portugal, two regulations are defined by the Portuguese authorities, the first implies that the production units for self-consumption can sell the surplus energy if they are connected to the grid. The second, regulation is for the small production units, which have to sell all the energy to the network. However, in both cases the connected power should be less than or equal to the contracted power and each has a different charging scheme.

In Sweden, if all apartments in the same building have the same grid subscription, then collective self-consumption is allowed. However, subscribers cannot transport electricity to the grid. The same, regarding collective self-consumption in the same building can be implemented in Germany and Austria. While in France, a new legal framework allows PV production sharing downstream a medium/low voltage transformer, consequently, electricity flows through the distribution grid.

Last but not least, the U.S customers are allowed to receive credit if they are consuming their share of produced power. Shared renewable energy in particular, has been embraced by fourteen states. In Colorado, law allows residents who live in the mountains with significant exposure to sunlight to tap into the benefits of solar energy without having to make a large personal investment. When subscribers move, they can take their subscriptions with them, so long as they remain within a covered geographic area [5]. While in California, new laws promote virtual net metering where consumers in a shared solar infrastructure can save money on their bills. Also, they receive a credit on their bill for power generated from the solar power system.

2.3 Impact on the Grid

Self-consumption's main purpose is to satisfy the connected demand and to sell or store the excess energy generated. However, it affects the charging scheme of the distribution system operator. In other words, if no modification is made for the existing charging scheme, it will result that consumers without self-consumption tend to have increased tariffs as opposed to self-consumption customers.

Storage systems compensate the drawbacks of self-consumption system. Losses decrease in the presence of a storage system, as well as the energy consumption and injection from and to the network. Other than that, they helped in voltage stabilization during the day.

To overcome the charging scheme problem, there should be an increase of the tariff's prices. The best way found was to increase the price of the contracted power which is unaffected by the self-consumption and is separate for each customer. In this way the self-consumption decreased payments is out balanced.

Self-consumption rate has an impact on the voltage quality of low voltage networks. "It was shown that for an average installed capacity above 5 kWp per household, the grid needs compensatory measures to keep the voltage inside the allowed limits" [6]. Nevertheless, voltage support and active power support can be provided through the combination of PVs and energy storage systems. According to [6], voltage quality can be maintained if the average monthly self-consumption rate is kept above certain values. Also, self-consumption rate should be within certain limits according to the properties of the connected line.

On one hand, self-consumption and more PV installations are being encouraged by governments, on the other hand, this increase can produce undesired effects to the grid if not taken care of properly. Negative effects can be due to high injected energy from PVs during peak irradiation hours and this leads to high voltage rises. Thus, energy storage systems are connected to absorb the surplus power. “For example, on June 2014, there was about 23 GW of solar power on the German grid, covering more than 50% of the total electricity demand at noon. Under this situation a huge amount of PV produced energy had to be curtailed to maintain the stability of the power system. A solution that can avert the curtailment PV generated power is the installation and operation of distributed energy storage systems. Such a solution can provide flexibility to the system by storing the surplus energy and shifting its consumption to periods with low production and high demand” [7]. Other drawbacks can be overloading of network equipment as well as stability problems. As mentioned before, energy storage systems can overcome these problems by absorbing excess energy, but it should be mentioned that there is a minimal storage capacity for overvoltage to be prevented.

2.4 Solar Panels

2.4.1 History and Evolution

Enough energy from the sun hits the Earth every hour to power our planet for an entire year [8]. Since solar energy have become a world leading source of renewable energy, more research and investments are being made for developing improved technologies concerning greater cost efficiency and consumer benefits.

At most basic, the theory of operation of the solar panel is based on light hitting certain metal surfaces causing the surface of the material to emit electrons, as when hitting other particular metals, it causes the material to accept electrons. Combining those two metals result in the flow of electrons and creating a conductor, and so comes the term photovoltaic.

The first discovery of the photovoltaic effect was in the 1800s, and more discoveries were made along the years, however, people still did not use the solar cells for producing electricity due to its inefficient capabilities. It was until around the mid-1900s when silicon solar cells were produced commercially, but was still uncommonly used owing to high costs. Solar energy usage started to become more familiar once technologies allowed the price to reduce and as oil prices rose. This was when people started shifting towards clean energy. Fortunately, researchers were able to develop solar panels that nowadays can reach up to an efficiency of 32% and higher, encouraging people to set up their own solar panel kit at their properties.

Renewable energy interference in the market is noticed as a reaction to the depletion of oil supply, climate changes and carbon impacts. Until 2007, Germany, US and Japan were the top photovoltaic developers with a total percentage of 72% of the installed power. In the present, China takes first place in terms of photovoltaic power connected with nearly 43 GW, relegating Germany to second place with 40 GW. Europe represents 42% of the photovoltaic power worldwide with almost 100 GW connected to its grid [1]. The top 5 developers of the solar technology in Europe are as follows. For Germany, the solar power consists almost exclusively of photovoltaic (PV) and accounted for an estimated 6.7 % of the country's net-electricity generation in 2015 [1]. Italy held in 2015 the second largest European producer of photovoltaic electricity with 22.7% of the total European production, behind Germany [1]. In the United Kingdom, the solar energy has taken its growth late, but due to the sharp drop in prices of photovoltaic cells that development is triggered [1]. For France, the photovoltaic initially limited to small size, but in 2015 it supplied 1.4% of national electricity production. For Spain, solar energy has experienced very rapid growth since the establishment of supportive policies from 2004; in 2007-2008 has been a "boom" in the installation of photovoltaic panels, propelling Spain to the rank of first solar power producer in the world; this growth was stopped in 2012-2013 by the suspension of support [1].

If the chosen types of solar panels and the environment are perfectly matched to one another, we have a very reliable and cost effective energy source. The figure below shows perfectly how solar power generation is increasing rapidly.

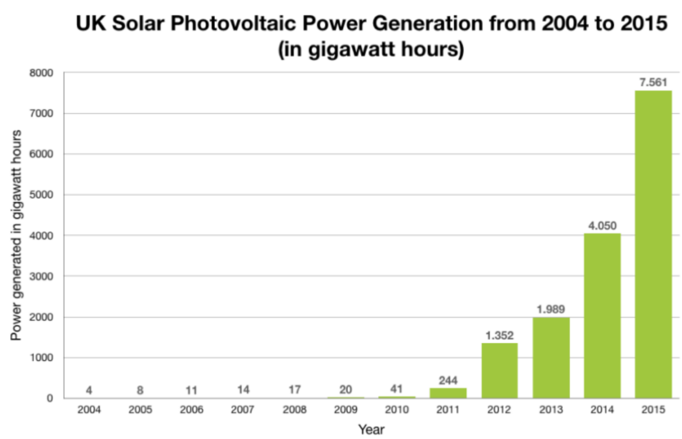


Fig. 2-6 Solar Panels Growth Profile in UK [9]

2.4.2 Types

There is a wide range of solar panels types variety, each with a different need, purpose and application. The most commonly used type is made of monocrystalline silicon or polysilicon. Monocrystalline solar panels (Mono-SI) are considered the purest one in terms of silicon's high purity. They are easily recognized from their uniform dark look and rounded edges.

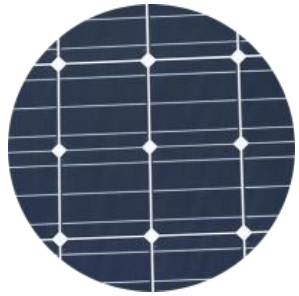


Fig. 2-7 Monocrystalline Solar Panels [9]

Famous for their high power output, which translates to being the most expensive, Mono-SI efficiency rates reach 20% today. Other advantages include their ability to the last the longest considering the fact that they are less affected by high temperatures compared to polycrystalline panels.

The second type, of solar panels is the polycrystalline solar panels (Poly-SI). Their unique shape of blue whole squares makes them easily distinguished and the manufacturing process is faster and cheaper than Mono-SI.

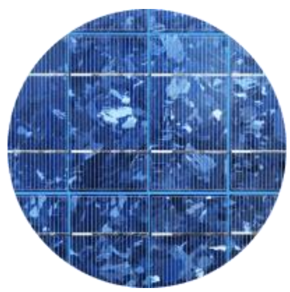


Fig. 2-8 Polycrystalline Solar Panels [9]

Efficiency is lower (around 15%), and they are affected by hot temperatures resulting in a shorter life span. Difference between the previous two types can be insignificant and the choice preference will have to depend on a specific situation, in which both will kind of deliver almost the same power output.

Another different type of technology is the thin film solar cells (TFSC) which are mainly used in smaller solar power systems. Thin film solar cells are an easy production, less expensive option. Its flexibility is the most outstanding feature of this type. However, they have a relative short life span and take a lot of space making them unsuitable for residential installations but for places where a lot of space is available.

Fig. 2-9 Thin Film Solar Cells [9]

Last but not least, a type which uses a variety of thin film technologies to allow the efficiency to reach the highest of 41%. Concentrated PV cell's (CVP and HCVP) high efficiency is because of their different setup. Curved mirror surfaces, lenses and sometimes even cooling systems are used to bundle the sun rays and thus increase their efficiency [10].

Fig. 2-10 Concentrated PV Cells [9]

To conclude, a simple comparison of all mentioned different types is shown in the following table.

Table 2-1 Solar Panel Types' Comparison [9]

Solar Cell Type	Efficiency-Rate	Advantages	Disadvantages
Monocrystalline Solar Panels (Mono-SI)	~20%	High efficiency rate; optimised for commercial use; high life-time value	Expensive
Polycrystalline Solar Panels (p-Si)	~15%	Lower price	Sensitive to high temperatures; lower lifespan & slightly less space efficiency
Thin-Film: Amorphous Silicon Solar Panels (A-SI)	~7-10%	Relatively low costs; easy to produce & flexible	shorter warranties & lifespan
Concentrated PV Cell (CVP)	~41%	Very high performance & efficiency rate	Solar tracker & cooling system needed (to reach high efficiency rate)

Further research and development of solar cells, and materials other than silicon, which use nanotechnology is under investigation. It is expected that the new technologies will be able to offer a less expensive and more flexible material for solar cells. While other studies for different materials aspire to reach efficiency of three times more than existing products on the market.

2.4.3 Manufacturers

The huge demand for the solar panel industry allowed its corresponding market to increase drastically. The decision making process gets harder as the number of manufacturers increase. From the performance and efficiency to the price and the quality, there are many factors that need to be taken into account when making a decision. The following will be a discussion of a few of the solar panels manufacturers.

LG Energy

LG Energy is world leading for various of reasons; starting from high quality going to its reliability and very high performance. Their solar panels are very popular across the globe, offering 25-year product and performance warranty. Their unique design of extremely strong double wall aluminum frames on all modules enhances its strength and durability.

Fig. 2-11 LG Energy Solar Panel [10]

The solar panels also go through several tests to ensure high quality and performance. Not to mention that the used technology helps in increasing the lifespan of the solar panels making it the longest in the market with energy generation with 86-88% capacity remaining even after 25 years.

Panasonic Solar Panels

This brand popularity owes to the fact that LG invested almost 40 years in the research and innovation which reflects itself in the solar panel quality and performance. The solar panels Panasonic offers are black have a traditional look.

Fig. 2-12 Panasonic Solar Panels [10]

Along with the 25-year warranty as well, an outstanding temperature coefficient provides more energy throughout the day. Also more electricity output can be harnessed because of its unique pyramid structure that accumulates sunlight and sun energy more efficiently. Last but not least, the manufacturing technology reduces energy losses and results in higher energy power output than conventional panels.

Hyundai Solar Panels

The company produces mainly residential solar panels, known for its high quality and the longest PV cell. Although its cheap price is tempting, the efficiency range of the solar panels put it in the standard rather than high efficiency category.

Fig. 2-13 Hyundai Solar Panels [10]

Hyundai now offers a newer 10-year warranty which is replacing the old 5-year warranty models. A specific series from Hyundai has an advantage of being suitable for extreme weather conditions.

2.5 Batteries

2.5.1 History and Evolution

Today advanced batteries suitable for numerous devices and their needs are available. But as different devices have different needs, the existence of several battery technologies is an advantage [11]. Since the first discovery of the battery, researches and studies were carried out for developing more technologies to adapt to the public's needs. These researches lead to rechargeable batteries which almost every appliance nowadays rely on. Battery technology already makes electric cars possible, as well as helping us to store emergency power [12]. Simply, batteries are energy storage devices where chemical energy is stored to be used in the future in the form of electrical energy. The standard construction of a battery is to use two metals or compounds with different chemical potentials and separate them with a porous insulator [13]. Batteries have three main components; anode which releases electrons that are acquired by the cathode, where the medium that provides the ion transport mechanism between the cathode and anode of a cell is called an electrolyte. Many features should be considered to produce a good quality battery such as power, weight and cost.

The battery was discovered during experiments with a behavior of electricity and magnetism. Constructed of alternating discs of zinc and copper with pieces of cardboard soaked in brine between the metals, the system produced electrical current.

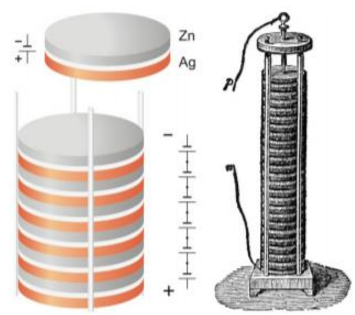


Fig. 2-14 Structure of the First Battery [11]

But this structure was unable to deliver electric current for long periods, hence, a more developed system was required. So a new cell that used two electrolytes: copper sulfate and zinc sulfate lasted longer. This battery, which produced about 1.1 volts, was used to power objects such as telegraphs, telephones, and doorbells, remained popular in homes for over 100 years [14].

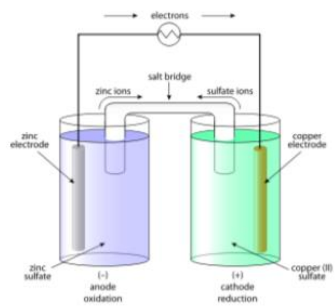


Fig. 2-15 Developed Battery Setup [11]

As the years passed, more types were invented for example the fuel cell, lead acid batteries and much more. In 1859, the first rechargeable battery was invented, the lead acid battery. The cell could be recharged applying reverse current. The construction was following: two lead sheets (lead anode and a lead dioxide cathode) separated by rubber strips were rolled into a spiral and immersed in the sulfuric acid solution [11].

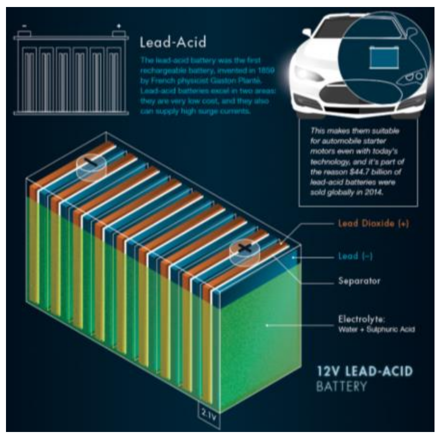


Fig. 2-16 The First Rechargeable Battery (Lead Acid) [15]

All battery types fall under two categories, primary and rechargeable batteries. When the reaction that produces the flow of electrons cannot be reversed the battery is referred to as a primary battery. When one of the reactants is consumed the battery is flat [13]. The most famous primary battery, zinc carbon battery, is the store bought ones. Studies showed that when the electrolyte is an alkali, the batteries lasted much longer. On the other hand, rechargeable batteries, also known as storage batteries, are recharged to their original condition by passing current through them in the opposite direction than that of the discharge. Some batteries included in this category are, nickel cadmium, nickel metal hydride, lead acid and lithium ion batteries.

2.5.2 Types

Nickel cadmium batteries lost 80% of their market share in the 1990s to batteries that are more familiar to us today. Their toxicity, due to cadmium, plays a huge role in their discontinuity [15].

Advantages

1- Long life cycle
2- Low maintenance
3- Wide range of options and sizes
4- Suitable to any type of climate

Disadvantages

1- Low energy density
2- Environmentally unfriendly
3- High cost compare to lead acid battery

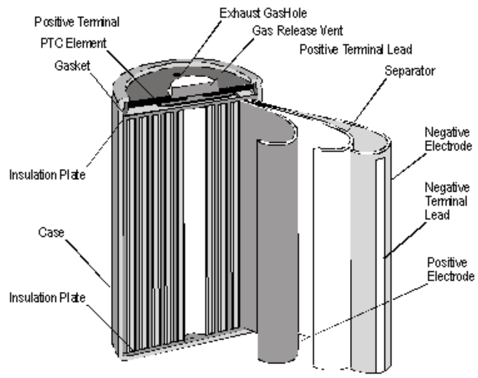


Fig. 2-17 Nickel Cadmium Battery Structure [16]

Nickel metal hydride eliminates the toxicity hazard of the cadmium by using a hydrogen absorbing alloy. It has become one of the most readily available rechargeable batteries for consumer use. They are used in some electronic devices such as power tools and digital cameras. In the past they were also incorporated in a hybrid vehicle.

Advantages

1- Long life cycle
2- Low maintenance
3- Safe to use

Disadvantages

1- High cost
2- Sensitive to overcharge

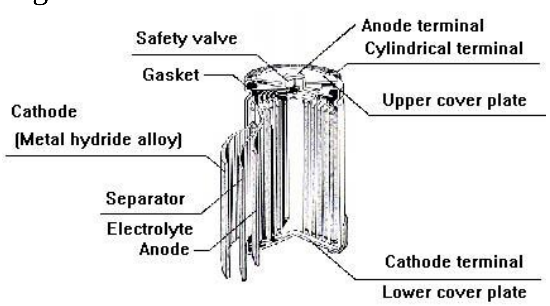


Fig. 2-18 Nickel Metal Hydride Battery Structure [17]

Lead acid batteries are the first invented rechargeable batteries. Lead acid cells are composed of alternating positive and negative plates, interleaved with single or multiple layers of separator material.

Advantages

1- Low cost
2- Wide range of sizes and capacities available
3- Starts from smaller than 1Ah to several thousand Ampere hours
4- Market availability
5- Quietly unaffected by temperature

Disadvantages

1- Environmentally unfriendly
2- Heavy weight
3- Unsuitable for fast charging
4- Overheating dangers

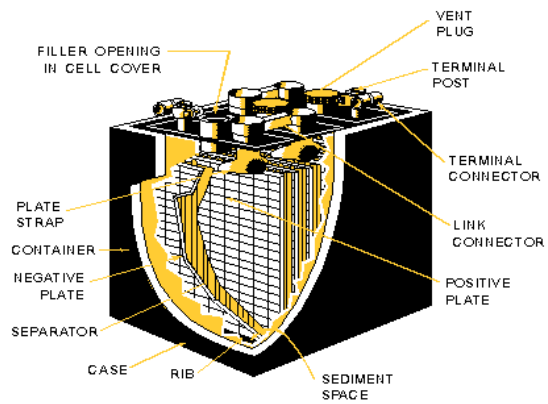


Fig. 2-19 Lead Acid Battery Structure [18]

Lithium ion batteries were commercially released in the early 90s. Lithium has one of the largest electrochemical potentials, therefore this combination produces some of the highest possible voltages in the most compact and lightest volumes. Lithium ion batteries are known for high energy densities and are formulated differently according to their application. Graphite is a common material for use in the anode, while, the electrolyte is of a lithium salt. A structure of lithium nickel cobalt aluminum oxide cathodes is used in the Tesla Model S vehicles. While lithium cobalt dioxide cathodes ones are used in laptops and smartphones.

Advantages

1- No maintenance required
2- Low self-discharge
3- Fast charging
4- Small memory effect
5- High energy density

Disadvantages

1- Expensive

2- Protective circuitry required
3- Ageing

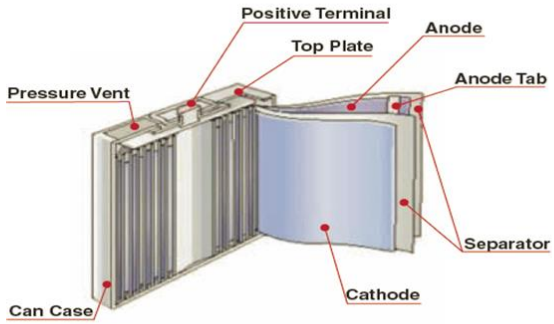


Fig. 2-20 Lithium Ion Battery Structure [19]

The following figure is a comparison between the previously mentioned battery types.

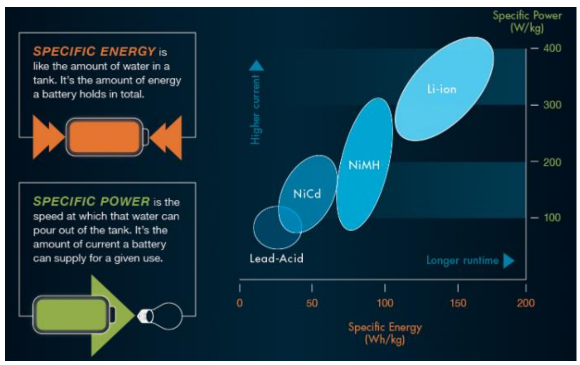


Fig. 2-21 Comparison between Battery Types [15]

Today are mainly used lithium-ion batteries due to their power-to-weight ratio. It took many years until these batteries were safe for commercial use. The instability of lithium caused explosions, so modern construction and protection circuits are needed [11].

2.5.3 Manufacturers

Avoiding carbon emission issues and the ever growing concern towards the environment encourage the usage of renewable resources accompanied with energy storage devices for power generation. This leads to an increased focus on more efficient and reliable energy storage and therefore, augmenting the demand for lithium-ion batteries [20]. Few of the world's leading lithium ion batteries manufacturers are discussed below.

Samsung SDI

Samsung SDI, subsidiary of Samsung, has one of the biggest shares in today's market. Innovation in the lithium ion technology for Samsung's clients is one of Samsung SDI's dedications. Currently, the entity's concerns are lithium ion batteries production and energy storage systems.

Toshiba

Toshiba has invested immensely in its R&D department for lithium technology. Presently the company is involved in production and sales of lithium ion batteries and relative storage solutions for automotive and telecommunications branches.

LG Chem

LG Chem is one of the most notable and pioneer manufacturers in the field of lithium ion batteries as it provides a wide diversity of industries. LG Chem has made deep intrusion spread across multitude of different sectors. The firm also manufactures heavy duty batteries for consumer merchandise such as smartphones and laptops.

Tesla

Tesla excel in the automotive industry, and this is due to the long lasting batteries that their cars are equipped with. Although, Tesla is currently purchasing the batteries from Panasonic, a future plan is to find their own factory for manufacturing the needed parts sufficient for their automotive industry. It is expected that once production starts, it will be the largest facility in the world dedicated to the production of lithium ion batteries [21].

2.6 Electric Vehicles

2.6.1 History and Evolution

In the old days, electric cars gained their popularity, against the steam and gas powered automobiles, as they were quiet, easy to drive and most importantly did not emit exhaust pollutants. High demand of the electric cars encouraged innovators to explore ways for improvement, like building a better battery for example. Further innovations lead to the invention of the first hybrid car in 1901. The vehicle was powered by electricity stored in a battery and a gas engine. Unfortunately, the discovery of cheap crude oil was the start of the electric vehicles manufacturing declination, it was until 1935 then electric vehicles disappeared from the streets [22]. However, this was not long until gas prices increased drastically shifting the public's interest towards electric vehicles again. The following timeline shows the evolution of electric vehicles after the oil crisis and increase in fuel costs.

1990	GM Impact Electric Concept Car
1990's	Many governments around the world produce "Clean Air Acts" or amend existing ones and introduce Energy Policies. Major car manufacturers respond.
1996	GM EV1 produced but lost GM money
1997	The Toyota Prius is born
1999	Scientists work to improve EV's and their batteries
2004	Tesla Motors is founded
2008	Tesla Roadster
2009 -	In the U.S. and across the world charging station infrastructures begin to roll out
2010	GM releases the first Plug-in Hybrid the Chevy Bolt
2010-onwards	EV battery costs plummet and various other major car brands beginning developing their own long-range, highway capable cars such as Nissan (Leaf), BMW, VW etc.

Fig. 2-22 Timeline for Electric Vehicles [23]

2.6.2 Types

There are different types of electric cars. To begin with, a hybrid (HEV) cannot be charged but does have a battery, the main energy source comes from gasoline. While, a plug-in hybrid (PHEV) can be charged as well as it can be driven using either its battery or fuel. As for all electric vehicles (EV, AEV, battery-electric cars etc), drive energy is from its battery and must be recharged from an electric source.

2.6.3 Manufacturers

Electric vehicles', which is the point of interest in this study, market is a competitive one with more and more manufacturers beginning to produce and sell electric cars. Because electric vehicles are still relatively new to the road, most car companies currently only produce one EV model. Because electric vehicles are still relatively new to the road, most car companies currently only produce one EV model. Users' choices are made according to their preference of the car with the highest range or the most inexpensive option. Below is a brief discussion of some of the top EVs manufacturers.

Tesla

Tesla is known for producing high quality, cutting-edge vehicles with high-end and creative features. Tesla Model S and Tesla Model X are their most popular vehicles as well as the lower-cost Tesla Model 3 that is increasing in demand nowadays. The Model S is Tesla's luxury sedan, Model X is the electric SUV and Model 3 is a low-cost sedan option for those not wanting to pay the high price for the Model S luxury vehicle.

Nissan

Nissan has sold the most EVs of any manufacturer worldwide [24]. Their electric car offerings are led by the Nissan Leaf which offers all the benefits of driving electric, while staying available with a relatively low price. The newest model has a better battery performance and a modified shape.

BWM

BMW i3, an all-electric luxury SUV, designed for travelling within the city and its suburbs. The i3 EV is the simplest of all, with outstanding construction and notable styling to make a great city car. A beneficial add-on for this vehicle is the small gasoline engine.

Many electric vehicle manufacturers are improving their battery charge times, making it possible for these cars to be charged and ready to hit the road more quickly [25]. Thus, if considering ditching fossil fuels for quiet and clean electric power, plenty of options are available in the market for an electric vehicle.

Chapter Three

3. Description of Model

This chapter is constructed as follows. First, the case studied retrieves the data from the ADRES-CONCEPT data matrix, so description of the matrix is introduced, how the data was retrieved and the steps taken to extract the needed data from the whole study. Next, the basic idea of the Simulink model created for the thesis is explained, both manually and automatically, followed by an explanation of creating PV panel's profiles and studying factors affecting the sun's irradiation. Lastly, functions for building the model are discussed, such as referring each solar system share to their corresponding user, energy storage system and electric vehicle charging scheme and in the end the scheme for billing users will be discussed.

The model, illustrated and simulated, is for one building with 30 houses under real circumstances of PV systems and their corresponding profile, battery storage and customer demand profiles.

3.1. ADRES-CONCEPT

The case studied is located in Gijon, Spain (latitude: 43.5322 and longitude: 5.6611). Sizing the PV installation suited for a house requires modeling of its electrical energy demand. First, a model of a building consisting of 30 households was built using Simulink. The power consumption for each house was loaded from the ADRES-CONCEPT research project, this project was funded by the Austrian Climate and Energy Fund and performed under the program "ENERGIE DER ZUKUNFT". The generated dataset consists of active and reactive power as well as voltage values per phase. The measurement was carried out for one week in summer and one week in winter with a time step of 1 sec (1 sec RMS values) at 30 households in Upper-Austria.

These data are provided as one Matlab file with following structure format:

Data.U is a matrix containing the voltage values (V) per phase and household. The number of rows is 1209600 (2 weeks x 7 days x 24 hours x 3600 seconds). The number of columns is 90 (3 phases x 30 households).

Data.PQ is a matrix containing the active (W) and reactive power (Var) values per phase and household. The number of rows is 1209600 (2 weeks x 7 days x 24 hours x 3600 seconds). The number of columns is 180 (2 power values x 3 phases x 30 households).

For the power consumption of each house, the total power consumption from the 3 phases were added together in order to know the demand for each household.

In order to test the satisfaction of the load demand of the 30 houses, a PV power profile was implemented using Matlab. Different factors were taken into consideration, like the tilt angle, the panels' location and the day of year … etc. With the aid of Matlab, storage was implemented by the use of a battery bank with the preferred capacity as well as management of the electric vehicle charging for each participant.

Energy management for the whole building was abided by certain rules. First, the electricity generated by the solar energy system must first feed into the connected loads, if there is any energy excess then the batteries are charged as for further excess the remaining energy is fed into the grid. This strategy is adopted in order to encourage energy self-consumption for individuals and to reduce the amount of energy imported from the grid. In other words, if at any time period, the total production is superior to the total consumption, then the community can play the role of a producer of energy and sell this energy on the market.

At each predefined time period, the energy generated by all participating producers is aggregated then virtually divided between participants according to their corresponding shares in the solar system. These rules notably take into account each participant's current consumption.

3.2. Simulink Model

Obviously the first step had to be the representation of the building. A model of the building including the circuit breakers, fuses and line impedances is built.

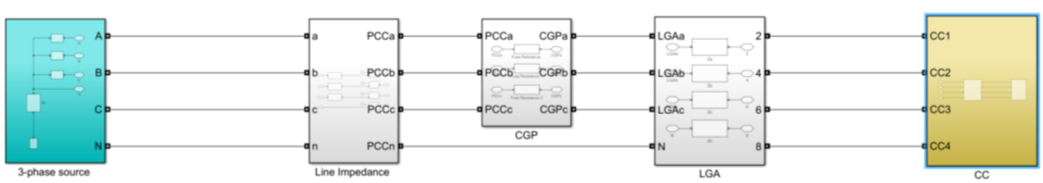


Fig. 3-1 Model of the Building

The 3-phase source block represents the power source cables that are coming into the building from the grid.

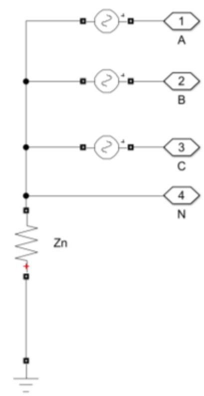


Fig. 3-2 3-Phase Source

Line impedance block consists of resistances and inductances to resemble the impedance of the cable.

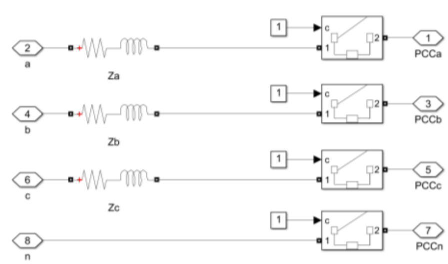


Fig. 3-3 Line Impedance

Caja General de Protección (CGP) is the main protection box containing protective fuses.

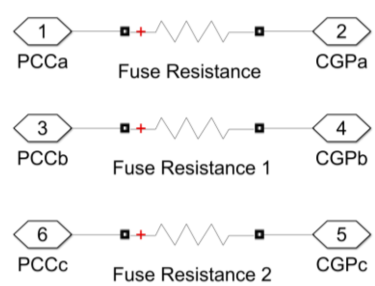


Fig. 3-4 CGP

While, Linea General de Alimentación (LGA) is considered the main feeding line, and is represented with resistances and inductances like the previous line impedance subsystem.

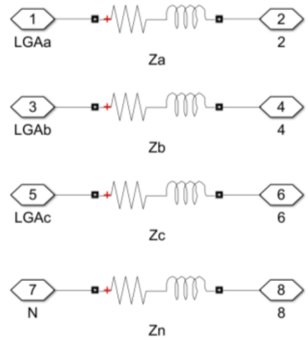


Fig. 3-5 LGA

Centralización de Contadores (CC) is the panels for smart meters' centralization to track the consumers' power usage. Finally, when the cables reach their destined floors, each phase in connected to its destined house through a breaker for its protection.

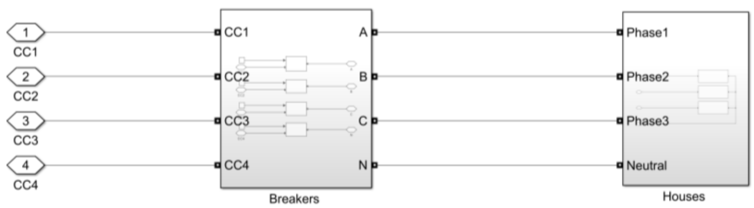


Fig. 3-6 CC

Simply, CGP has the fuses that protect the LGA. The LGA feed all the building, it starts in the CGP and it ends in the CC where the smart meters for the users are located.

Each house representation is made by implementing a controlled power source. This controlled power source gets its values from the ADRES-CONCEPT matrix. As it has been mentioned above, the active and reactive power readings for each house is calculated by using a simple code and then are assigned to their corresponding houses.

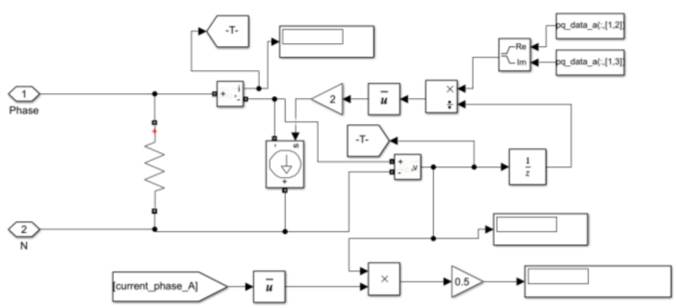


Fig. 3-7 One House Representation

The active and reactive power are input to the real and imaginary ports respectively to calculate the apparent power which is then divided by the measured voltage of the house. This calculation results in a current that drives the controlled current source block.

This whole setup was built manually, in which each block was placed separately and connected by hand. As for selecting the day when the consumption needs to be tested, the active and reactive power matrices had to be altered to have the values of one specific day, as for the running time of the model, it had to be modified as well. It was a long, time-consuming process that led to the conclusion of re-building this model automatically; by code writing. An additional huge drawback for this method was the process of adding more houses to the model. If the tester wants to add the whole 30 households, one house had to be copied and pasted 30 times. Not only this, but changing the active and reactive power consumption was a must for each block to match a specific house. How this was avoided will be discussed next.

Building the model automatically could not be avoided at this stage. Different commands to add blocks and lines were used. The most useful part was the ability to specify the number of houses connected to each phase, not only this, but which house is connected to which phase was easily decided.

```
%Phases Assignment
Phase_A=[21,2];
Phase_B=[11,12];
Phase_C=[1,22];
```

Fig. 3-8 Houses Connected to Corresponding Phases

For example, in the previous figure, phase A had houses of numbers 21 and 2 connected to it, as for phase B it was connected to houses 11 and 12, finally houses 1 and 22 were connected to phase C. Therefore, the ease of houses declaration to their phases is clear now.

Creating a new system and opening it were the first steps in constructing the code for building the model automatically, then settings configurations.

```
new_system('bldngmdl');
open_system('bldngmdl');

set_param('bldngmdl','Solver','FixedStepDiscrete','FixedStep','1');
set_param('bldngmdl','StopTime','1209601')
```

Fig. 3-9 Commands for Starting the Building Process

Notice that the stop time in this case was 1209601 which is the total number of seconds for the two weeks under study. If the requirement is to study one day, then the time should be 86400 which is the total number of seconds for one whole day.

The blocks used in the system were all added in a separate Simulink file, called mylib, to make their access easier. Further commands used were for the actual re-building of the model, like adding the blocks and connecting them together. Most importantly, when adding the block, the user can define its position on the screen to ensure that blocks are not overlapping.

add_block: Add block to model

add_line: Add line to Simulink model

delete_block: Delete blocks from Simulink system

delete_line: Delete line from Simulink model

add_param: Add parameter to Simulink system

delete_param: Delete system parameter added via add_param command [34]

After adding the blocks and connecting them, sometimes the need to altered in many ways. It can be either their orientation or the parameters' values that to block holds. This is accomplished by using the following set of commands.

get_param: Get parameter names and values

set_param: Set system and block parameter values

```
%Building the Line impedance subsystem
add_block('simulink/Ports & Subsystems/Subsystem','bldngmdl/Line impedance','Position',[200,105,330,195]);
delete_line('bldngmdl/Line impedance','In1/1','Out1/1');
delete_block('bldngmdl/Line impedance/In1');
delete_block('bldngmdl/Line impedance/Out1');

add_block('mylib/Series RLC Branch','bldngmdl/Line impedance/Za','Position',[170,320,230,400]);
set_param('bldngmdl/Line impedance/Za','Resistance','Ra1');
set_param('bldngmdl/Line impedance/Za','Inductance','La1');
add_block('mylib/Series RLC Branch','bldngmdl/Line impedance/Zb','Position',[170,450,230,530]);
set_param('bldngmdl/Line impedance/Zb','Resistance','Rb1');
set_param('bldngmdl/Line impedance/Zb','Inductance','Lb1');
add_block('mylib/Series RLC Branch','bldngmdl/Line impedance/Zc','Position',[170,580,230,660]);
set_param('bldngmdl/Line impedance/Zc','Resistance','Rc1');
set_param('bldngmdl/Line impedance/Zc','Inductance','Lc1');

add_block('mylib/InPort','bldngmdl/Line impedance/a','Position',[90,345,130,375]);
add_block('mylib/InPort','bldngmdl/Line impedance/b','Position',[90,475,130,505]);
add_block('mylib/InPort','bldngmdl/Line impedance/c','Position',[90,605,130,635]);
add_block('mylib/InPort','bldngmdl/Line impedance/n','Position',[90,735,130,765]);
```

Fig. 3-10 Example of Building the Line Impedance Block using Matlab

The critical step was to match the connected house to its power consumption loaded from the ADRES-CONCEPT data matrix. This was earned by the following set of commands.

```
% for phase A
for i=1:rows
        pq_data_a(i,1)= i;
    for j=1:length(Phase_A)
      P1_a=Data.PQ(i,(((Phase_A(j)-1)*6)+1));
      Q1_a=Data.PQ(i,(((Phase_A(j)-1)*6)+2));
      P2_a=Data.PQ(i,(((Phase_A(j)-1)*6)+3));
      Q2_a=Data.PQ(i,(((Phase_A(j)-1)*6)+4));
      P3_a=Data.PQ(i,(((Phase_A(j)-1)*6)+5));
      Q3_a=Data.PQ(i,(((Phase_A(j)-1)*6)+6));
      P_a=P1_a+P2_a+P3_a;
      Q_a=Q1_a+Q2_a+Q3_a;


      pq_data_a(i,((j-1)*2+2))= P_a;
      pq_data_a(i,((j-1)*2+3))= Q_a;
   end
end
```

Fig. 3-11 Power Data Loading for each House Connected to Phase A

All the previous was just the representation of the model, or the layout of the existing system without adding the PVs and their accompanied energy storage. The following step was to create the PV panel profile.

3.3. Solar Irradiation

In the coming sections, the whole model will be dealt with through Matlab scripts. First, the solar irradiation's affecting factors will be studied to create a PV panel profile for a certain, preferred, location on Earth. Second, extracting the power readings of a certain day for a specific house from the ADRES-CONCEPT matrix. Consequently, the user is able to get desired readings, such as the power consumption over specified smart meter intervals as well as the energy consumed and so on. The next step was to expose the created PV panel profile to alternating weather conditions, such as the clouds' density, the PV panel area and its efficiency for each day out of the 14 days separately. After success of the solar part, the battery charging and discharging profiles were created with respect to certain factors that will be discussed. In addition, the EV charging stations related to each house, the consumption will be added to each household. Last but not least, a function was created to calculate each individual's consumption with respect to their share of the building's installed solar system and reports will be conducted accordingly. In the end all of this will be collected again to build a whole Simulink model with all the system's parts.

In order to calculate the solar irradiation over a surface that can reach up to 1000 W/m^2, a few factors should be taken into consideration.

Solar Angles

The axis about which the Earth rotates is tilted at an angle of 23.45^o. The Earth's tilted axis results in a day-by-day variation of the angle between the earth-sun line and the earth's equatorial plane, called the solar declination δ. [35]

$$\delta \;=\; 23.45\, sin[360\; x\; \frac{284+N}{365}] \qquad (3.1)$$

where N = year day, with January 1 = 1.

Each day during the year the angle δ varies resulting in the seasons changing, and accordingly the solar radiation distribution over the Earth's surface is changed as well as the duration of the daylight. The fact that the Earth rotates, is what causes the sun's apparent motion.

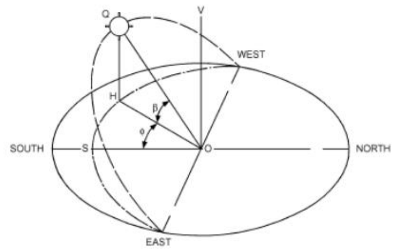


Fig. 3-12 Apparent Daily Path of the Sun

The position of the sun can be defined in term of its altitude β and its azimuth φ. At solar noon, the sun is exactly on the meridian, as a result the azimuth is 0° and the noon altitude β_N is given by the following equation;

$$\beta_N = 90^o - LAT + \delta \tag{3.2}$$

where LAT = latitude

Because the earth's daily rotation and its annual orbit around the sun are regular and predictable, the solar altitude and azimuth may be readily calculated for any desired time of day when the latitude, longitude, and date (declination) are specified. [35] Apparent solar time (AST) must be used, expressed in terms of the hour angle H, where

$$H = (Number\ of\ hours\ from\ solar\ noon)\ x\ 15° = \frac{Number\ of\ minutes\ from\ solar\ noon}{4} \tag{3.3}$$

Solar Time

AST differs from local standard time (LST), and the AST can be determined from the following equation.

$$AST = LST + Equation\ of\ time + (4min)(LST\ meridian - Local\ longitude) \tag{3.4}$$

The equation of time, in minutes, defines the difference in time in which the sun runs slower or faster than the LST.

As for finding the previously mentioned solar altitude β and azimuth φ, the hour angle H, latitude LAT and declination δ should be known at first, then the following equations can be used;

$$sin\ \beta = \cos(LAT)\ cos\delta\ cosH + \sin(LAT)\ sin\delta \tag{3.5}$$

$$sin\varphi = {cos\delta\ sinH}/{cos\beta} \tag{3.6}$$

$$cos\varphi = {(cosH\ cos\delta\ \sin(LAT) - sin\delta\ \cos(LAT))}/{cos\beta} \quad (3.7)$$

Incident Angle

If there is a surface where the irradiation on this surface needs to be calculated, an angle called the incident angle is important in the calculations as it affects the intensity of the direct component of solar radiation striking the surface and the surface's ability to absorb, transmit or reflect the sun's rays. [35] The incident angle θ, is defined as the angle between the line normal to the irradiated surface and the earth-sun line. To determine θ, the surface azimuth ψ and the surface-solar azimuth γ must be known. The surface azimuth is the angle between the south-north line and the normal to the intersection of the irradiated surface with the horizontal plane. The surface-solar azimuth, angle is designated by γ and is the angular difference between the solar azimuth φ and the surface azimuth ψ. [35]

For surfaces facing east of south;

$$\gamma = \varphi - \psi \text{ (in the morning)} \quad (3.8)$$

$$\gamma = \varphi + \psi \text{ (in the afternoon)} \quad (3.9)$$

For surfaces facing west of south

$$\gamma = \varphi + \psi \text{ (in the morning)} \quad (3.10)$$

$$\gamma = \varphi - \psi \text{ (in the afternoon)} \quad (3.11)$$

For south facing surfaces $\psi = 0^o$, so $\gamma = \varphi$ for all conditions, where the angles δ, β and φ are always positive.

Consequently, for a surface with a tilt angle Σ, the incident angle can be calculated as follows

$$cos\varphi = cos\beta\ cos\gamma\ sin\Sigma + sin\beta\ cos\Sigma \quad (3.12)$$

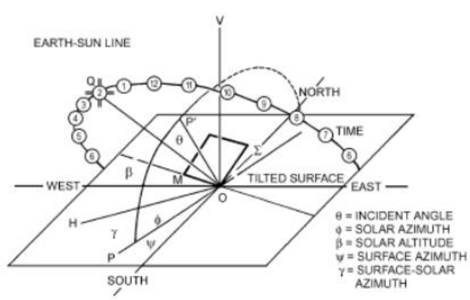


Fig. 3-13 Solar Angles with Respect to a Tilted Surface

Solar Radiation at the Earth's Surface

Normally, some of the sun's direct radiation I_D is scattered through the atmosphere and what actually reaches Earth is known as diffuse radiation I. The intensity of the direct normal irradiation I_{DN} at the earth's surface is given by the following equation;

$$I_{DN} = A\, e^{-B/sin\beta} \tag{3.13}$$

Where A and B are coefficients related to the atmosphere and it varies according to seasons, distance of the earth from the sun and the air's water vapor content.

To conclude, the total solar irradiation $I_{t\theta}$ of a surface on the Earth consists of the sum of the direct component $I_{DN}cos\theta$ plus the diffuse component $I_{d\theta}$ coming from the sky plus reflected radiation I_r, that may reach the surface from any adjacent surfaces.

$$I_{t\varphi} = I_{DN}\, cos\varphi + I_{d\varphi} + I_r \tag{3.14}$$

The diffuse component is difficult to estimate because of its non-directional nature and its wide variations. [35] So a dimensionless parameter C, depending on dust and moisture content of the atmosphere, that changes throughout the year is derived, as a result, the diffuse component is calculated.

$$C = I_{dH} / I_{DN} \tag{3.15}$$

The following equation may be used to estimate the amount of diffuse radiation $I_{d\theta}$ that reaches a tilted or vertical surface; [35]

$$I_{d\theta} = C\, I_{DN}\, F_{ss} \tag{3.16}$$

where;

$$F_{ss} = \frac{1+cos\Sigma}{2} \tag{3.17}$$

which can also be defined as the angle factor between the surface and the sky.

The reflected radiation I_r from the foreground is given by;

$$I_r = I_{tH}\, \rho_g\, F_{sg} \tag{3.18}$$

where;

ρ_g = reflectance of the foreground

I_{tH} = total horizontal irradiation

F_{sg} = angle factor between surface and Earth $= \frac{1+cos\Sigma}{2}$ (3.19)

The maximum daily amount of solar irradiation that can be received at any given location is that which falls on a flat plate with its surface kept normal to the sun's rays so it receives both direct and diffuse radiation. For fixed flat-plate collectors, the total amount of clear-day irradiation depends on the orientation and slope.

For example, the solar irradiation on 29th of November 2016, in Gijon with tilt angle of 23^o and the panel is facing east-south, is shown below.

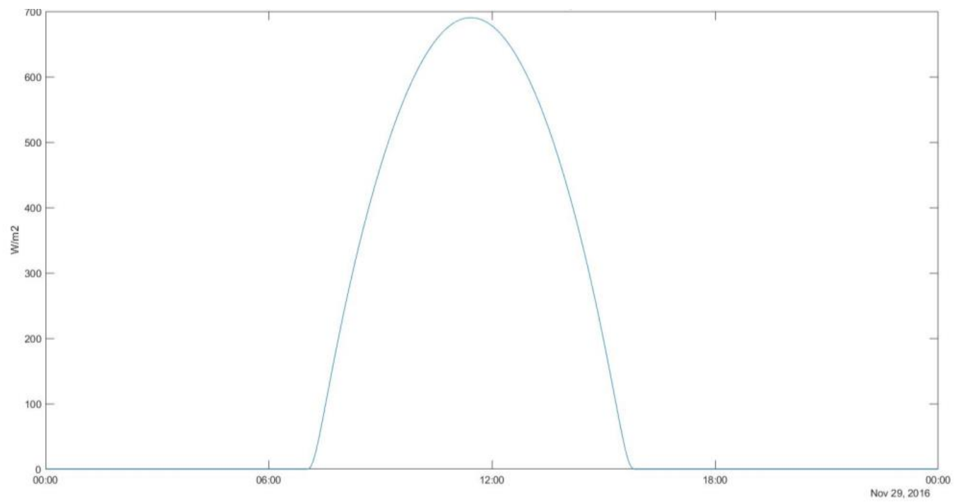


Fig. 3-14 Solar Irradiation on Nov. 29, 2016

The above PV panel profile has a peak of almost 700 W/m^2 and does not depend on any weather conditions that will be introduced to the system later on.

3.4. Retrieving Power Readings

In this part, a function that was used to read power from the ADRES-CONCEPT data matrix and calculates power and energy consumption over smart meter intervals, for a house on specific day, will be discussed.

The ADRES-CONCEPT data matrix has power and voltage readings of 30 houses over 14 days based on one second intervals. The goal was to get the readings for a certain house on a certain day out of this big data. This was achieved by a function in which its inputs were day, house and smart meter interval. Day is an entry of a number from 1 to 14 (inclusive), house number from 1 to 30 and smart meter interval on 15-minute basis.

After adding active and reactive power values for the three phases of each house, a matrix for the whole 14 days for all the houses was created, but with one column for the active power and another for the reactive power. This procedure was implemented using two for loops where the outer loop was to go through the total number of rows of 1296000 seconds for the two weeks, while the inner loop was going through the 30 houses, where each house had 6 values, 3 for active power and 3 for reactive power.

In order to get the data of the definite day, the starting second of the day was the key point for such a procedure. So when entering the day as an input, it should be known how many seconds to be skipped from the data above. The following statement is for the active power column.

(day-1)*86400+1:day*86400,((house-1)*2+1)

For example, if the data for day 4 is to be retrieved, then the data starting from the second after 259200 to 345600 seconds is needed, this is easily achieved from the above statement.

(4-1)*86400+1:4*86400 = 259201:345600

However, for these rows there are data for 30 houses, so the other part of the equation is to retrieve the data of the needed house. For example, if house number 7 is needed then the active power column will be number 13.

(7-1)*2+1 = 13

An interesting factor that needed to be taken into consideration was the accumulative sum of the energy at each second for the whole day. This was the purpose of the command "cumsum" in which, in a column matrix for example, at each instant it added all the values above. Taking into consideration the conversion from power into energy, the following command was used.

cumsum(Dat_day.P/(3.6*1e6))

where Dat_day.P is the active power values of a certain house on a certain day.

Knowing that a single day has 1440 minutes, and dividing this by the smart meter interval, gives the number of readings per day. For instance, the power at 15 minute intervals is the sum of the readings throughout this 15-minute period.

sum(Dat_day.P((i-1)*(sm_interval*60)+1:1:i*(sm_interval*60)))

where i is the number of the smart meter interval of the day and sm_interval is the smart meter interval declared by the user.

So, if the smart meter interval is on 15-minute basis and the consumed power after half an hour from the beginning of the day needs to be calculated. Then,

((2-1)*(15*60)+1:1:2*(15*60)) = 901:1:1800

Meaning that the sum of the power readings starting from the second 901 of the day up to second 1800 will all be added to give the total power consumed over this period.

Another function was built where it functions in the same way, however, the values of the current and voltages of each house was measured from the Simulink model. To retrieve the data from the workspace, a different set of commands were used. The problem was that the workspace had voltages and currents reading of multiple houses, so the challenge was to filter and choose the house which the user entered as an input of the function. A command to evaluate an expression in workspace “evalin”, was used, where it controls which workspace the expression is evaluated in.

3.5.PV Panel Profile

This section describes the function that was used to calculate the power produced by the PV panel after being exposed to different factors. This function deals with a group of houses on a single day. Determining the house goes back to the fact that each individual has their own share of the PV power output, and accordingly each is charged separately. So both, the house number and the share of the house owner in the solar system, are inputs to this function. Along with the day, smart meter interval and the weather condition. The weather condition can be decided to be either sunny, cloudy or heavy clouds.

The first step was to specify the PV panels’ area and the efficiency on the system, then from the previously discussed functions, the power consumption readings of each house and the sun’s irradiation are both returned back to this function. A switch case is created to give random numbers which corresponds to the weather condition on this day. Within this switch case, two affecting factors are created. One is for determining how much sun is the panel is exposed to, where if the input of the weather condition is sunny, then the exposure is from 80-100%, for cloudy days the exposure ranges from 60-80% and for days with heavy clouds the exposure goes down to 30-50%.

1-rand(1)/5, the solution is a random number between 0.8 and 1.

0.7+(rand(1)-0.5)/5, the solution is a random number between 0.6 and 0.8.

0.4+(rand(1)-0.5)/5, the solution is a random number between 0.3 and 0.5.

The second factor was to create a matrix with 86400 values (the total number of seconds per day) to give the effect of the clouds’ presence during the day which will obviously affect the PV panel power output. Almost the same idea behind creating random values for the weather factor was implemented as well.

In the end, the PV power output is referred to each house by multiplying the total generated power by the affecting factors.

PV_area*PV_eff*PV_factor_weather*share_house(i)*house_info(i).Irrad.*PV_clouds;

PV_area: PV panels' area

PV_eff: System's efficiency

PV_factor_weather: Panel exposure to sun

Share_house(i): Individual's share of the total generated PV power

house_info(i).Irrad: Sun's irradiation on this day

PV_clouds: Clouds' density throughout the day

3.6.Electric Vehicle Charging

In this section the electric vehicle charging scheme will be discussed. Charging begins and ends according to the user's vehicle availability at the charging station. An economical approach for the user was implemented to reduce the bills as much as possible.

To begin with, the function takes inputs such as all connected houses to the system from the previous functions, the house number of the user willing to charge their vehicle and the time when the vehicle is available at the charging station.

A matrix with the indices of the total number of seconds per day is created, where the hours of the vehicle's availability is marked with 1 so that further on in the process, it is known when to implement the charging scheme. Data of the user is extracted from the structure containing all the houses which are connected to the system. This step is important in order to analyse the user's share of the PV power output as well as the user's house power consumption, accordingly an economic charging scheme is followed.

The EV's battery capacity was estimated to be 10 kWh when fully charged. A random function generated a number that was considered the distance moved by the vehicle, as a result it was easily calculated how much the battery was discharged, in other words, what percentage of the battery's capacity is left and how much does it need to charge.

bat_init = 10;

EV.distance=45+randi([-10 10],1,1);

EV.kwh_100=15;

```
EV.ch_consump=EV.kwh_100*EV.distance/100;

EV.bat_cap = ((bat_init-EV.ch_consump)*100)/bat_init;

EV.bat_cap_init = EV.bat_cap;
```

As it had been mentioned, the battery capacity is 10 kWh when fully charged. EV.distance generates a random number ranging from 35 to 55 which represent the distance moved by the vehicle. EV.kwh_100 represents how many kWh does the battery consume with every 100 km moved by the vehicle. EV.ch_consump is to calculate the actual decrease in the battery's capacity in kWh, while EV.bat_cap represents the available battery's charge percentage that has to be recovered by the charger. Next, with respect to the charger's ratings as current, voltage and power, the time taken to charge the battery was determined easily.

The following step was to calculate the house's excess of power. Excess in terms of PV power generated that was not used within the house. The reason for this was to control the time when the EV was charging. For example, the EV was allowed to start charging only during two conditions. First, if the battery capacity was below 80% of the full capacity, second, if the battery's capacity is below 95% and there was power excess from the user's needs, only then the battery can start its charging again. Before implementing or going through any of these conditions, it must be checked that the EV is available for charging at the very first place. In this way, users can suffice their preliminary needs with the ability of reaching the fully charged state at almost no extra costs.

```
if ((EV.bat_cap<=80) || ((excess(k)>0) && (EV.bat_cap<=95)))
```

In the very end the house data was updated with power consumption from the EV charging of this specific house.

3.7. Energy Storage System

This section is related to the energy storage system installed with the solar panels. It should be known that the individuals subscribed in the system has shares in the total battery capacity similar to the PV power output. The function starts with taking an input of information about all the houses connected to the system and like everything in this model, the procedures are carried out for a single previously specified day.

The function starts with giving a random energy capacity for the battery's current state of charge, while declaring some parameters such as the power that the battery can fully give when fully charged, battery's nominal rating in kWh, minimum power that can extracted from the battery and the battery's efficiency. Following, was calculating the PV power output and the load of all the houses, however, not the total load was summed up, only the share of the load corresponding to the user's share in the solar system.

load_PV = ((house_info(n).house_share)*(house_info(n).P)) + (house_info(n).house_share)*transpose(house_info(n).EV.P) + load_PV ;

load_PV is the power consumption of the houses plus their corresponding vehicles.

The charging scheme is as follows, if the PV power exceeds the houses, EVs and battery's maximum power needs and the battery is not charged, thus, the battery will be charged with maximum power and if there is any excess from the PV generated power, it is considered surplus to the grid.

If the PV power output is more than the users' consumption only and the battery is not charged, then after satisfying the load, if there is any extra generated power; charge the battery.

If PV generated power is greater that the consumption and the battery is charged, therefore, give the network any excess power after supplying the load.

If the loads' needs are more than the PV generated power and the battery's maximum power output combined and the battery is charged, then the load is supplied from the PV and with the battery's maximum power output. If still the load is unsatisfied, the grid starts supplying the load. In this case the battery is discharging.

If the load is more than the PV generated power output but not more than the battery's maximum power output and the battery is charged, therefore, the battery gives the load the rest of the power which it needs and the PV cannot give. In this case there is no grid support but the battery discharges as well.

Lastly, if the load is greater than the PV generated power and the battery is not charged, then the battery capacity remains the same and the network provides the system with any shortage.

3.8.Consumption Calculation

After building the whole model, this section will discuss the function generated to charge each customer individually. The limitation was the fact that electrons do not get to decide in which direction they should move, electrons move through the less resistive path. So, a user can have a 20% share of the solar system, but at an instance their consumption is more than their available power to use from the solar system. There is nothing to limit the power drawn from the energy storage system or the PV generated output, or nothing to force the user to start consuming energy from the grid rather than the solar system. This makes it unfair to other unavailable consumers at the moment, as no energy will be left for their future use. So the billing scheme was as follows, each user was able to consume whatever energy they need from wherever available source that can give this energy, however, at the billing time, it will be checked how much energy can this user consume from the solar system, if it is within their permissible limits then it is fine, if not, and they violated their neighbors' share, then they will have to pay on their neighbors' behalf.

For the whole building there are 3 energy sources; first is PV generated power output which is responsible for supplying the load and charging the connected batteries, second is the energy storage system that is charged from the PV and used to supply the load when there is no available energy out of the PV and last is the conventional energy supply from the grid. Each household has a fixed energy percentage share of the solar system, the PV and the batteries supply. Thus, in order to know how much a user exceeded their contracted share, their power consumption is checked at first. After checking the power consumption, it is deducted from this specific user's share of the PV generated power output, if the load is satisfied then the process ends, if not, check the battery's state of charge. If at this instance the battery is charged, then deduct from the battery the remainder from the load that the PV could not supply, then if the load is satisfied the process ends here, otherwise the grid supplies the energy in which both the PV and the battery were not able to. However, if from the very beginning the battery was not charged, the grid supplies the load with what the PV could not satisfy.

The above scheme will be explained clearly in the following flowchart.

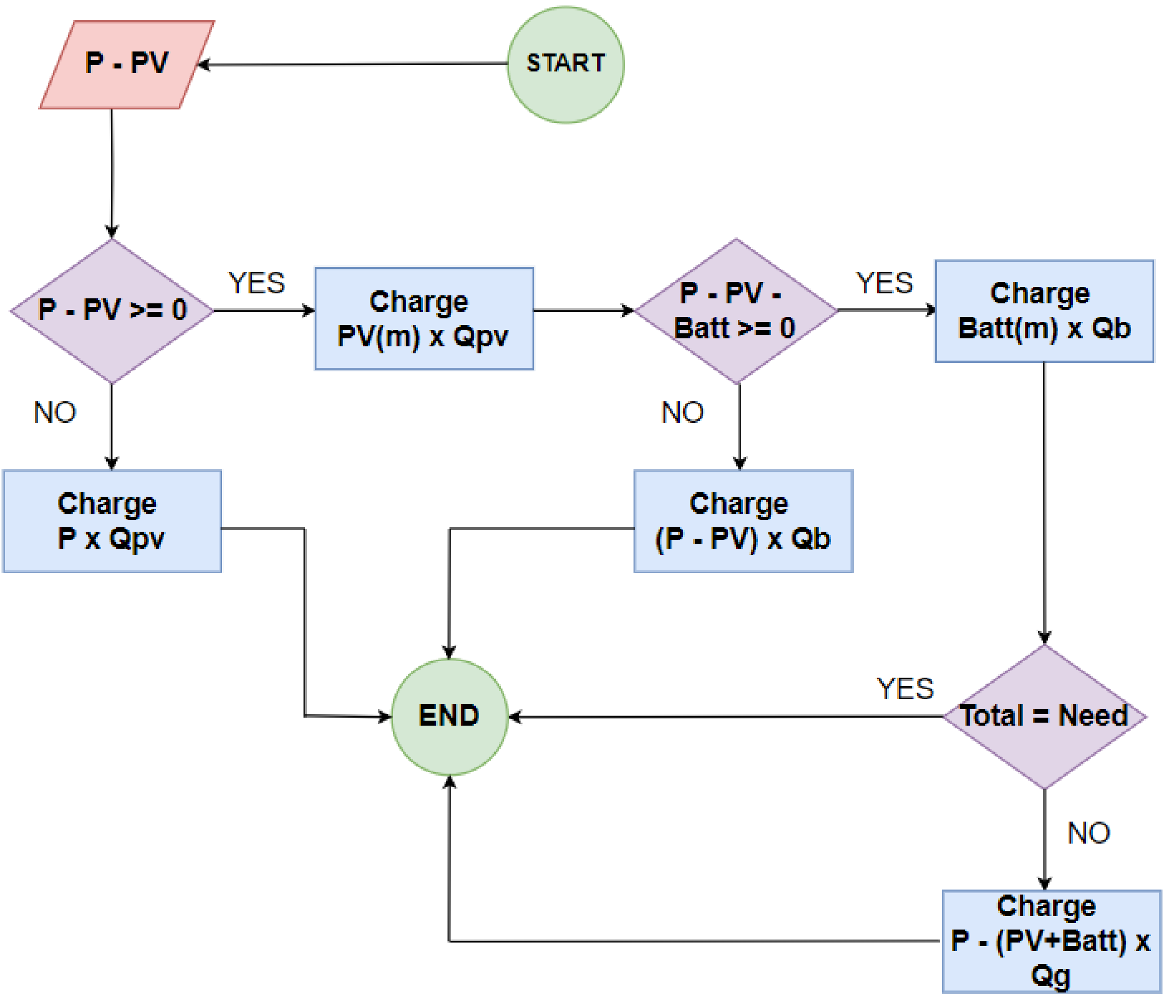


Fig. 3-15 Flowchart for Billing Scheme in Building

P: Load power

PV: Panels' generated power output

Batt: Battery's state of charge

Qpv: €/kWh for PV supply

Qb: €/kWh for battery supply

Qg: €/kWh for grid supply

(m): Given instance

It can be explained as follows, get total consumption of the house P, calculate how much it can get from the PV, calculate how much it can get from the battery, both considering the shares of the user in the solar system. Deduct total power consumption from what the PV can give, charge with Qpv of what the PV can give if the power consumption is less than the PV generated power output. If the power consumption is more than the PV generated power output, then check is the battery is charged or not, if charged check what the battery can give to the corresponding house then deduct the energy from the battery and charge with Qb of what the battery can give if the power consumption still exceeds the available energy, if not then charge with Qb of the extracted power from the battery. If the load is still not satisfied, charge from the grid with Qg of the remainder of the load in which both the PV and battery cannot give.

In this scenario each user is charged individually regarding their shares in the solar system, so it no longer matters where the electrons supplying the load are coming from, because in the end each will be billed according to their corresponding shares.

One last addition was that according to EDP, there is a fixed sum of money that has to be paid monthly regardless the customer's consumption. This fixed amount is based on the contracted power, which has to be more than or equal to the installed load at the house. Variating charges that is according to the customer's energy usage, has two amounts depending on the time of the day when the energy is being consumed. Both charges were added in the function for each individual house.

3.9. User Interface

This section discusses a function in which all the previous functions were added together to give the final outlook of the project before adding everything in a single Simulink model.

This function introduces user interface to make it easier for the customer to observe their consumption and generation without the complication of having to deal with Matlab scripts. Once the function is loaded, the user has to answer a set of questions in order to identify themselves and their preference of solar system's share.

The set of questions are;

What day it is?

Which houses are connected?

What is the smart meter reading interval?

What is the house share of each of the connected houses?

How is the weather on this day?

What time period is your vehicle available?

What is your house number?

After these questions, the program analyzes all the data and brings back the needed data such as, power consumption of the houses, PV generated power output according to each house's share, surplus going into the grid from the whole building, how much energy does the building consume from the grid and the bills for energy consumption calculation.

The following example will show the profiles for 2 houses connected to the system, house number 3 and number 15, with 60 and 40% shares of the solar system respectively. It is the second day of the first week and the weather is sunny. Each user will enter their EV's availability as well, while the smart meter interval is at hourly basis.

```
What day it is? 2
Which houses are connected? [3,15]
What is the smart meter reading interval? 60
What is the house share of each of the connected houses? [0.6,0.4]
How is the weather on this day? 1
What time period is your vehicle available? [18,22]
What is your house number? 3
What time period is your vehicle available? [15,23]
What is your house number? 15
```

Fig. 3-16 User Interface of the Model

The following figures will show the load profiles (house and EV consumption) against the PV panel profile for each of the houses.

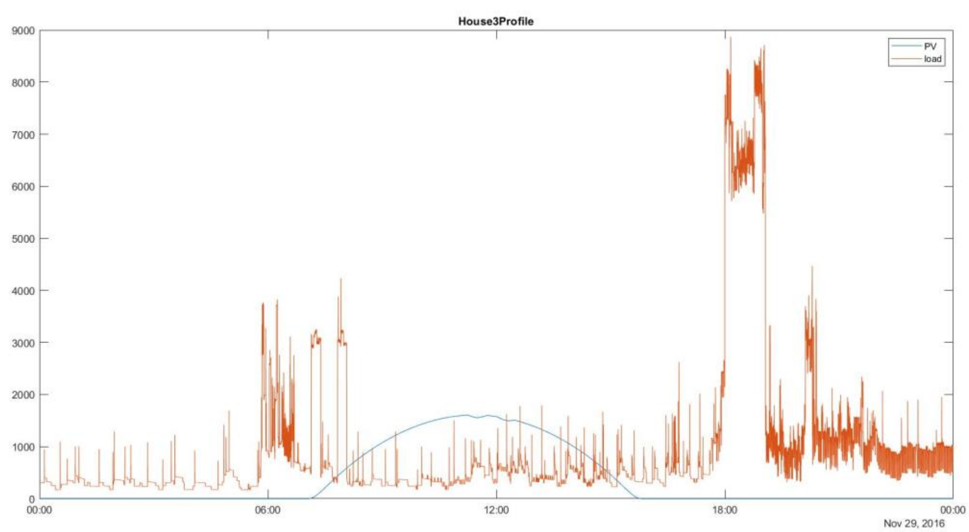


Fig. 3-17 Profile of the First Connected House

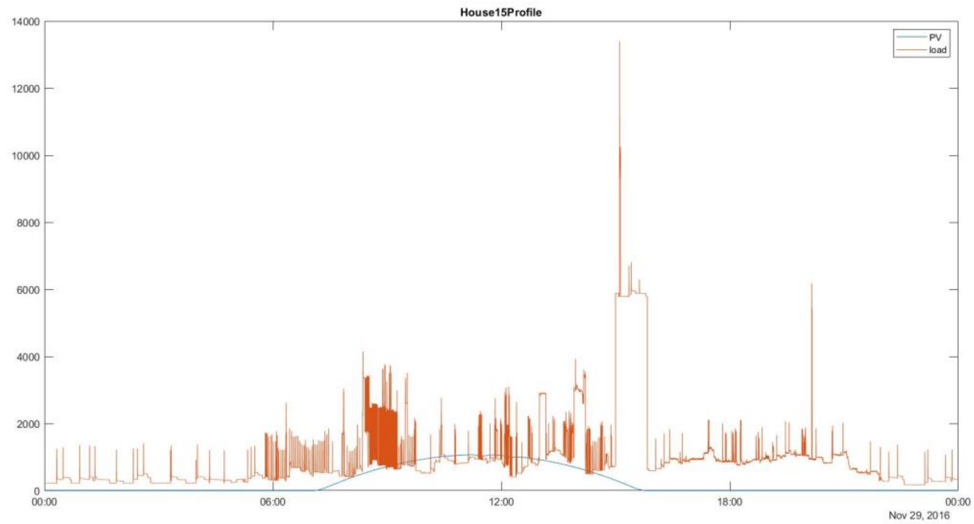


Fig. 3-18 Profile of the Second Connected House

Now it is obvious how the share of the solar system for each individual have a drastic effect on their corresponding PV generated output and their self-sufficiency needs. For example, at around noon the corresponding PV power output for house 3 was around 1400 W/m^2 while at the same time the generated power output from the PV for house 15 was around 900 W/m^2.

3.10. Building Model Programmatically

The last and final step of building this model, was to create a Simulink model containing all the system's components from the load of the house, the EV charger consumption, the PV panels and the energy storage system.

Unlike the previously created Simulink model, the model is not built with manually introducing which houses are connected to which phase. However, the function for creating the model takes the information from the function in the previous function and automatically distributes the houses on the phases, taking into consideration that the connected houses should be a multiple of 3 to avoid the system's unbalance. For simplification of the model, the inverter for the solar system and the one for the EV charger were not added to the system, but rather, the total power from both were divided over the three phases to represent the connection of the inverter.

The following figures will show the Simulink model after adding 3 houses, their corresponding vehicles, the PV panels and the battery bank.

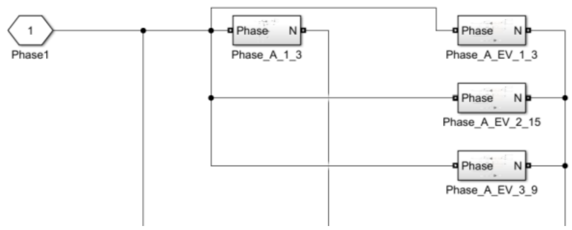


Fig. 3-19 Phase A House and EVs Connection

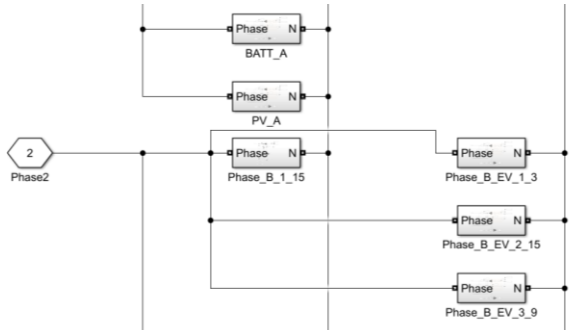


Fig. 3-20 PV and Battery Connected to Phase A, House and EVs Connected to Phase B

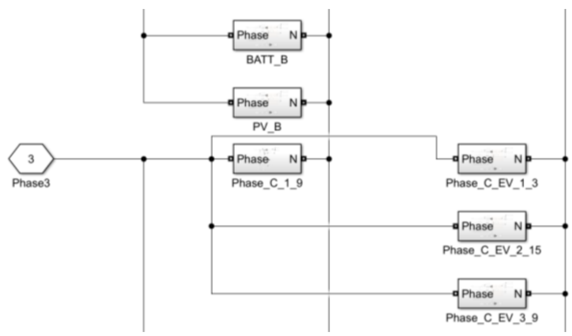


Fig. 3-21 PV and Battery Connected to Phase B, House and EVs Connected to Phase C

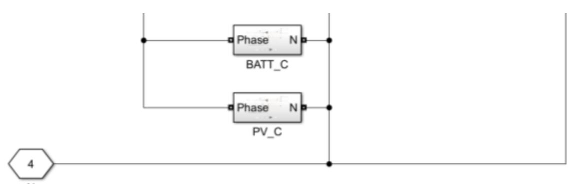


Fig. 3-22 Phase C PV and Battery Bank Connection

As it shows, houses 3,15 and 9 were added to the Simulink along with their corresponding vehicles. Also, the PV panel and battery bank representation were added to the 3 phases.

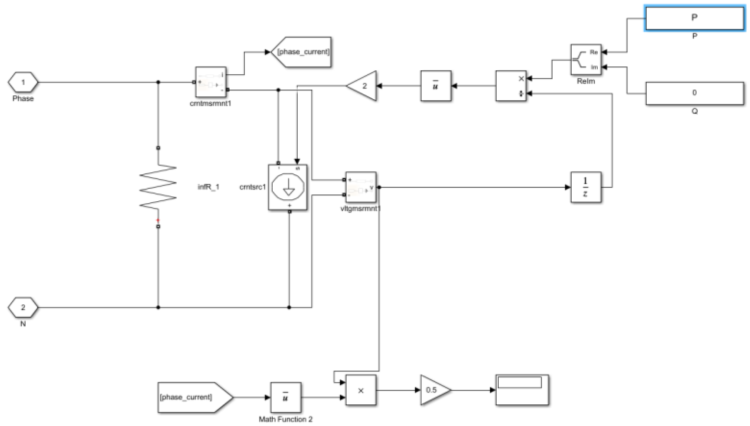


Fig. 3-23 PV, Battery and EV Representation

The active and reactive power are input to the real and imaginary ports respectively to calculate the apparent power which is then divided by the measured voltage of the house. This calculation results in a current that drives the controlled current source block. However, in this case the reactive power does not exist due to the fact that the corresponding elements are of DC nature.

Chapter Four

4. Results and Tests

This chapter is for carrying out different tests on the studied model and comparing results to confirm the success of a shared solar system as well as to find the most optimum setup that each consumer will benefit from.

4.1.PV Panels' Profiles

As it has been mentioned, the study carried out for the thesis was for 2 weeks during the year, one during the summer and the other during the winter. The next figures will compare the solar irradiation between a summer day and a winter day, with all angles constant. The tilt angle in this case is 23^{o}.

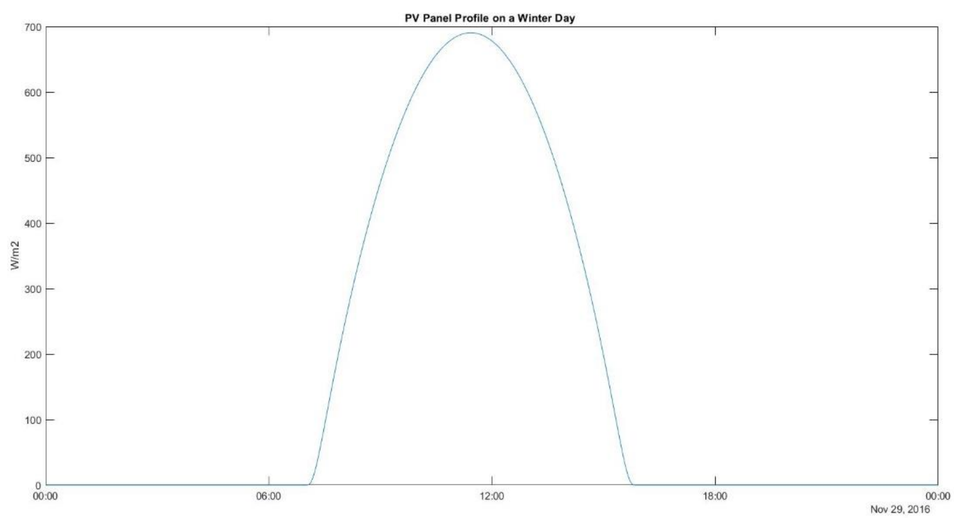


Fig. 4-1 Winter PV Panel Profile

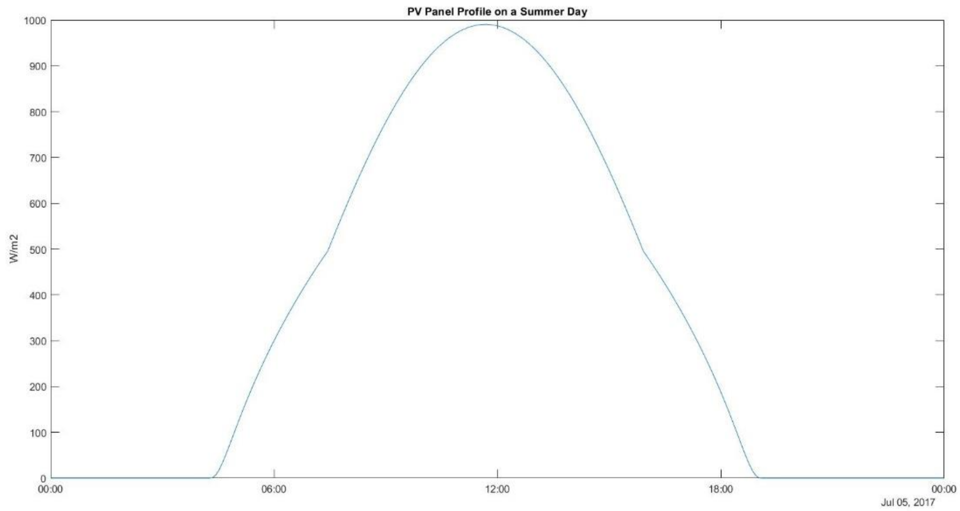


Fig. 4-2 Summer PV Panel Profile

The figures prove the fact that the sun's irradiation during summer days is stronger than winter days. Also, it is obvious that summer days have longer daylight hours, thus, the benefit out of the solar system increases.

Now, the tilt angle will change from 23^o to 0^o to observe the effect of the tilt angle on the generated PV panel profile.

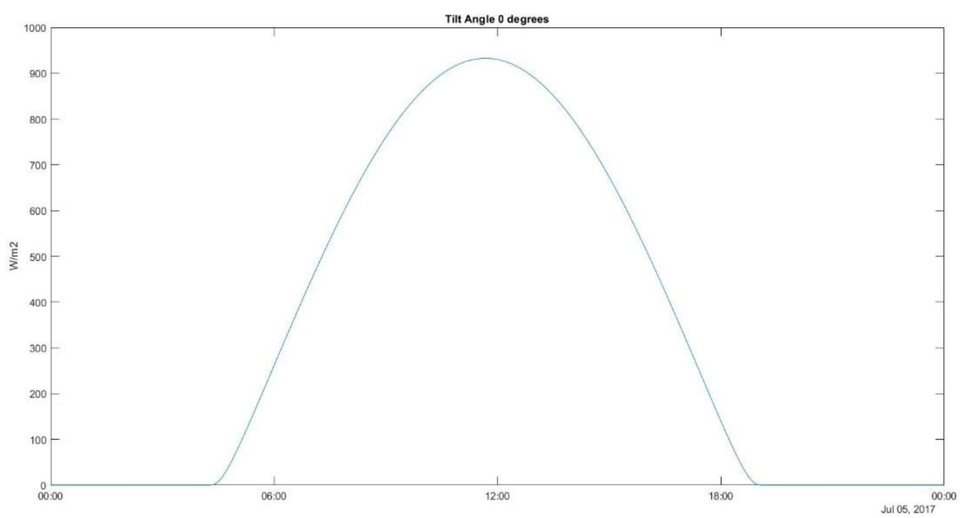


Fig. 4-3 PV Panel Profile with the Panels Horizontal

The above test shows that the tilt angle is a crucial factor affecting the PV panel profile, and that the tilt angle affects the smoothness of the profile as well as the generated power output.

However, the above figures only show the irradiation, independent of weather conditions and solar panels' area. The following figures will show the PV generated power output for one single house on a summer day, but with different weather conditions and PV panels' area.

First, the PV panels' area will be kept at $25m^2$ and all other conditions will be kept constant unless the weather condition, it will change between sunny, cloudy and heavy clouds.

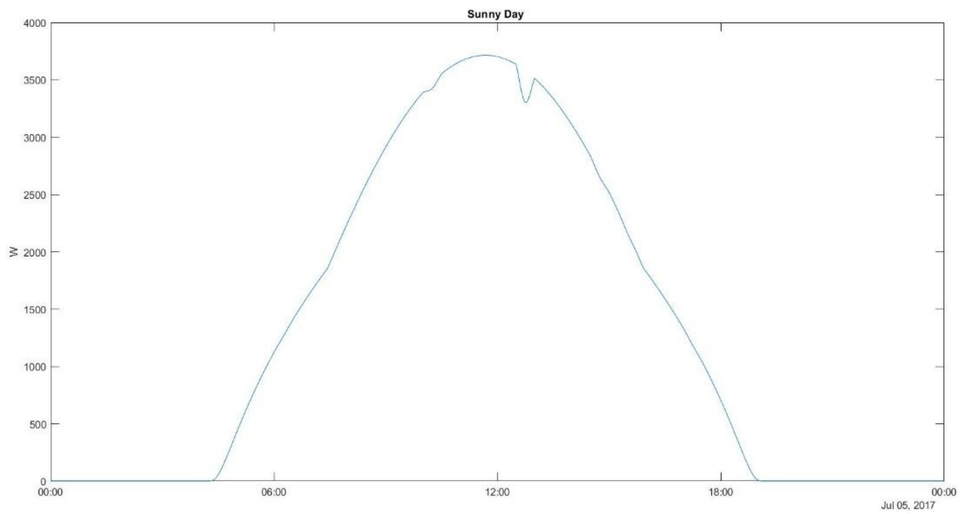


Fig. 4-4 PV Generated Power Output on a Sunny Day

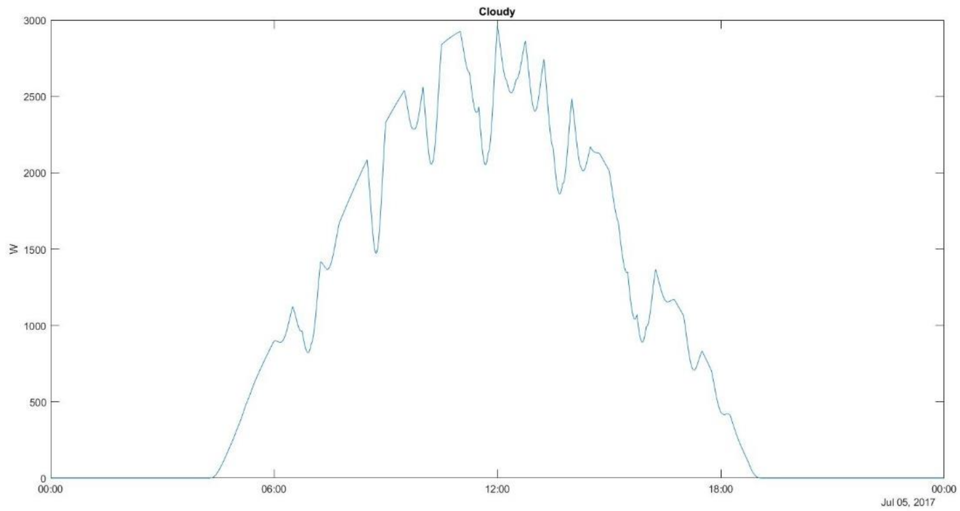


Fig. 4-5 PV Generated Power Output on a Cloudy Day

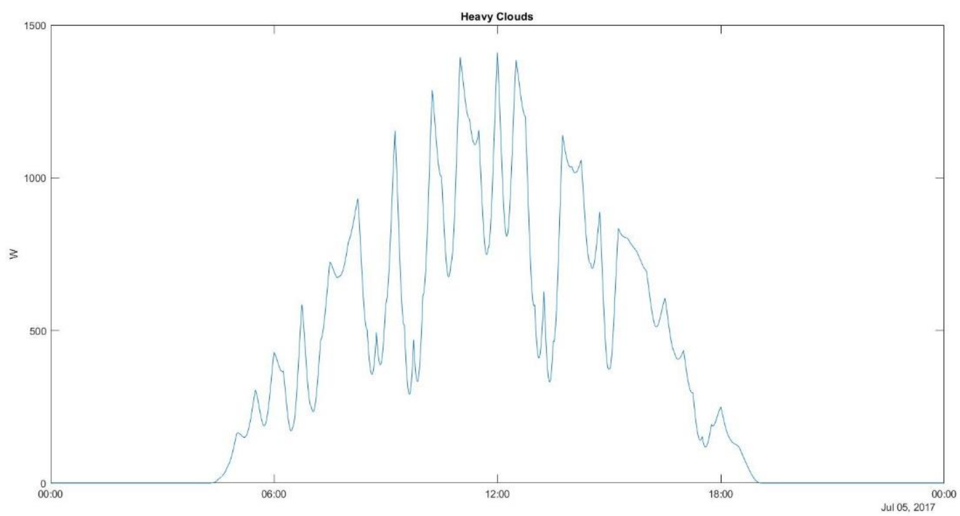


Fig. 4-6 PV Generated Power Output on a Day with Heavy Clouds

Since, clouds limit the exposure of the sun to the PV panels, therefore the drastic decrease in the PV generated power output is observed as clouds density increase.

Another factor that will affect the PV generated power output, will be the PV panels' area. All variables will remain constant other than the area in the following test.

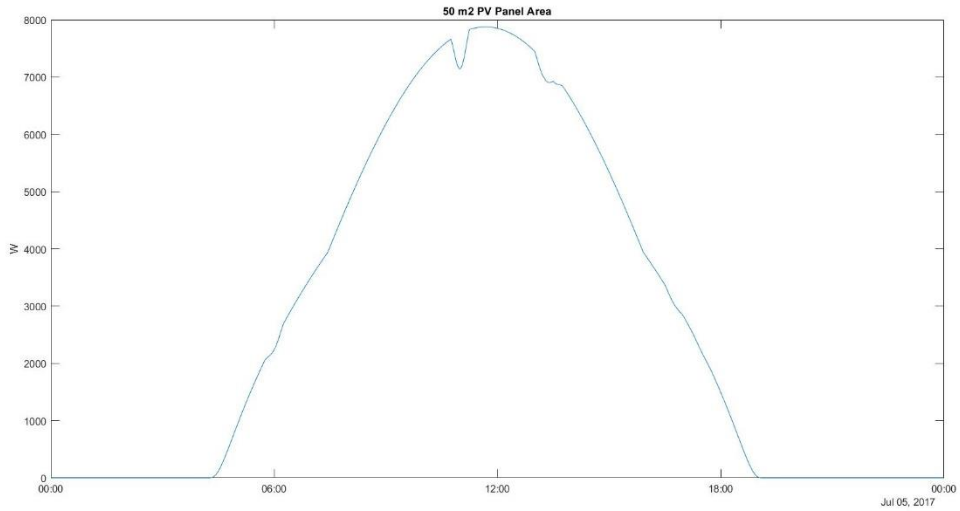


Fig. 4-7 PV Generated Power Output on a Sunny Day with 50m2 area

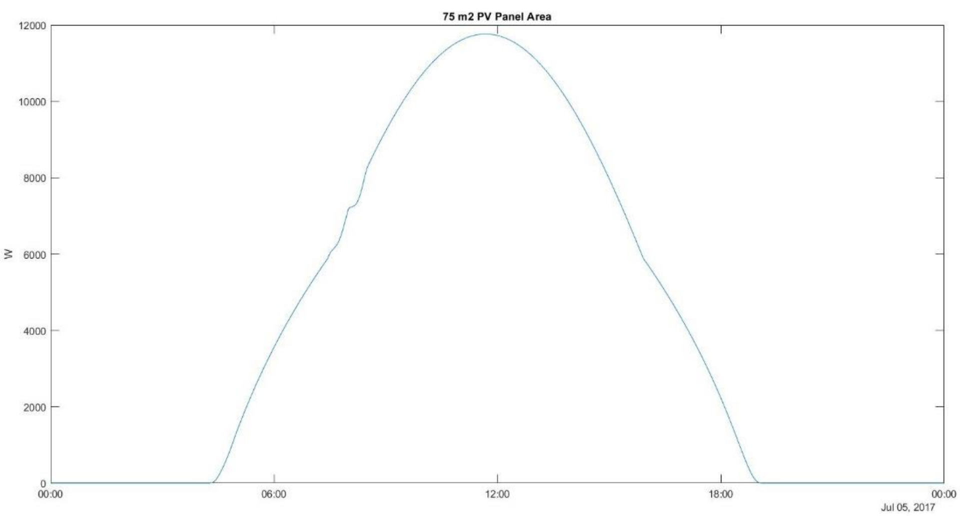


Fig. 4-8 PV Generated Power Output on a Sunny Day with 75m2 Area

As the PV panels' area increases, this allows more surface area to be exposed to the sun, hence more generated power output.

PV panels' variables not only affect its profile or its generated power output, but has an impact whole system, like the surplus energy to the grid that will be shown below.

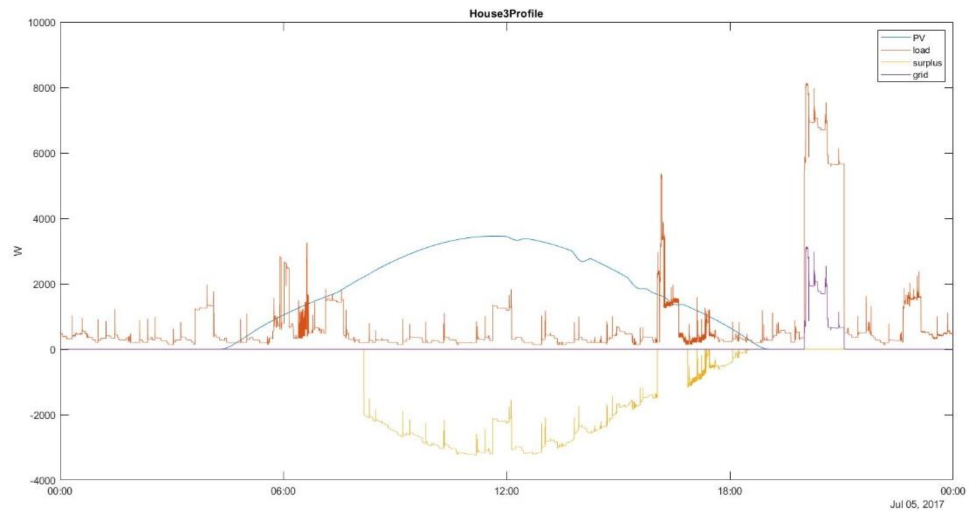


Fig. 4-9 Data for a Single House with PV Panel area 25m2

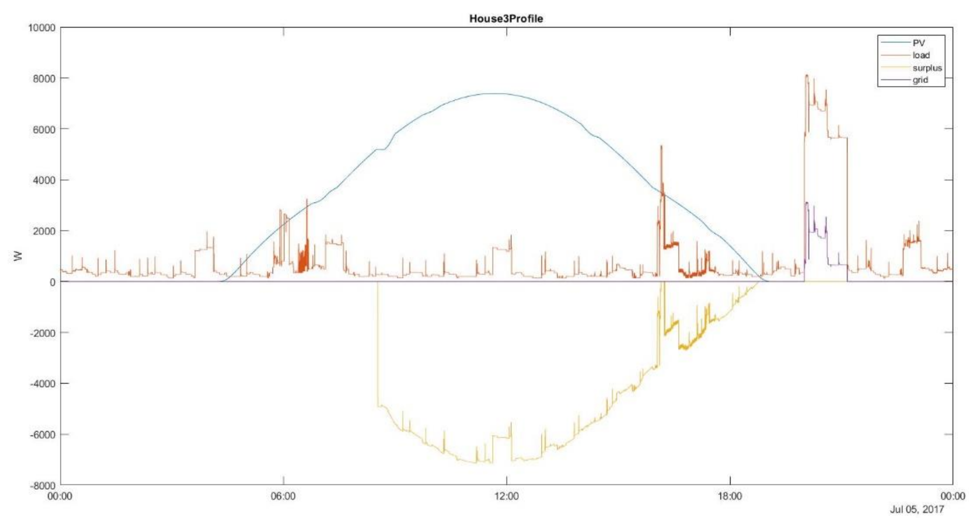
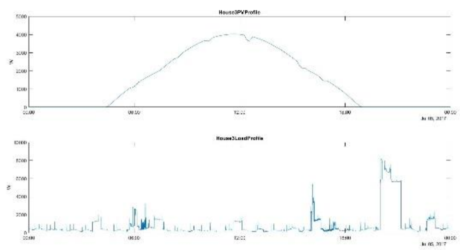
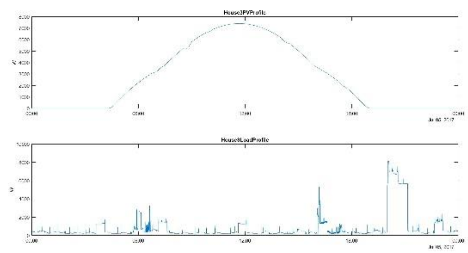
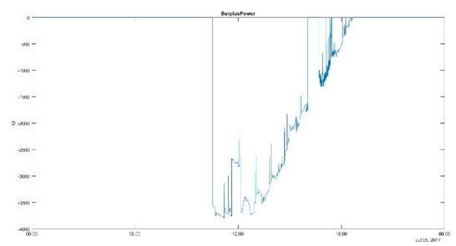
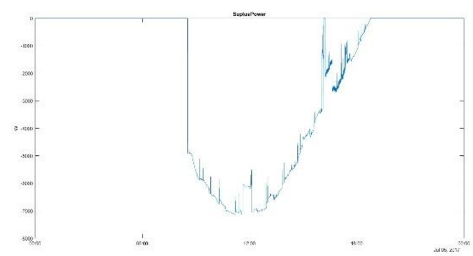


Fig. 4-10 Data for a Single House with PV Panel Area 50m2

The effect that the PV generated power output on the surplus energy to the grid is significant. The more generated power from the PV, the less dependent the user is on the grid, and the more excess energy is available. This excess energy can be used in various ways, either for charging the energy storage system, or for selling to other users like in other systems for example or finally for throwing it into the public network. In this case the surplus energy represents the energy given to the grid from the installed solar system.

Table 4-1 Comparison of Surplus Energy for Different PV Panel Areas

25 m^2	50 m^2
	
	

4.2.Financial Effect of Self-Consumption

In this section, the economic benefits of an installed solar system will be shown. The model will run under two conditions, the first is with a solar system installed, of 50 m^2 PV panels' area, and the other has no solar system installed. This time the test uses house number 9, considering a sunny summer day.

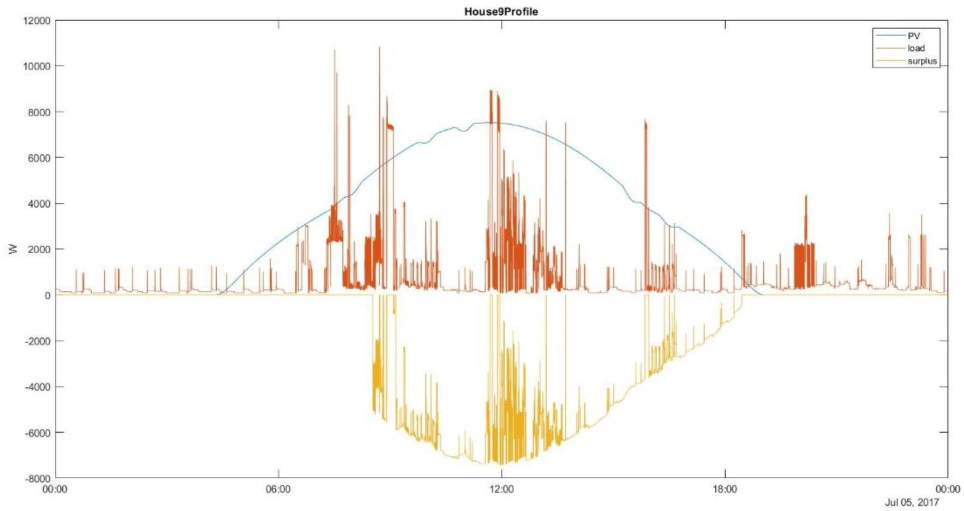


Fig. 4-11 Self-Consumption on a Sunny Day

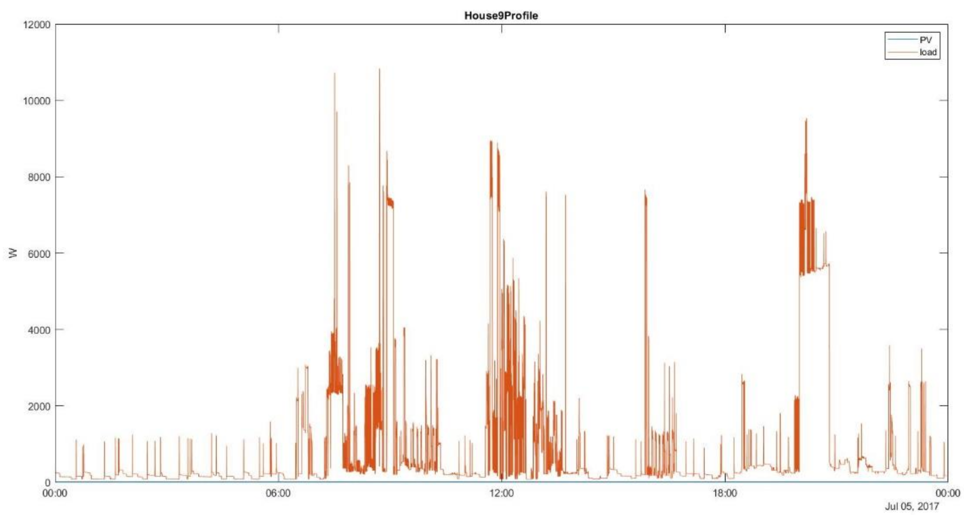
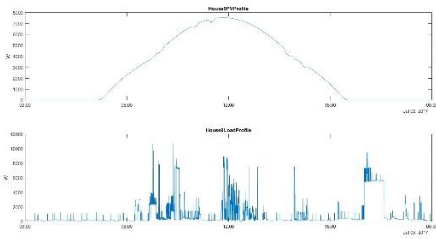
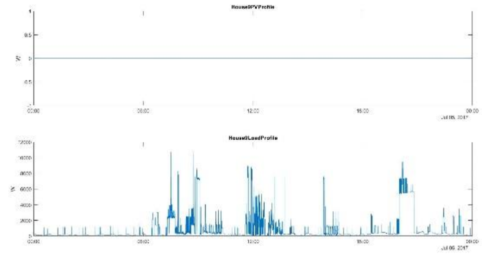
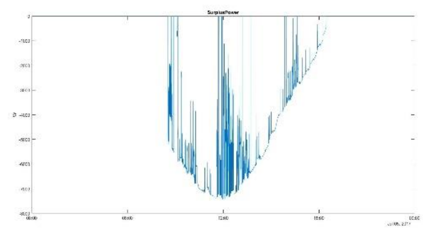
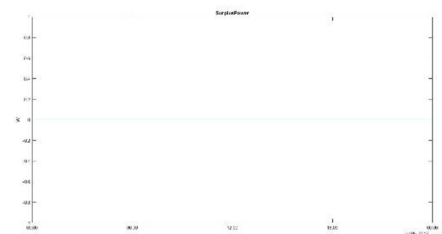
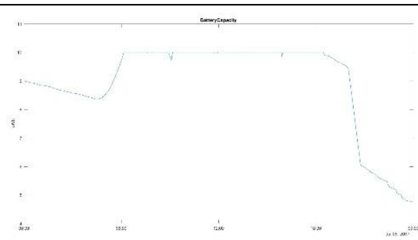
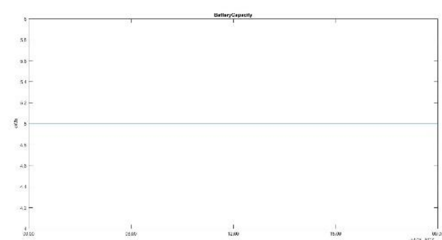


Fig. 4-12 No PV Generated Power Output

The difference between both conditions is in the PV generated power output, when the PV generated power output does not exist, the surplus energy does not exist as well.

Table 4-2 Comparison between Presence and Absence of a Solar System

Self-Consumption	No Solar System
	
	
	
Total energy cost per day = 1.2645 €/kWh	Total energy cost per day = 1.5145 €/kWh

Since, there is no generated power from the solar system, there will not be any excess energy to be provided to the grid. Another notable difference, is that the battery bank does not charge, taking into consideration that it only charges from the PV generated power output. Most importantly, the financial difference between the 2 systems shows in the total energy cost per day. This difference may not be a huge one, but it should be taken into account that it is only per day, and it will accumulate over the month to give a significant reduction in the energy bills.

4.3.EV Charging Scheme

Electric vehicles in this model are charged as follows, EV was allowed to start charging only during two conditions. First, if the battery capacity was below 80% of the full capacity, second, if the battery's capacity is below 95% and there was power excess from the user's needs, only then the battery can start its charging again.

Electric vehicles of three houses were connected to the model in order to check the operation of the charging scheme and whether it fulfills the stated conditions or not.

The first house, house number 11, had its EV connected to charge starting from 11h to 17h. Second house's, house number 17, was available from 18h to 23h while the last house's, house 24, availability was from 17h to 20h.

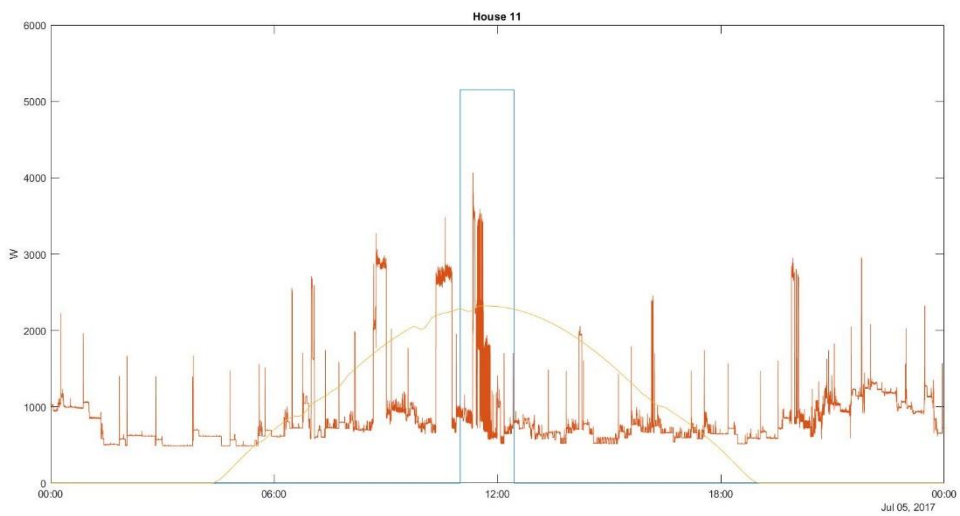


Fig. 4-13 PV, Load and EV Profiles for House 11

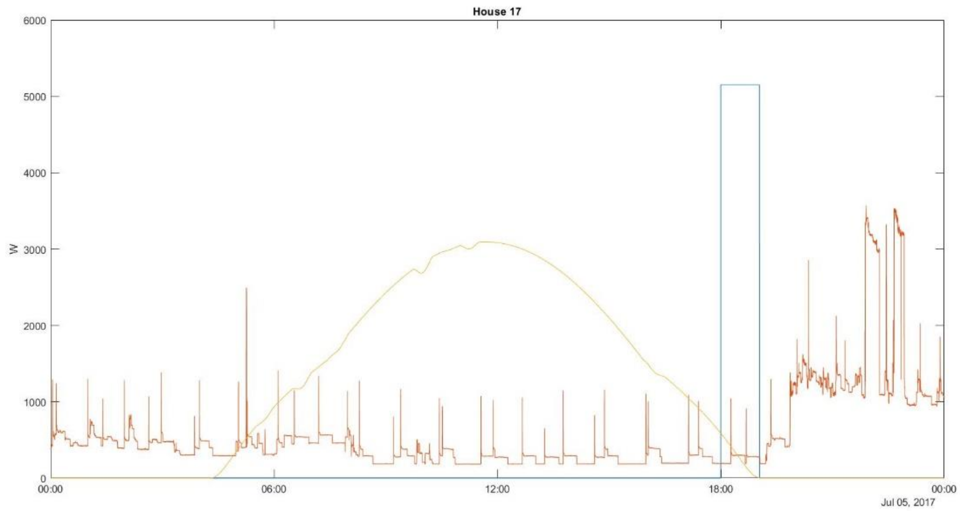


Fig. 4-14 PV, Load and EV Profiles for House 17

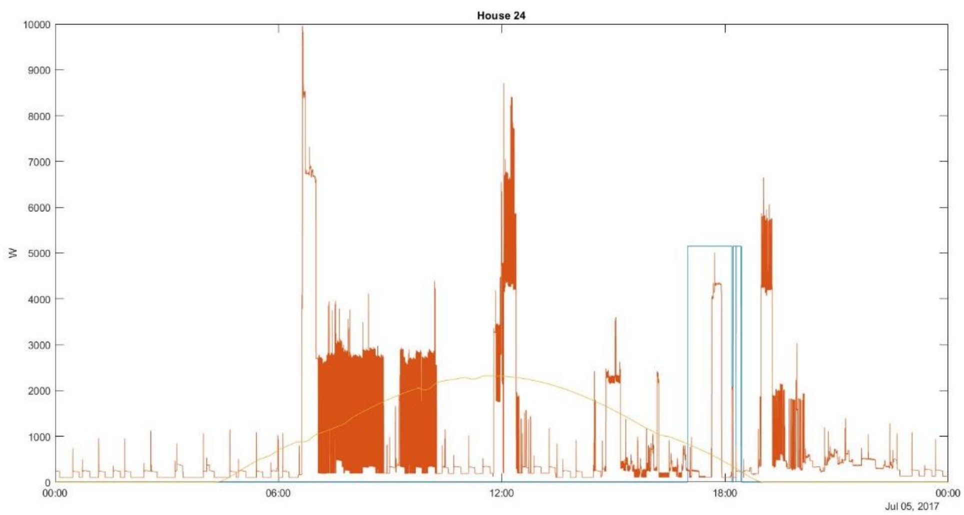


Fig. 4-15 PV, Load and EV Profiles for House 24

Power drawn from the EV charger started at the indicated time by each user, the time in which the vehicle is stated to be available. However, not all the vehicles' state of charge reached the maximum, the reason was the condition limiting the charger to exceed 80% if there is no excess power from the PV available. This control action was significantly observed in house number 24. The EV started charging once it was plugged in, as the battery percentage was below 80%, then it stopped once it reached 80%, however, after some time due to the presence of excess generated power output the battery started recharging again, but at an instance there was no longer excess power to continue charging the battery so the charging cycle had to stop. This process continues, in term of charging and discharging regarding the excess energy, until the battery reaches the specified state of charge, then the process stops.

distance	53
kwh_100	15
ch_consump	7.9500
bat_cap	95.0036
bat_cap_init	20.5000
ch_Irated	32
ch_Prated	7.3600
ch_Preal	5.1520
ch time hours	1.5431

Fig. 4-16 EV's Battery Properties for House 11

distance	49
kwh_100	15
ch_consump	7.3500
bat_cap	80.0092
bat_cap_init	26.5000
ch_Irated	32
ch_Prated	7.3600
ch_Preal	5.1520
ch_time_hours	1.4266

Fig. 4-17 EV's Battery Properties for House 17

distance	52
kwh_100	15
ch_consump	7.8000
bat_cap	95.0010
bat_cap_init	22.0000
ch_Irated	32
ch_Prated	7.3600
ch_Preal	5.1520
ch_time_hours	1.5140

Fig. 4-18 EV's Battery Properties for House 24

For each house, the distance in which the vehicle has moved is noted as distance, in which it consumes 15 kWh every 100 km noted as kwh_100, and it needs ch_consump of energy to be fully charged again. All vehicles start with a battery capacity of bat_cap_init and the battery's state of charge reaches bat_cap when fully charged. The ratings of the charger's power are calculated as follows; ch_Irated is the rated current in which, with the outlet's voltage, is used to calculate the rated power ch_Prated, however, due to the charger's unideal efficiency, the actual output power is ch_Preal and it takes ch_time_hours hours to recharge the battery to the desired state of charge.

4.4.Energy Storage System Charging Scheme

Energy storage system of the proposed model only charges when the PV generated power output satisfies the connected load and has excess power to give in order to charge the battery bank. The following test will have a single house connected to the system on a sunny summer day, and the charging profile of the energy storage system will be observed with respect to the generated PV power output and the total load consumption of the house added to its connected EV.

The tested house, house number 26, is the only property connected to the system. The data extracted from ADRES-CONCEPT data matrix shows a constant load profile of the house, it can be estimated that the house has no one inside it and that the drawn power is for the necessities of electrical equipment that are always connected. However, at 19h an electrical vehicle was connected, this explains the rise in the load profile of the house.

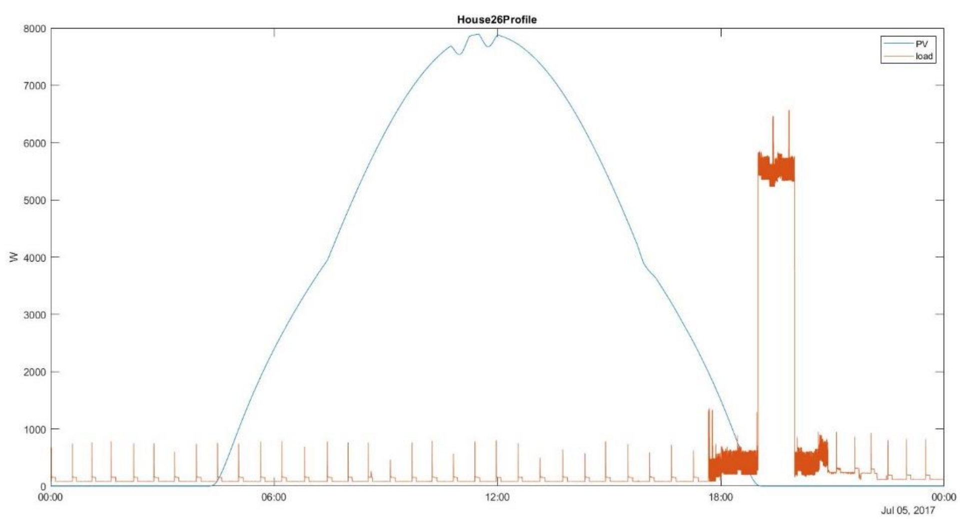


Fig. 4-19 PV and Load Profile of House 26

Things to estimate from house number 26 PV and load profile are, the battery bank of the energy storage system of the building will not start charging except after the intersection of the PV generated power output and the load profile, somewhere between 4 and 5 a.m., also that there will be no surplus energy out of the building except when the battery reaches full charged capacity. Another observation is that the battery should start supplying the connected load after the PV generated power output falls below the load demand of the house, somewhere around 18h and 19h.

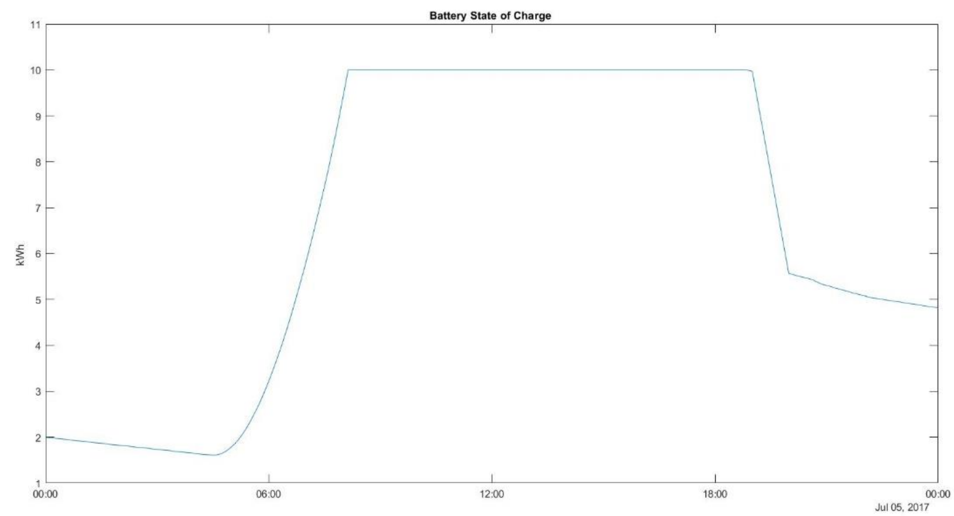


Fig. 4-20 Energy Storage System Charging Scheme

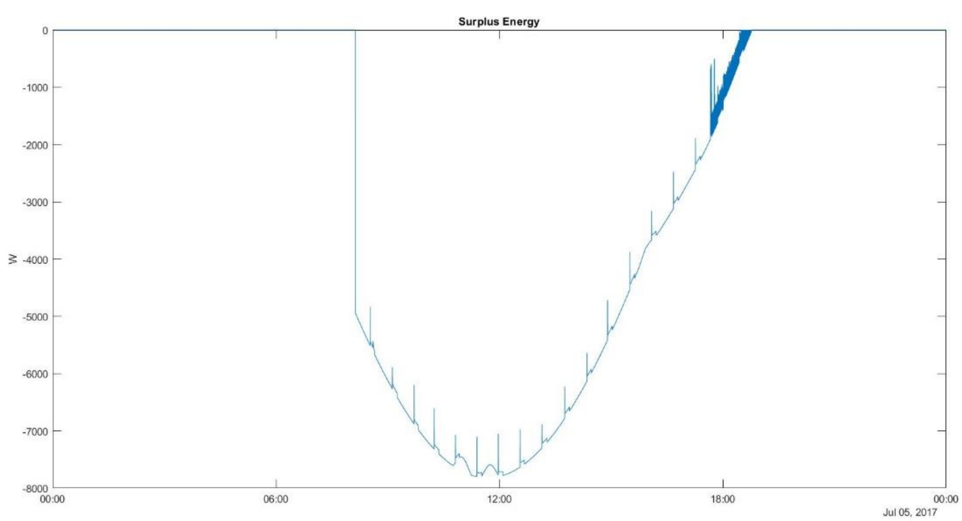


Fig. 4-21 Excess Generated Energy that is not Used by the House

The day starts with a certain state of charge for the battery, it starts discharging as the load demand is more than the generated PV power (which is nonexistent at the time), only when the PV power output satisfies the load and more, the battery starts charging until reaching its maximum capacity. When the energy storage system reaches maximum capacity and the PV still generates more power than the load demand, there will be available surplus energy to give to the grid. On the contrary, the system stops giving energy to the grid once the PV generated power output falls below the load demand level and the battery starts discharging to satisfy the load and the grid gives any excess energy that the energy storage system cannot fulfill. For example, at 19:52h the load demand was 5692 W, and the energy storage system's rating is 5000 W maximum power output. This means that there should be grid support of the remainder power, 692 W.

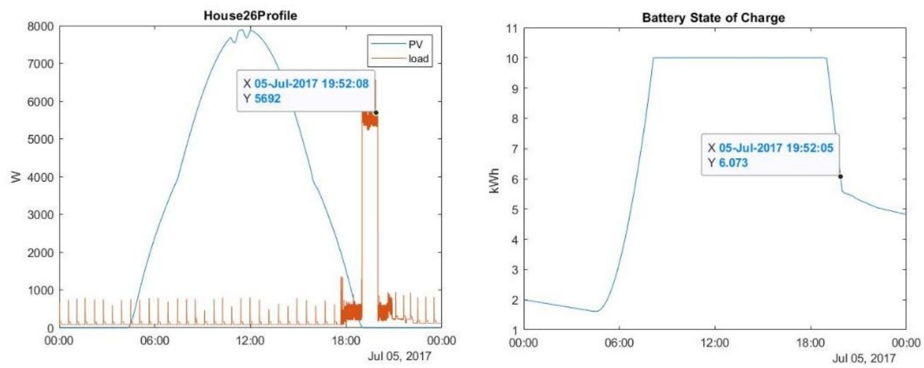


Fig. 4-22 Data from Building at 19:52

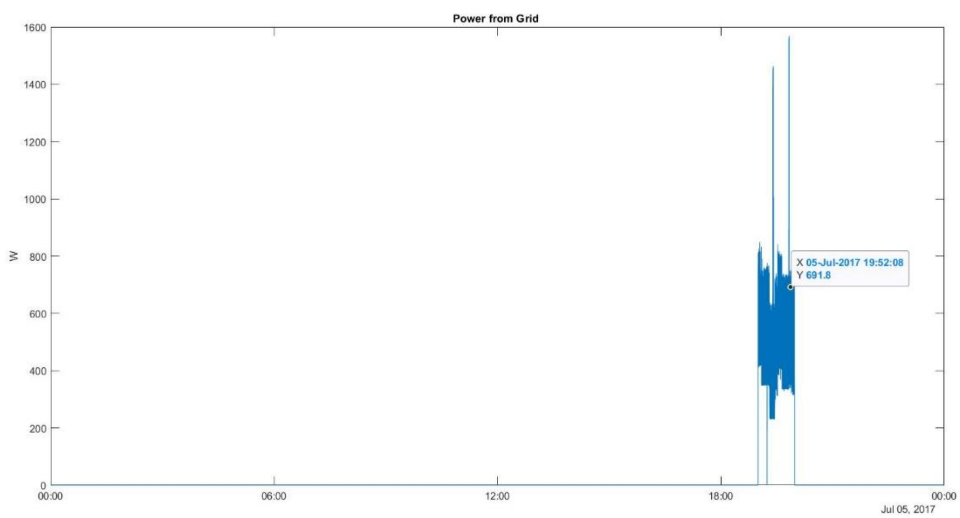


Fig. 4-23 Power Support from the Grid

Energy storage charging scheme can be concluded as follows;

Charging when PV power output is greater than the load demand.

Constant when PV power output is greater than load demand and the battery's state of charge is equal to its nominal rating.

Discharging when PV power output is less than the load demand.

4.5.Simulink Power Readings

In this section, it will be tested whether Simulink model's blocks consume and produce the same power and energy as developed from the Matlab functions. First, the Simulink model of the building on its own is tested on a random day. The next figure is a plot of the load consumption out of the ADRES-CONCEPT data matrix against the Simulink output of the same house.

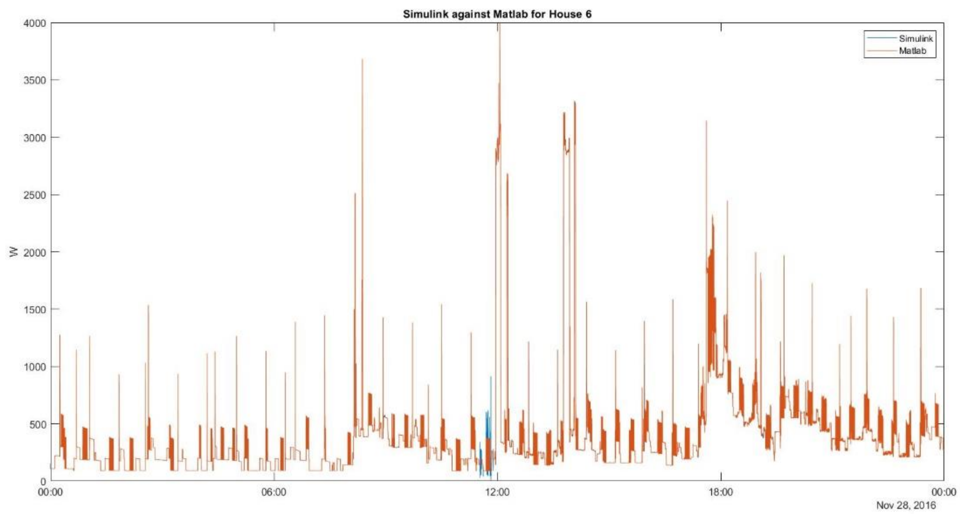


Fig. 4-24 Test Control of the Building Simulink Model's Power Consumption

It is clearly shown that both consumptions are almost identical. The slight difference is due to the representation of the house in the Simulink model. A controlled power source, which depends on both active and reactive power is used to represent the house and both values are used to force current to be drawn by the controlled current source, therefore, the coupling between both active and reactive power causes the seen glitches.

Secondly, the whole system was collected in one Simulink Model to guarantee that the whole system has a smooth operation with no component violating the other.

On a sunny summer day, 3 houses were connected along with their EVs. House 6's EV was available at 10h, house 15's EV was available at 18h and lastly house 21's was available at 17h. Simulink model's results should show a rise in the power consumption at the times when the EVs were connected, however, it should be taken into consideration that one vehicle's consumption is divided over the 3 phases to represent the inverter connection in real life, thus, the power output from the Simulink of one corresponding EV block will be 1/3rd the actual power consumption.

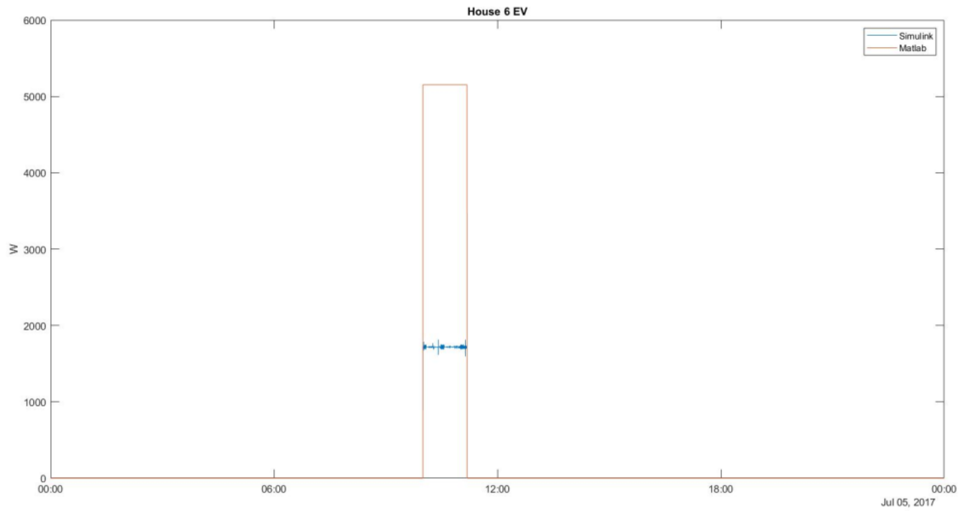


Fig. 4-25 Simulink Model Power Consumption of House 6's EV for One Phase

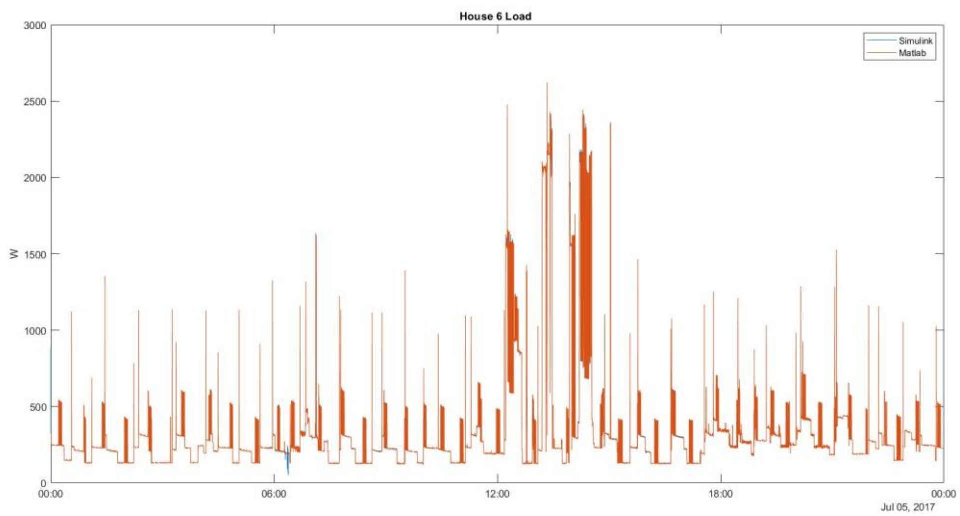


Fig. 4-26 Simulink against Matlab Power Consumption for House 6

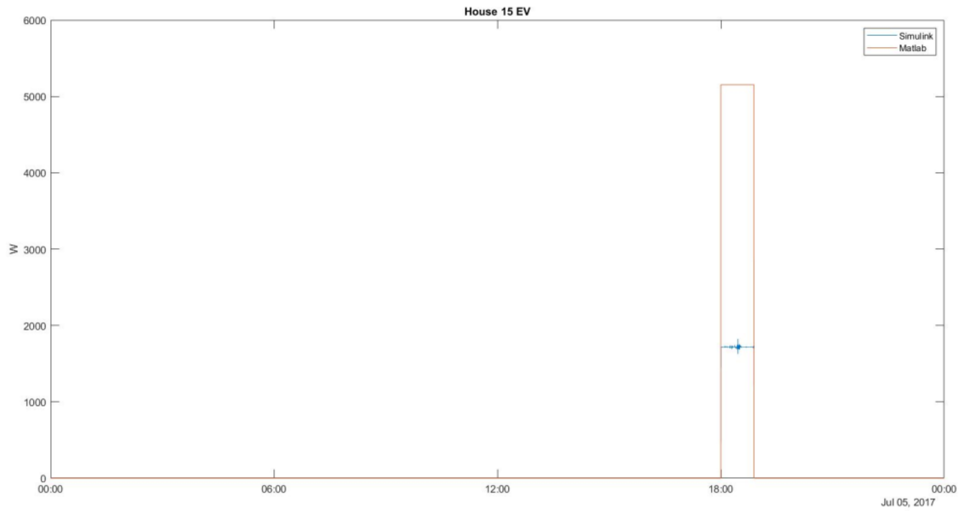


Fig. 4-27 Simulink Model Power Consumption of House 15's EV for One Phase

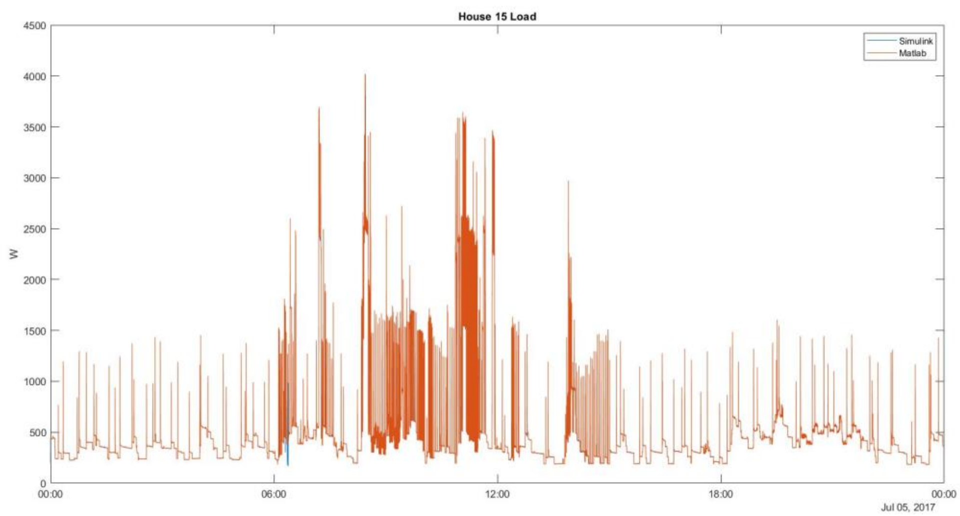


Fig. 4-28 Simulink against Matlab Power Consumption for House 15

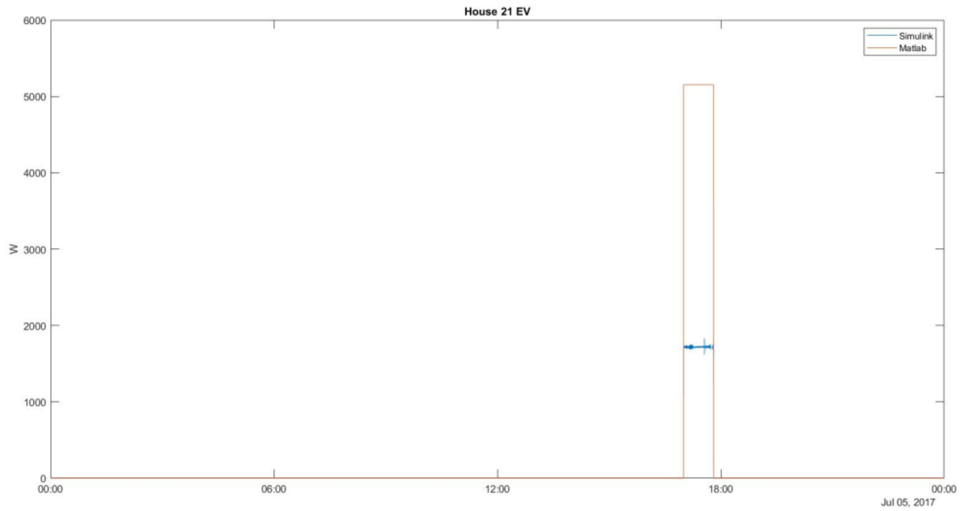


Fig. 4-29 Simulink Model Power Consumption of House 21's EV for One Phase

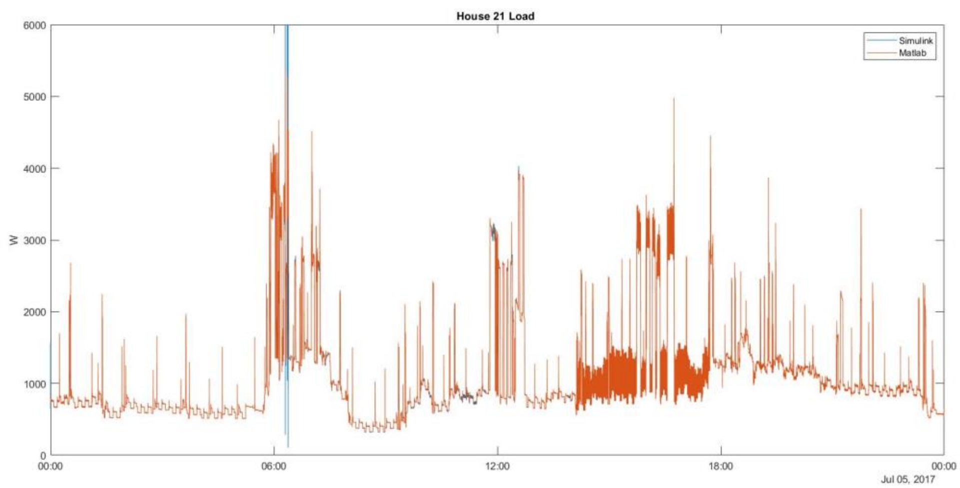


Fig. 4-30 Simulink against Matlab Power Consumption for House 21

Load and EV chargers' consumption match each other just fine, from both the Simulink and Maltab results.

As for the PV generated output, the total power was divided all over the 3 phases as well.

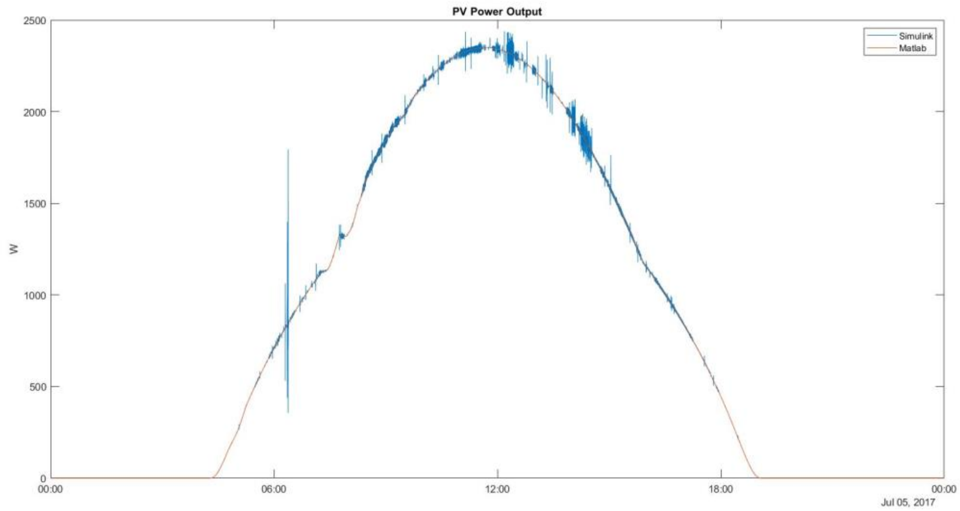


Fig. 4-31 PV Power Output Corresponding for One Phase

From now on, it is assured that the whole system's theory of operation is up to the required standards.

4.6.Building Different Models

Shared solar systems can be for any property within the same distribution network. So in this section, the installed shared solar system will be tested for 2 building configurations, small building for only 3 houses and a large one with 15 houses. The impact a shared solar system will have on each configuration will be shown in this section. The PV panels' area is 50 m^2 with tilt angle 23^o, it is a sunny summer day and the smart meter interval for taking readings is on a 60-minute basis.

4.6.1 Small Building

Consists of houses number 7,16 and 29, with solar shares of 0.35,0.25 and 0.4 respectively.

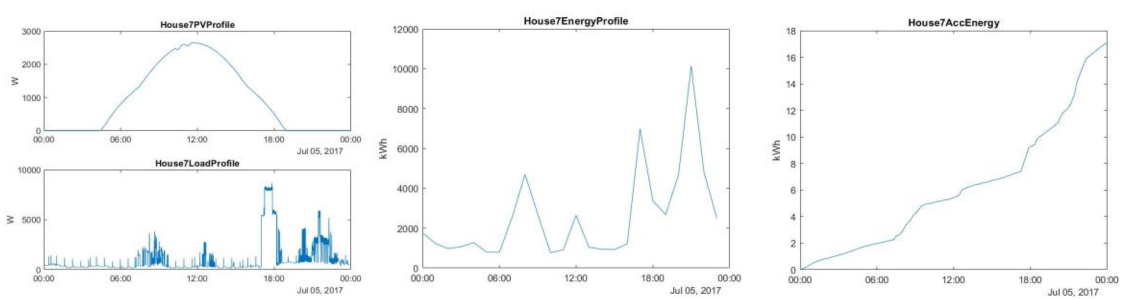


Fig. 4-32 First House Profiles in a Small Building

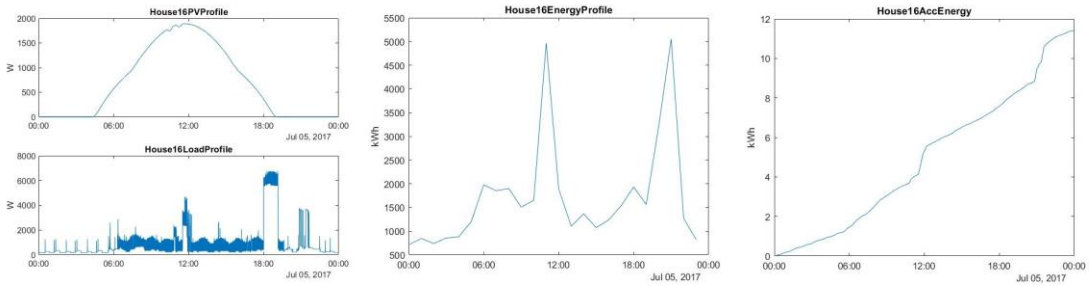


Fig. 4-33 Second House Profiles in a Small Building

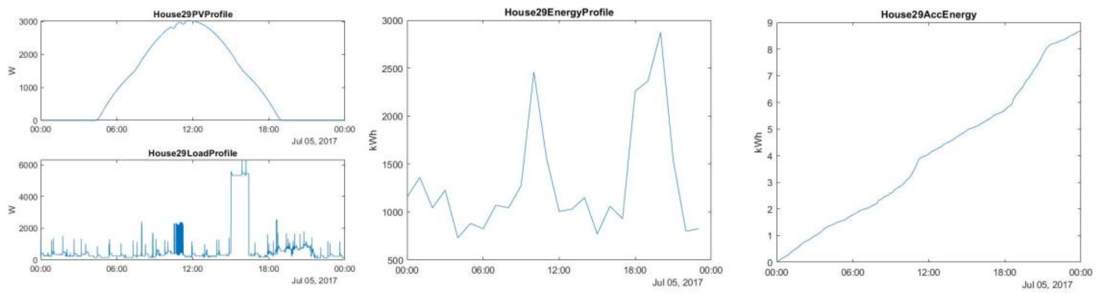


Fig. 4-34 Third House Profiles in a Small Building

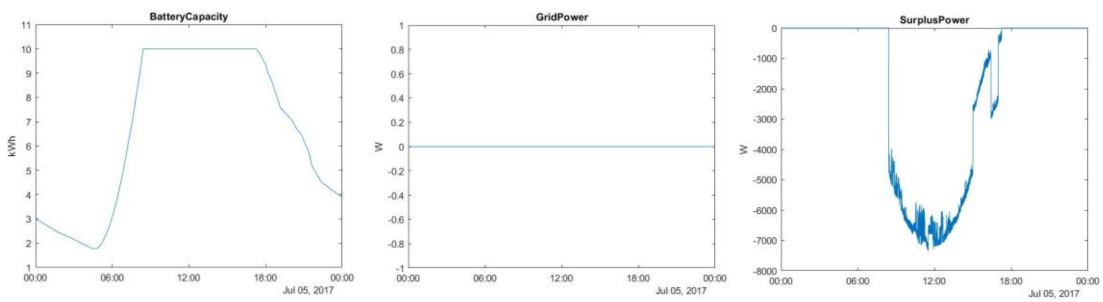


Fig. 4-35 Small Building Properties; ESS Capacity (left), Grid Supplied Power (middle) and Surplus Power from the Building (right)

house	total_cost_day
7	0.6907
16	0.5461
29	0.3013

Fig. 4-36 Total Consumption for each House in terms of €/kWh per Day in a Small Building

The building is self-sufficient as there is no grid support.

4.6.2 Large Building

Consists of houses number 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26 and 30 with solar shares of 0.04, 0.04, 0.04, 0.02, 0.2, 0.02, 0.04, 0.02, 0.06, 0.2, 0.02, 0.04, 0.14, 0.02 and 0.1 respectively.

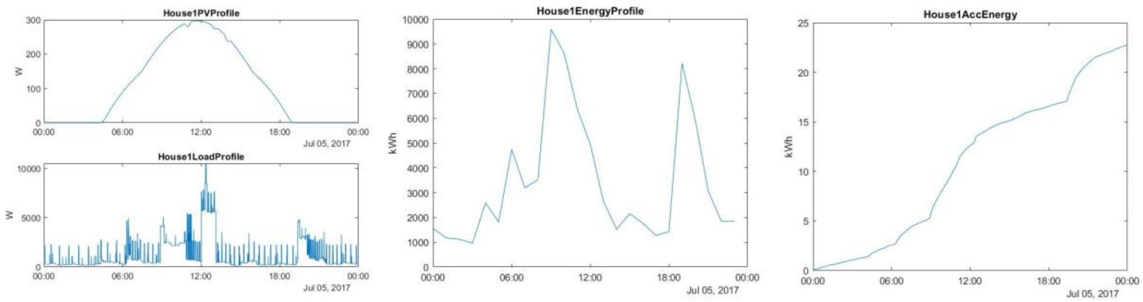


Fig. 4-37 First House Profiles in a Large Building

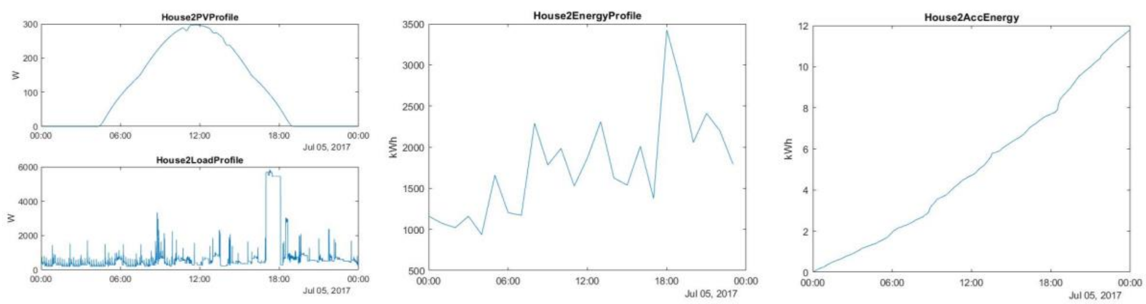


Fig. 4-38 Second House Profiles in a Large Building

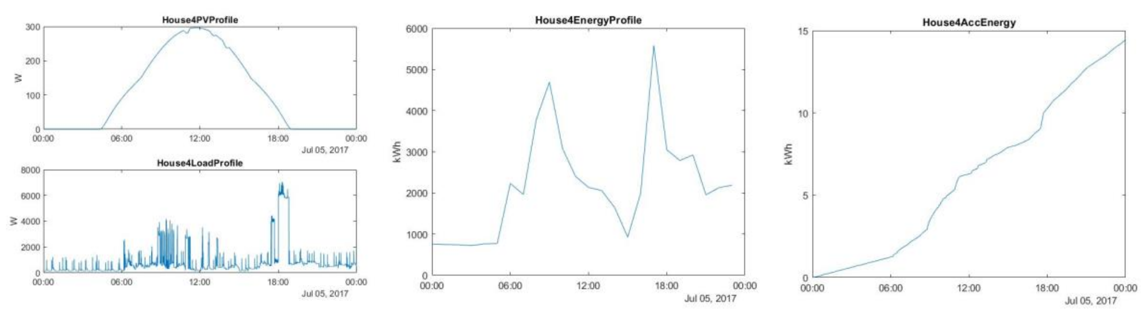


Fig. 4-39 Third House Profiles in a Large Building

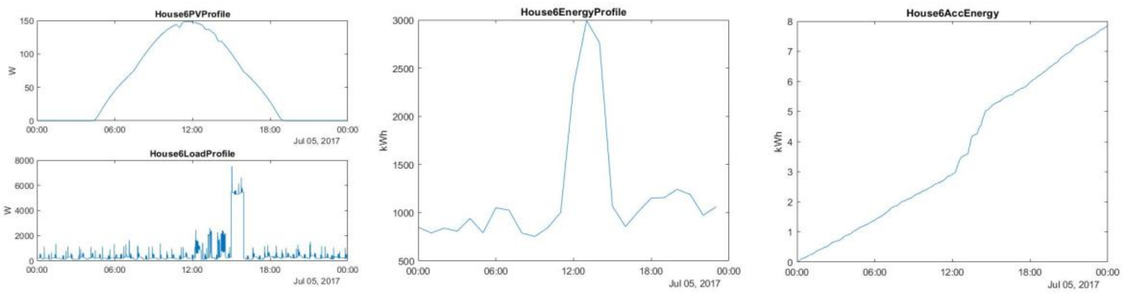


Fig. 4-40 Fourth House Profiles in a Large Building

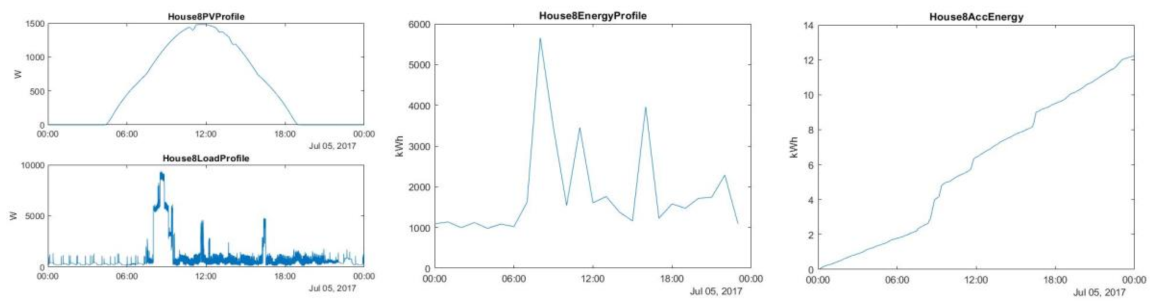


Fig. 4-41 Fifth House Profiles in a Large Building

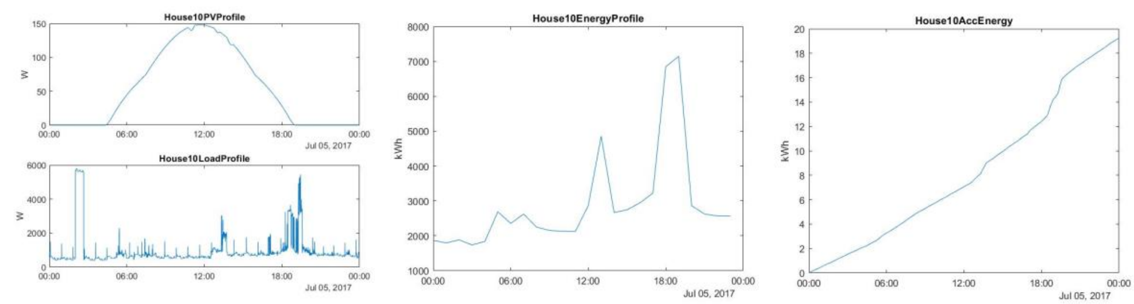


Fig. 4-42 Sixth House Profiles in a Large Building

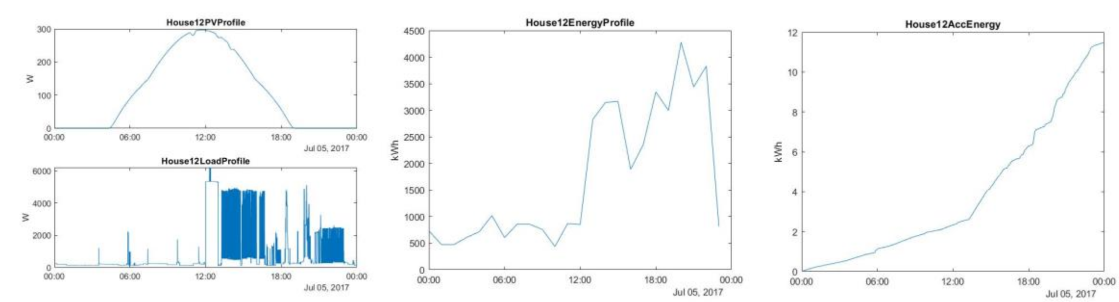


Fig. 4-43 Seventh House Profiles in a Large Building

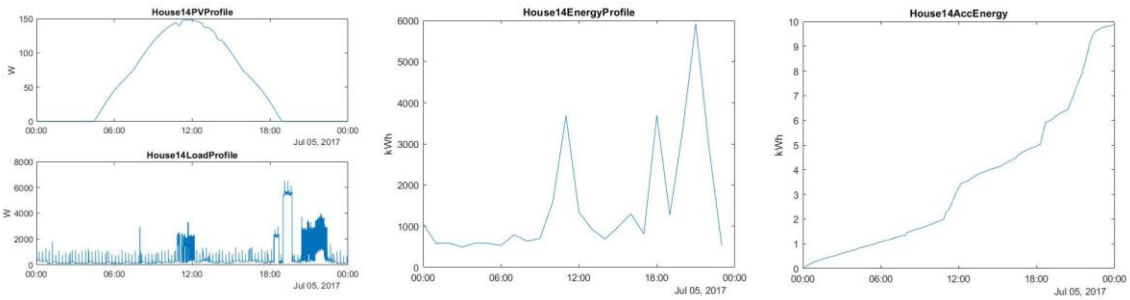


Fig. 4-44 Eighth House Profile in a Large Building

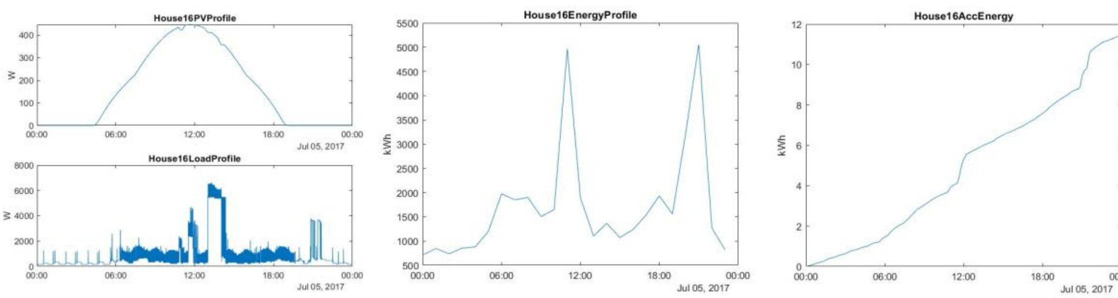


Fig. 4-45 Ninth House Profile in a Large Building

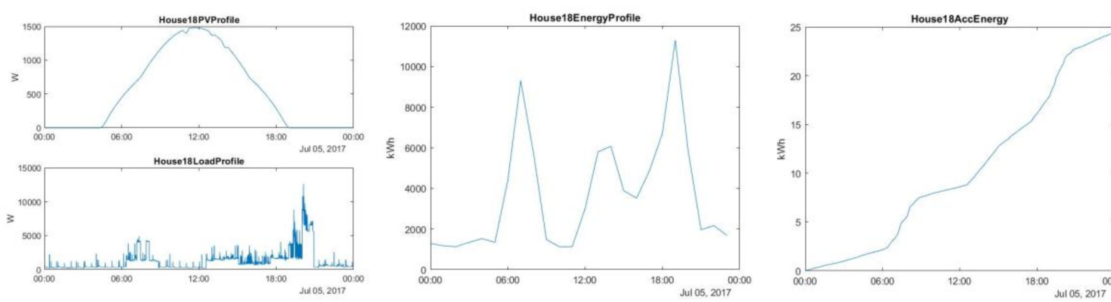


Fig. 4-46 Tenth House Profile in a Large Building

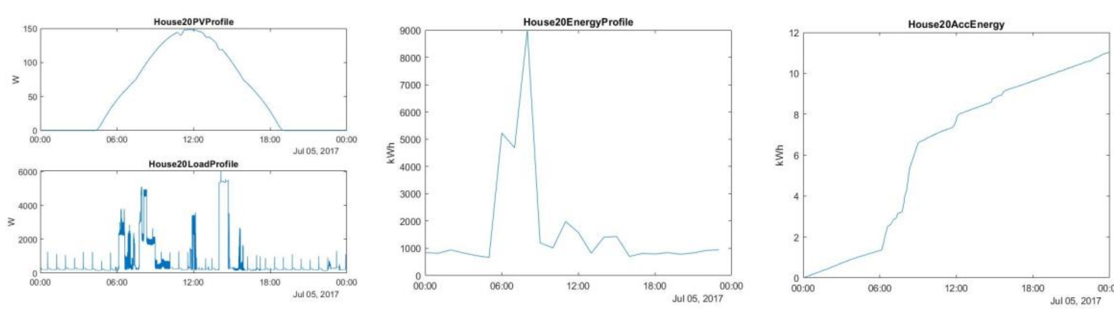


Fig. 4-47 Eleventh House Profile in a Large Building

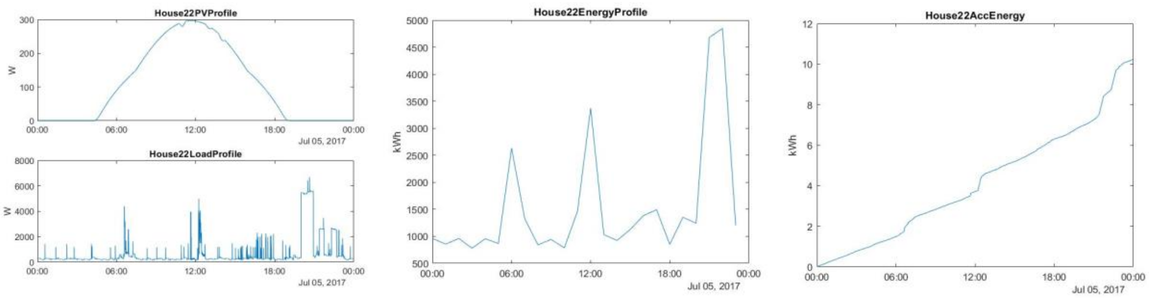


Fig. 4-48 Twelfth House Profile in a Large Building

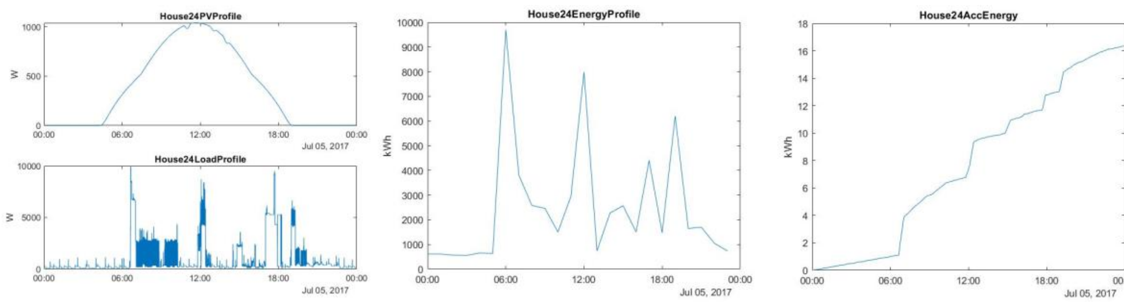


Fig. 4-49 Thirteenth House Profiles in a Large Building

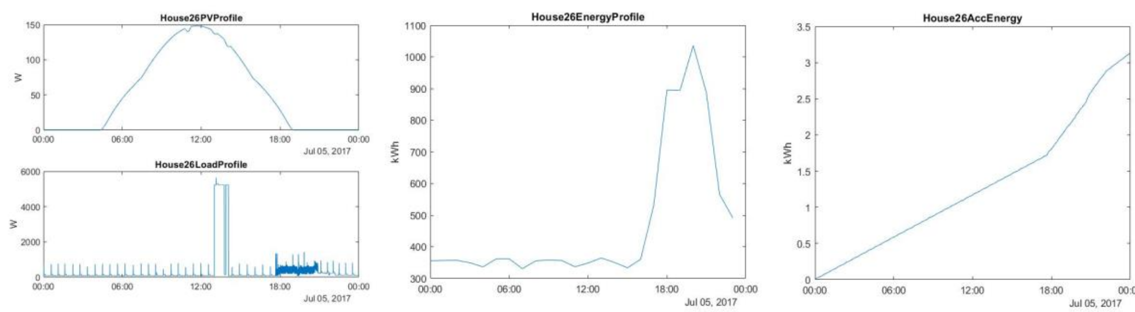


Fig. 4-50 Fourteenth House Profiles in a Large Building

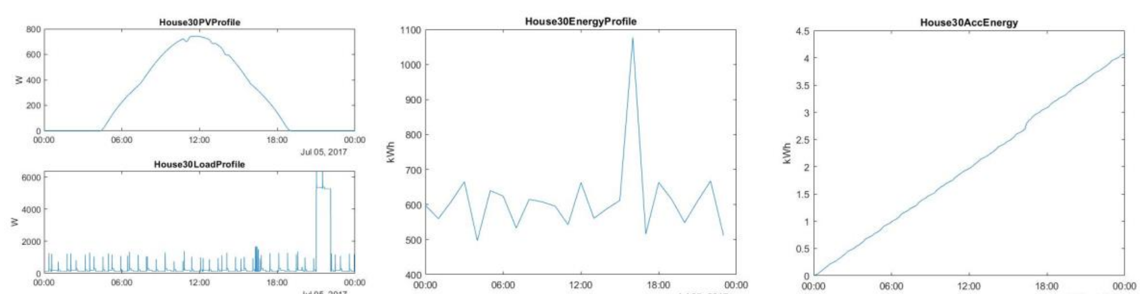


Fig. 4-51 Fifteenth House Profiles in a Large Building

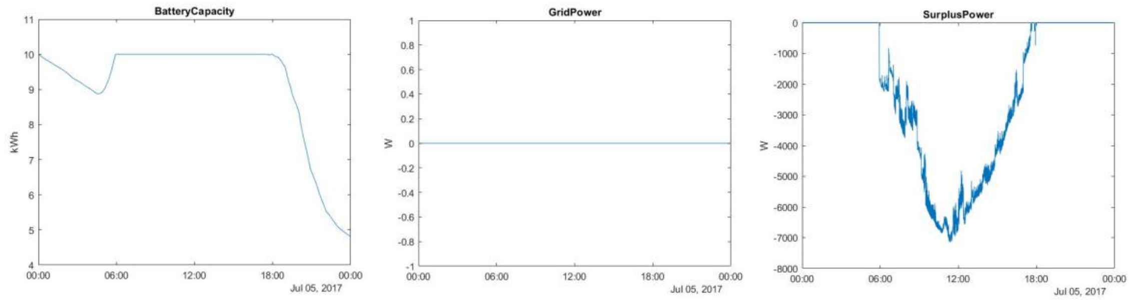


Fig. 4-52 Large Building Properties; ESS Capacity (left), Grid Supplied Power (middle) and Surplus Power from the Building (right)

house	total_cost_day
1	0.6364
2	0.3899
4	0.5197
6	0.3062
8	0.5610
10	0.6368
12	0.5982
14	0.4670
16	0.5461
18	1.0310
20	0.5972
22	0.5831
24	1.1633
26	0.1655
30	0.1969

Fig. 4-53 Total Consumption for each House in terms of €/kWh per Day in a Large Building

The building is self-sufficient as well, however, it is noticed that as the number of participant's increase, their individual share of the solar system decreases, and thus the PV generated power output that can be used individually.

4.6.3 Small Building with no Self-Consumption

The same houses in the small building were connected but this time there was no PV panels to supply the load and no energy storage system. The grid was the only power source to the system, accordingly there was no surplus energy to be delivered to the network.

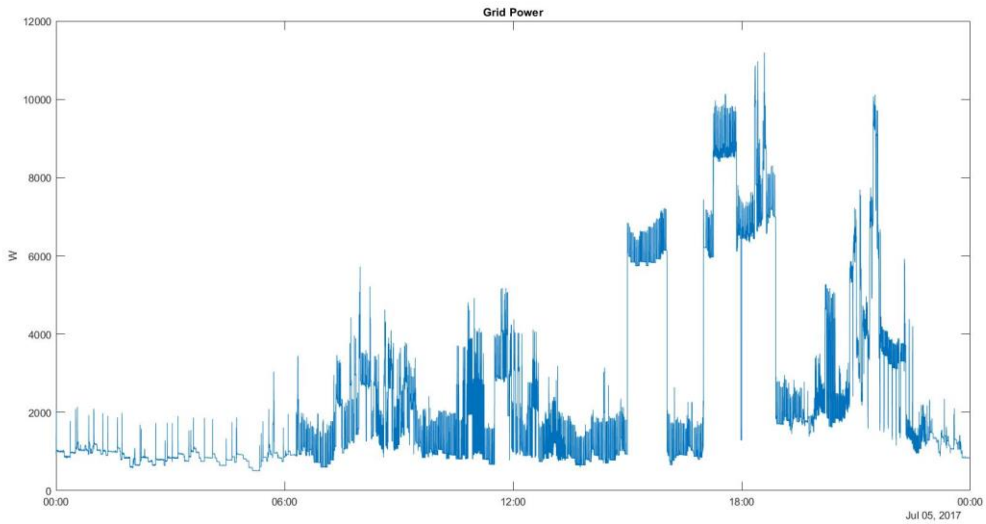


Fig. 4-54 Power Supplied by the Grid in Case of No Self-Consumption for Small Building

As for the total cost, as the configuration of the building was studied during a single day, the increase in price was insignificant.

house	total_cost_day
7	1.0407
16	0.8961
29	0.6513

Fig. 4-55 Total Consumption for each House in terms of €/kWh per Day in a Small Building with No Self-Consumption

The increase in the total cost per day in the energy might seem negligible, however, when these slight increases are added up in the end of the month, there will be a significant drop in the user's bills.

4.6.4 Large Building with no Self-Consumption

The same houses in the large building were connected but this time there was no PV panels to supply the load and no energy storage system.

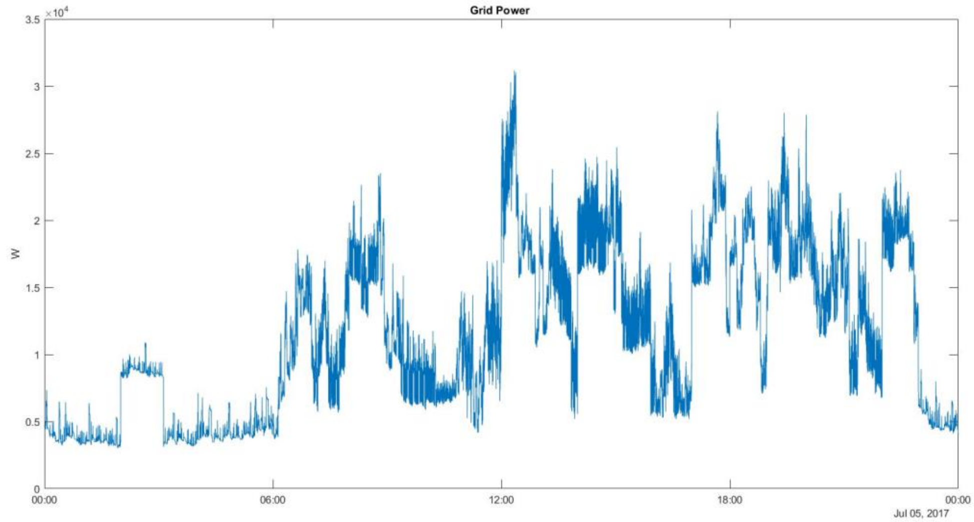


Fig. 4-56 Power Supplied by the Grid in Case of No Self-Consumption for Large Building

The building's primary source is the power network due to the absence of the shared solar installation. The grid is used to supply all the 15 houses' loads in addition to their EVs.

house	total_cost_day
1	0.9864
2	0.7399
4	0.8697
6	0.6562
8	0.9110
10	0.9868
12	0.9482
14	0.8170
16	0.8961
18	1.3811
20	0.9472
22	0.9331
24	1.5133
26	0.5156
30	0.5469

Fig. 4-57 Total Consumption for each House in terms of €/kWh per Day in a Large Building with No Self-Consumption

An increase in the total cost per day for energy is observed as well in the large building configuration.

Chapter Five

5. Conclusions and Outlook

This chapter presents the main conclusions reached out of the work, and puts the light on the main covered issues and the present work situation. Then an outlook is proposed for the future work.

5.1.Conclusions

With the efforts of reducing carbon emissions by governments, distributed generation's usage is increasing by the second. Energy consumers are not only consuming energy from the grid, they are producing their own as well. Everyone is striving towards a better environment and as an incentive there are financial benefits for the user. This has led local schemes to increase in importance and to play a significant role in the future energy systems. The above study is evidence that shared solar energy systems are beneficial for the users and the environment, not to mention the added economical value of such a system.

The following points are the main aspects that have been studied and conclusions reached in each.

- The difference between self-consumption systems, such as solar sharing and collective self-consumption.
- The different types and manufacturers of PV panels, energy storage systems and electric vehicles.
- A simulation platform has been implemented for one building with 30 houses under real circumstances of PV systems and their corresponding profile, battery storage and customer demand profiles.
- Supporting functions and scripts have been designed to support the created model.
- As a final step, tests have been carried out for different models to reach the optimum setup for such a system.

5.2.Future Work

Success of the proposed system is an encouragement for its implementation on a larger scale, not only for one building. Future work is a suggestion of implementing the studied solar system on a whole town along with studying its impact and the financial and economic aspects to ensure the success of the system on a large scale as well.

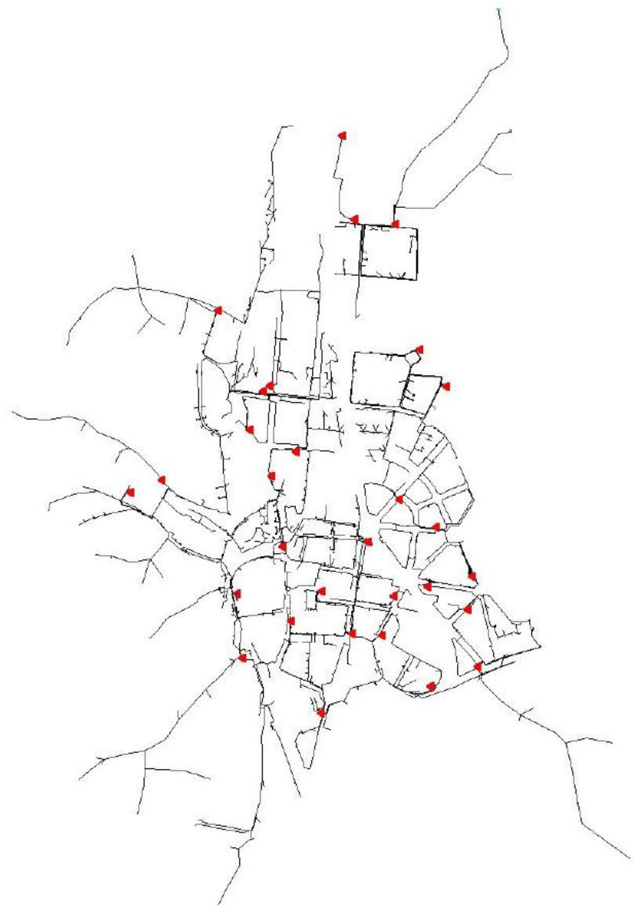


Fig. 5-1 Town Proposal for Shared Solar Installation

Other additions can be related to energy trading, in order to increase the customers' gains from the system and accordingly it will be an added incentive for contributing in a solar shared system.

Power networks are undergoing a fundamental transition, where customers now are able to consume as well as produce energy so that they are allowed to manage their consumption and production of energy. This was not happening in the past due to poor communications means and a not very complex control infrastructure. Previously, a retail supplier was in charge of the energy transactions on the subscribers' behalf. Though, now under a contract based on each individual's consumption, customers with an energy storage system benefit from energy trading within their local distribution network. In addition to selling excess energy to the grid, customers can now sell their excess energy to other customers and this is known as energy trading. On the other hand, customers in demand of energy, can buy it from other customers offering their surplus at a discounted price. In such way, sellers make profit by selling their surplus energy and buyers can save on their energy bill by buying energy at a discounted price, while both sides help in minimizing energy costs, reducing the load on the grid and fully utilizing clean renewable energy. So, since the surplus energy from one customer can be available for the other at a fraction of the grid's energy price, both sellers and buyers would benefit out of such a scenario as well as reducing the energy bill and the grid load. In such systems, there should always be an energy storage system in order for the excess energy to be stored. So, the storage units can be used to meet internal demand, while the excess generation could be used to meet local demands in a neighborhood for example. [36]. "Sellers are users with a surplus of energy stored in energy storage units, gathered from renewable sources such as solar panels. Buyers, on the other hand, are users unable to meet their demands due to aspects such as intermittent generation and high consumption." [36].

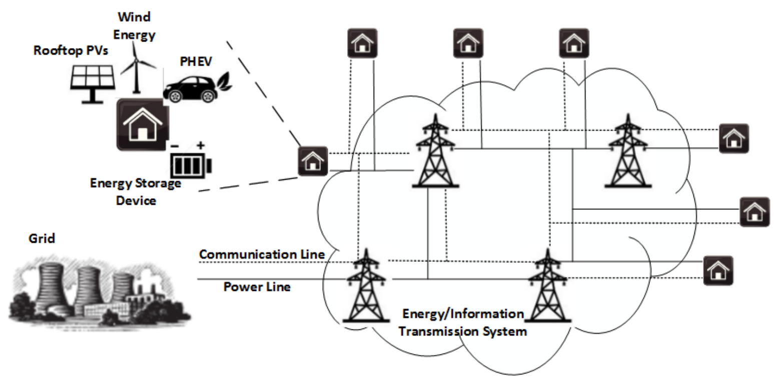


Fig. 5-2 Smart Grid for a Neighborhood Architecture [36]

In a conventional electricity market, during PV energy generation shortage periods, households buy electricity from suppliers and when there is energy excess the surplus is sold to the same supplier. On the other hand, peer to peer energy trading provides options to trade energy within the distribution network. This scenario allows local funds to remain within the local economy since households are able to exchange energy locally through local buying and selling prices. Peer to peer energy sharing describes energy trading between individuals where excess electricity is rather transferred to a demanding neighbor rather than to the grid. In simple words, peer to peer energy sharing means that energy is traded without the necessity of finding an intermedia. Peer to peer energy sharing is becoming the new trend and people are preferring it over the conventional peer to grid trading. However, this requires more complex control measures to ensure reliable transactions within the specified network. Moreover, the energy pricing is variable throughout the day depending on where the consumed energy is coming from. This can be of an economic benefit for the consumer, since one can decide when and how much energy to consume and accordingly control the bills, in other words, a person can learn to rationalize their consumption.

Consequently, peer to peer energy trading could be used to coordinate the transactions between prosumers and this is due to the rise of renewable energy generation installations, energy storage systems and decent communications. Peer to peer's booming platform give prosumers the luxury of choosing their preferred source/destination of the energy they consume/produce, while minimizing power losses. Since then, it was revealed that peer to peer energy sharing is able to reduce the energy cost of the community by 30% compared to the conventional peer to grid energy trading [37]. The energy market's demand for renewable resources accompanied with energy storage increases in order to avoid greenhouse gas emissions.

References

[1] A. Tazarine, H. El Omari, *Designing of a Photovoltaic System for Self-Consumption at the Faculty of Technical Sciences of Settat*

[2] X. Chen, J. Zhao, and M. He, *PV Power Generation Credit Sharing towards Sustainable Community Solar*

[3] C. Plaza, J. Gil, *Distributed solar self-consumption and blockchain: Solar energy exchanges on the public grid within an energy community*

[4] R. García-Valverde, J.A. Teruel, J.A. Villarejo, *PV self-consumption in cities: Solarfighter Experience*

[5] E. A. Adadevoh, *Powering Africa through Shared Solar Energy*

[6] A. I. Nousdilis, A. I. Chrysochos, G. C. Christoforidis, *The Impact of Photovoltaic Self-Consumption Rate on Voltage Levels in LV Distribution Grids*

[7] A. I. Nousdilis, G. C. Christoforidis, *Investigating the Impact of Decentralized Energy Storage Systems in Active Low-Voltage Distribution Networks*

[8] https://www.clearwaycommunitysolar.com/blog/understanding-community-solar/evolution-solar-panels/

[9] https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels

[10] https://www.semprius.com/best-solar-panel-manufacturers/

[11] M. Krepelkova, *Evolution of batteries: From experiments to everyday usage*, 2017

[12] https://www.visualcapitalist.com/evolution-of-battery-technology/

[13] https://phys.org/news/2015-04-history-batteries.html

[14] https://www.thoughtco.com/battery-timeline-1991340

[15] E. N. Markoulakis*, A Simulink Circuit Model for Measurement of Consumption of Electric Energy Using Frequency Method*

[16] https://www.upsbatterycenter.com/blog/nickel-cadmium-battery/#prettyPhoto/0/

[17] https://www.jmcusa.com/hydrogen-storage-alloy.html

[18] http://www.tpub.com/neets/book1/chapter2/1e.htm

[19] https://www.fmanet.org/blog/2010/10/01/lowering-costs-lithium-ion-batteries-ev-power-trains

[20] https://www.marketwatch.com/press-release/top-20-lithium-ion-battery-manufacturing-companies-2018-2018-09-12

[21] https://www.eletimes.com/top-10-lithium-ion-battery-manufacturers-in-the-world

[22] https://www.energy.gov/timeline/timeline-history-electric-car

[23] https://interestingengineering.com/a-brief-history-and-evolution-of-electric-cars

[24] https://www.energysage.com/electric-vehicles/buyers-guide/top-ev-companies/

[25] https://www.carmax.com/articles/best-electric-cars

[26] P. Arboleya, A. Koirala, L. Suárez, B. Mohamed, and C. González-Morán, *Impact Evaluation of the New Self-Consumption Spanish Scenario on the Low Voltage Terminal Distribution Network*

[27] L. Fusheng, L. Ruisheng and Z. Fengquan, *Microgrid Technology and Engineering Application*, 2016

[28] G.B. Gharehpetian and S. M. M. Agah, *Distributed Generation Systems Design, Operation and Grid Integration, 2017*

[29] Z. Smara, A. Mahrane, M. Chikh, F. Chekired, S. Berkane, A. Meflah, A. Triki, *Evaluating the Self-consumption of a Solar House in Coastal Region of Bou Ismaïl, Algeria*
[30] J. Garcia-Villalobos, P. Eguia, E. Torres, A. Etxegarai, *Impact of Photovoltaic Self-consumption on Power Losses and Voltage Levels of MV Distribution Networks*
[31] C. Long, J. Wu, C. Zhang, L. Thomas, M. Cheng, N. Jenkins, *Peer-to-Peer Energy Trading in a Community Microgrid*
[32] M. Stephant, K. Hassam-Ouari, D. Abbes, A. Labrunie, B. Robyns, *A Survey on Energy Management and Blockchain for Collective Self-Consumption*
[33] A. Coelho, M. Matos, *IMPACT OF SELF-PRODUCTION IN THE OPERATION AND REGULATION OF DISTRIBUTION NETWORKS*
[34] https://www.mathworks.com/help/simulink/programmatic-modeling.html
[35] *ASHRAE Handbook – HVAC Applications*, 2011, Chapter 35
[36] N. Yaagoubi, H. T. Mouftah, *Energy Trading in the Smart Grid: A Game Theoretic Approach*
[37] C. Long, J. Wu, Y. Zhou, N. Jenkins, *Peer-To-Peer Energy Sharing Through a Two-Stage Aggregated Battery Control in a Community Microgrid*
[38] https://www.investopedia.com/terms/f/feed-in-tariff.asp
[39] T. Morstyn, M. D. McCulloch, *Multi-Class Energy Management for Peer-to-Peer Energy Trading Driven by Prosumer Preferences*
[40] B. Turnšek, I. Papicˇ, B. Blažic, *k Influence of self-consumption on distribution network operation: The Slovenian Case*
[41] S. Nguyena, W. Penga, P. Sokolowskib, D. Alahakoona, X, Yub, *Optimizing rooftop photovoltaic distributed generation with battery storage for peer-to-peer energy trading*
[42] M. Kharseh, *Solar Radiation Calculation*
[43] http://www.goddardconsulting.ca/simulink-creating-using-matlab-code.html#BuildingAModel
[44] https://uk.mathworks.com/help/simulink/ug/approach-modeling-programmatically.html
[45] https://blogs.mathworks.com/simulink/2010/01/21/building-models-with-matlab-code/
[46] https://uk.mathworks.com/help/simulink/programmatic-modeling.html
[47] https://uk.mathworks.com/help/simulink/slref/block-specific-parameters.html#mw_e98d6a6c-3e97-43ad-81bf-cc13b85d1787
[48] https://uk.mathworks.com/help/simulink/slref/common-block-parameters.html
[49] https://uk.mathworks.com/help/simulink/slref/model-parameters.html
[50] https://www.mathworks.com/matlabcentral/answers/194890-parameterize-simulink-goto-and-from
[51] https://study.com/academy/lesson/apparent-solar-time-vs-mean-solar-time.html
[52] https://sciencing.com/calculate-solar-insolation-8435082.html
[53] https://sciencing.com/calculate-solar-time-8612288.html
[54] https://www.fuelcellstore.com/blog-section/battery-energy-storage-for-the-pv-system
[55] https://www.solartechnology.co.uk/support-centre/calculating-your-solar-requirments
[56] https://www.solaronline.com.au/solar_system_basics.html
[57] https://www.solarchoice.net.au/blog/kW-vs-kWh-solar-battery-power-energy-capacity
[58] https://www.solarchoice.net.au/blog/lg-chem-range-battery-storage-products-australia
[59] http://www.3e.eu/solar-sharing-right-collective-self-consumption/
[60] https://www.sciencedirect.com/topics/engineering/distributed-power-generation

[61] Z. Liu, *Global Energy Interconnection*, 2015
[62] https://www.dg.history.vt.edu/ch1/introduction.html
[63] https://www.edpenergia.es/es/hogares/gas-y-electricidad/precios/?provincia=leon
[64] https://www.edpenergia.es/es/hogares/gas-y-electricidad/precios/tipos-de-tarifas/
[65] https://www.edpenergia.es/es/hogares/gas-y-electricidad/precios/mercado-regulado/
[66] https://www.fitariffs.co.uk/fits/principles/
[67] https://www.energymatters.com.au/panels-modules/
[68] https://www.solarpowerauthority.com/a-history-of-solar-cells/
[69] http://www.altenergy.org/renewables/solar/latest-solar-technology.html
[70] https://www.carmagazine.co.uk/electric/best-electric-cars-and-evs/

APPENDIX

Onsite energy consumption is more adequate due to the difference between electricity selling and buying prices. In recent years, feed-in-tariff schemes have been broadly promoted across the world, in order to encourage renewable and low-carbon electricity generation. Feed-in-tariff relates to electricity generated by a renewable energy system which is used on property. It is also considered “an economic policy created to promote active investment in and production of renewable energy sources” [38]. Their benefits can be stated as follows; first a generation tariff payment which is based on the total electricity generated and the energy type. Second, an export tariff payment which is for any energy exports made and last, lower electricity bills. A continuous reduction of the tariff rate has been seen, inspiring an alternative solution of trading the excess energy of a consumer within the neighborhood, this process is known as peer to peer energy trading. Peer to peer energy trade describes flexible energy trades between consumers or as called now peers, where the excess energy is traded among local customers.

Self-Consumption Rate (SCR): Fraction of electrical energy generated by the PV system that is directly consumed onsite or stored for later use, over the total PV generated energy.

Self Sufficiency Rate (SSR): Ratio of the renewable energy generated by the PV system, which is used to supply the prosumer’s own needs, over the total consumed energy.