



COMILLAS
UNIVERSIDAD PONTIFICIA

ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS
INDUSTRIALES

TRABAJO FIN DE GRADO

INVESTIGATION OF GRID INTERACTIVE
PHOTOVOLTAIC PLANTS WITH ENERGY
STORAGE

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Director: Fabio Immovilli

Madrid

Modena

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INVESTIGACIÓN DE PLANTAS FOTOVOLTAICAS INTERACTIVAS CON ALMACENAMIENTO DE ENERGÍA.

Autor: Zamora Fraguas, Jacobo.

Director: Immovilli, Fabio.

Entidad Colaboradora: Universita Degli Studi Di Modena e Reggio Emilia.

RESUMEN DEL PROYECTO

La energía solar se está convirtiendo en una fuente de energía cada vez más importante, empezando a sustituir a otras formas más convencionales de producción de energía. A través de simulaciones, en este proyecto vamos a establecer una planta fotovoltaica óptima y rentable para cualquier escenario, de manera que cualquiera pueda tener acceso a estas tecnologías y beneficiarse de ellas. El análisis se centrará en dos escenarios diferentes, una oficina y un hogar. Los resultados mostraron una clara diferencia entre ellos, ya que el hogar requería sistemas de almacenamiento más grandes, pero, por otro lado, una instalación fotovoltaica más pequeña. Pero, en general, se descubrió que las tecnologías fotovoltaicas se han vuelto rentables.

Palabras clave: Sistema de almacenamiento de energía, energía fotovoltaica, energías renovables, irradiación solar.

1. Introducción

La energía fotovoltaica es una fuente de energía de cero emisiones que ofrece importantes beneficios para la sociedad, por lo que se considera una fuente de energía renovable que, al ser inagotable y doméstica, ofrece mucha más seguridad que una fuente de energía importada. Hasta la última década, la energía fotovoltaica se utilizaba en aplicaciones especializadas de bajo consumo, debido a sus elevados precios. Las primeras células fotovoltaicas se produjeron en los años 50 y se utilizaron principalmente en satélites en órbita. En los años 70 se introdujeron grandes mejoras que abrieron una serie de oportunidades para las aplicaciones terrestres, y las células fotovoltaicas se convirtieron en una fuente de energía popular para pequeños electrónicos de consumo, al tiempo que se iniciaba el desarrollo para usos residenciales y comerciales.

A medida que las tecnologías avanzaban, también se hacían más asequibles, lo que implica que cada vez más gente está interesada en alimentar sus casas con ellas. Pero debido a su coste y a la complejidad de las plantas fotovoltaicas, no tenemos los conocimientos suficientes para saber si va a merecer la pena para alimentar nuestro hogar y nuestras oficinas.

Poder determinar el tamaño óptimo de una planta fotovoltaica ha sido un gran reto durante muchos años para los investigadores en el campo de las energías renovables. Como la demanda de energía sólo puede estimarse, nunca podemos estar seguros de las dimensiones perfectas de una carga determinada, pero podemos hacer frente a estas incertidumbres con medidas de seguridad como bancos de baterías para el almacenamiento de energía o sobredimensionando la planta. Poder determinar qué camino tomar sigue siendo un problema sin resolver, por lo que para ayudar a la decisión hay que tener en cuenta otros aspectos del proyecto, como los impactos económicos y medioambientales. Ser capaces de encontrar el equilibrio será la clave no sólo para lograr nuestro objetivo, sino que ayudará a identificar el camino que se puede tomar para ayudar al crecimiento de las energías renovables y limpias.

Todo esto nos lleva a una fuente de energía más desarrollada y rentable, lo que nos da la oportunidad de seguir explorando cómo estas tecnologías pueden ser utilizadas diariamente por todos. En este proyecto trataremos de establecer e investigar un criterio de dimensionamiento para una pequeña planta fotovoltaica utilizada en un entorno residencial o comercial pequeño. Teniendo la capacidad de poder determinar, dada una instalación particular, qué tamaño y qué componentes debe tener nuestra instalación fotovoltaica.

2. Definición del proyecto

Lo primero que hay que hacer es obtener información sobre el funcionamiento de las plantas fotovoltaicas y buscar una forma óptima de establecer un criterio para centrarnos en algunos aspectos de las demandas y producciones energéticas para posteriormente establecer cómo va a ser nuestro sistema.

A continuación, hay que determinar nuestros escenarios de uso buscando datos útiles sobre las demandas de carga energética de los hogares y las oficinas. Así, se puede hacer una conjetura sobre el tema para luego comparar con los resultados obtenidos en las simulaciones y ver si tienen sentido.

Después de establecer nuestros escenarios, utilizando MATLAB y el Sistema de Información Geográfica Fotovoltaica (PVGIS) se realizan los cálculos para establecer y hacer un modelo de las plantas fotovoltaicas en función de las diferentes demandas de carga obteniendo los datos suficientes para poder establecer finalmente un criterio de dimensionamiento basado en nuestros resultados computacionales.

Una vez establecidas las plantas óptimas para nuestros escenarios, podemos ver los posibles criterios de dimensionamiento y sacar conclusiones sobre los resultados obtenidos, a la vez que hacemos una extrapolación de los cálculos para que los criterios establecidos puedan ser utilizados para cualquier situación.

3. Descripción del modelo

Para nuestro modelo, hemos optado por una arquitectura interactiva con la red porque si se da el caso de que se necesite más energía de la que estamos produciendo o tenemos almacenada, no podremos alimentar nuestra carga. Y en el caso de que estemos produciendo más de lo que necesitamos y tengamos las baterías llenas, siempre podemos alimentar la red, por lo que no se malgasta energía. Como existe la posibilidad de no tener suficiente energía con una configuración sin la red, es más inteligente optar por un sistema híbrido. Siempre existe la posibilidad de tener una planta más grande con más paneles y más baterías, pero como es más caro, no saldría económico.

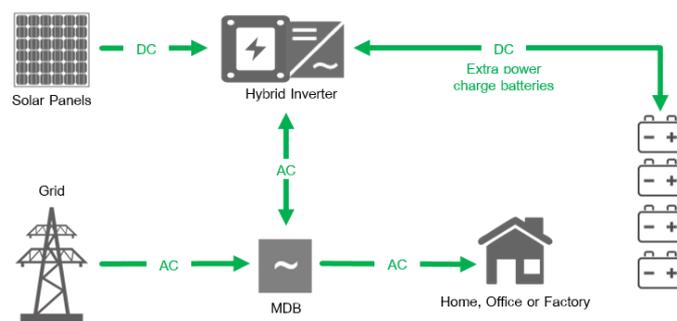


Figura 1. Sistema híbrido.

También optamos por utilizar sistemas de almacenamiento de energía para que, cuando la generación sea mayor que la producción, podamos garantizar que la demanda esté siempre cubierta cuando nuestra producción sea baja.

Como hemos dicho, vamos a comparar la carga de un hogar con la de una oficina. Vamos a analizar la curva de carga eléctrica de un hogar de Suiza [1]. Como es de esperar en un hogar, hay una diferencia entre los días de verano y los de invierno, y picos de consumo en lugar de una curva de consumo más estable, más típica de las oficinas.

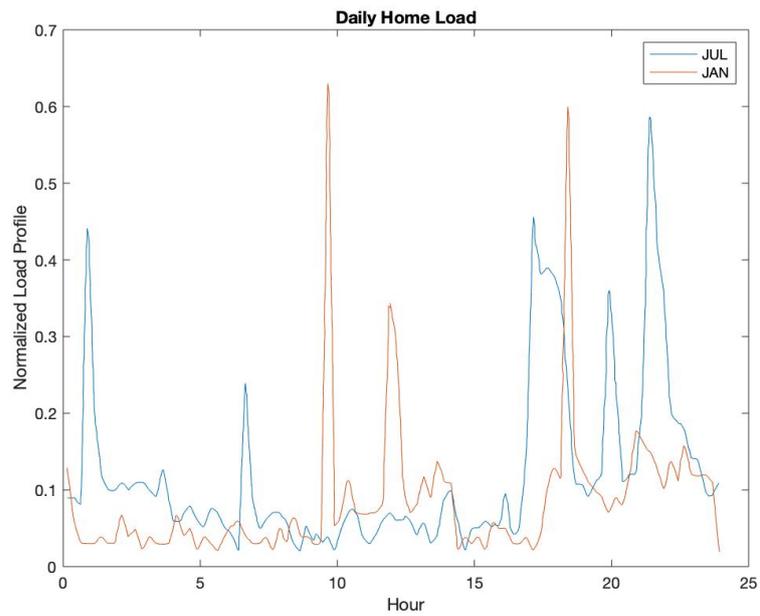


Figura 2. Perfiles de carga en MATLAB de nuestra carga doméstica.

Para el análisis de nuestro edificio de oficinas, hemos elegido un edificio de oficinas de Nueva Zelanda [2], como también era de esperar, tenemos un consumo constante a lo largo del día y una diferencia de consumo entre el verano y el invierno.

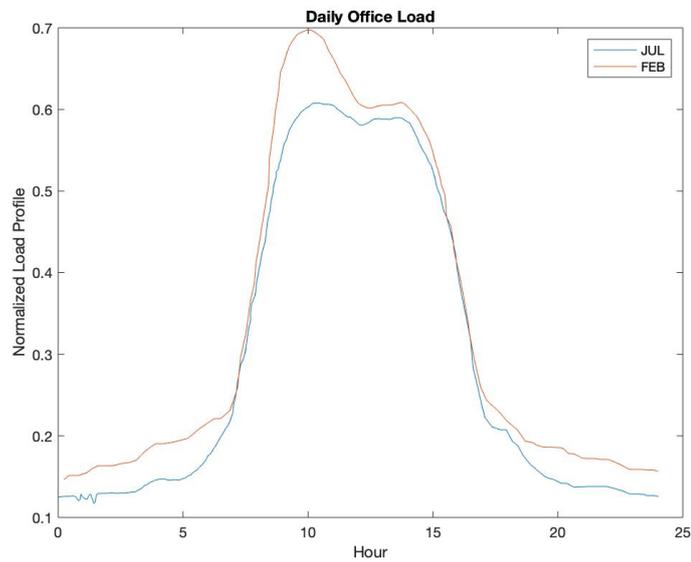


Figura 3. Perfiles de carga en MATLAB de nuestra carga de oficina.

Las demandas de las oficinas, como se ha mencionado anteriormente, suelen ser de mayor tamaño, por lo que tendrán una planta fotovoltaica más grande que las demandas de las oficinas.

Por último, vamos a elegir dos ubicaciones diferentes para nuestro análisis. Pensamos que, como el sol irradia de forma diferente dependiendo de la latitud, esto va a tener un efecto en la energía producida, siendo mayor cuanto más cerca estemos del ecuador. Por lo tanto, queremos ver realmente si este efecto es lo suficientemente grande como para marcar una gran diferencia. Por eso nuestras dos localizaciones han sido Málaga y Santander.

4. Resultados

Lo primero que vimos fue que había una diferencia entre las ubicaciones, que repercutía en los tamaños de nuestras plantas fotovoltaicas para la misma carga en diferentes lugares. Confirmando que cuanto más cerca del ecuador, más producción se tiene.

En segundo lugar, determinamos que, a pesar de la diferencia de tamaño en nuestros dos tipos de carga diferentes, ambos necesitan el mismo tamaño de batería. Esto se debe a dos razones, no tenemos una batería lo suficientemente pequeña como para ser óptima para nuestra carga doméstica, y como nuestra carga de oficina tiene una curva de consumo similar a la de producción, necesitamos menos almacenamiento, y por lo tanto nuestra batería más pequeña es suficiente para ambos lugares.

Análisis de costes

También hemos descubierto que, en teoría, una planta más pequeña debería darnos el resultado más rentable para nuestros escenarios. Por eso vamos a analizar el coste total para ver si es cierto. Con el escenario de la Oficina de Santander se analizarán los costes.

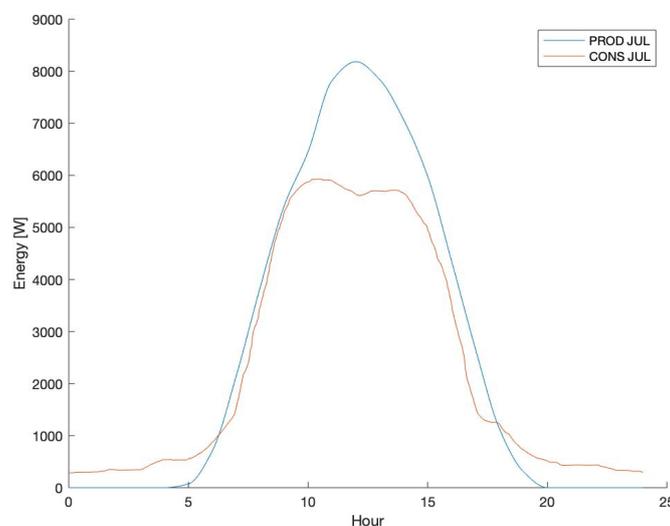


Figura 4. Carga de la oficina de Santander en verano y una planta fotovoltaica de 14kWp

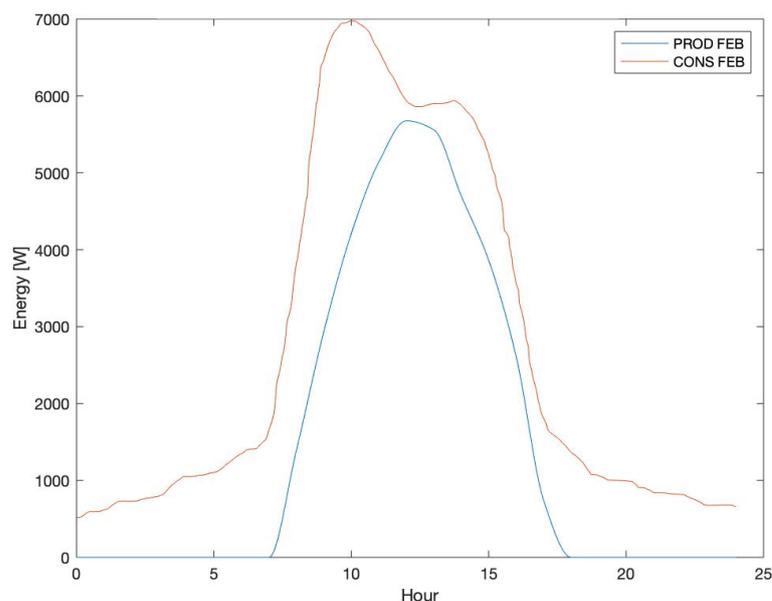


Figura 5. Carga de la oficina de Santander en invierno y planta fotovoltaica de 14kWp

Nuestra planta fotovoltaica elegida tiene una instalación de 14kWp con un coste de 8400€ y una batería LG CHEM de 3,3kWh con un coste de unos 2400€. Ahora debemos tener en cuenta que como nuestra planta es pequeña durante más o menos la mitad del año, vamos a necesitar comprar electricidad para la red. Con una estimación de un precio medio de la electricidad en España este 2021 de 0,20€/kWh estimamos dado nuestros datos obtenidos, que, si necesitamos 29,016kWh cada 24h durante la mitad del año (182,5 días) obtenemos un coste anual de energía de: 1095€ al año.

Sin planta fotovoltaica, en nuestro edificio de oficinas, tuvimos un consumo diario de 56,01kWh en verano y 65,78kWh en invierno esto nos dará un coste anual de: 14667€.

Por lo tanto, nuestra instalación fotovoltaica en total costará alrededor de 10800€ más 1095€ al año de energía, ya estamos ahorrando dinero en nuestro primer año, porque estos costos son más bajos que nuestro escenario anual sin planta fotovoltaica.

5. Conclusiones

1. Aunque no se ha podido establecer un criterio de dimensionamiento, hemos determinado ciertos parámetros y directrices sobre cómo enfocar una carga determinada para que sea más fácil establecer una planta fotovoltaica rentable para cualquier carga.
2. Hemos aprendido que ahora mismo es rentable establecer una planta fotovoltaica, y que es posible ahorrar dinero a corto plazo con ella. Todas las especulaciones acerca

de que no es un sistema energético costoso se han demostrado erróneas, ya que podemos ver que podemos recuperar fácilmente nuestra inversión.

3. El sistema de almacenamiento de energía está demostrando ser también rentable, aunque sigue siendo caro y con la posibilidad de tener que cambiarlo cada pocos años debido a su envejecimiento, hemos visto que están empezando a ser óptimos en un escenario a pequeña escala.

6. Referencias

- [1] S. Yilmaz, J. Chambers, M.K. Patel, "Comparison of clustering approaches for domestic electricity load profile characterisation - Implications for demand side management, Energy, Volume 180, 2019, Pages 665-677, ISSN 0360-5442, <https://www.sciencedirect.com/science/article/pii/S0360544219310060>
- [2] Nuria Martín-Chivelet, David Montero-Gómez, Optimizing photovoltaic self-consumption in office buildings, Energy and Buildings, Volume 150, 2017, Pages 71-80, ISSN 0378-7788, <https://www.sciencedirect.com/science/article/pii/S0378778817304796>

INVESTIGATION OF GRID INTERACTIVE PHOTOVOLTAIC PLANTS WITH ENERGY STORAGE

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Supervisor: Immovilli, Fabio.

Collaborating Entity: Universita Degli Studi Di Modena e Reggio Emilia.

ABSTRACT

Solar energy is becoming a more important energy source, starting to replace other more conventional forms of energy production. Through simulations, in this project we are going to establish an optimal and a cost-effective photovoltaic plant for any given scenario, so that anyone can have access to this technologies and benefit from them. The analysis focused on two different scenarios, an office and a household. Results showed a clear difference between them, with the household requiring bigger storage systems but, on the other hand, a smaller photovoltaic installation. But, all in all, it was discovered that PV technologies have become cost-effective.

Keywords: Energy storage system, photovoltaic energy, renewables, solar irradiation.

1. Introduction

Photovoltaic (PV) energy is a zero-emission energy source that offers substantial benefits for society, it is therefore considered a renewable energy source that, as it is inexhaustible and domestic, offers much more security than an imported energy source. Until the last decade, PVs were used in specialised low energy applications, due to its high prices. The first PV cells were produced in the 1950s and were primarily implemented in orbiting satellites. In the 70s huge improvements were made that opened a number of opportunities for terrestrial applications, PVs became a popular power source for small consumer electronics as the development for residential and commercial uses began.

As technologies advanced, they are also getting more affordable, all of this implies that more people are interested in powering their houses with them. If we take a closer look to photovoltaic (PV) technologies, we can see this advancements and also great projection of people wanting to use them. But due to its cost and complexity of PV plants we do not have enough knowledge to know if it's going to be worth it to power our home and offices.

Being able to determine the optimal size of a PV has been a major challenge for many years for researches in the field of renewable energies. As energy demand can only be estimated we can never be sure on the perfect dimensions of a given load, but we can cope with these uncertainties with security measures such a battery banks for energy storage or by oversizing

the plant. Being able to determine which way to go remains an unresolved problem, so in order to help with the decision other aspects of the project must be taken into account, such as economic and environmental impacts. Being able to find the balance will be the key to not only achieving our goal but will help identify a path which can be taken to help with the growth of renewable and clean energies.

All of this is leading us to a more developed and cost-efficient energy source, which gives us the opportunity to keep exploring how these technologies can be used daily by everyone. In this project we will try to establish and investigate a sizing criterion for a small PV plant used in a residential or small commercial environment. Having the capacity to be able to determine, given a particular installation, how big and which components our PV installation should have.

2. Project definition

The first thing to do is obtain information on how PV plants work and search for an optimal way of establishing a criterion in order to focus on a few aspects of energy demands and productions to later on establish how our system is going to be.

Then our use case scenarios must be determined by searching for useful data regarding home and office energy load demands. So, an educated guess can be made on the subject to later compare with the results obtained in the simulations and see if they make sense.

After establishing our scenarios, using MATLAB and Photovoltaic Geographical Information System (PVGIS) calculations are made in order to establish and make a model of the PV plants depending on the different load demands obtaining enough data to be able to finally establish a sizing criterion based on our computational results.

After establishing the optimal plants for our given scenarios, we can take a look at the possible sizing criteria and make conclusions regarding the obtained results whilst making an extrapolation from the calculations so that the criteria established can be used for any given situation.

3. Model description

For our model, we went with a grid interactive architecture because if there was an instance where more energy is needed than the one we are producing or have stored, we won't be able to feed our load. And in the event that we are producing more than we need and we

have our batteries full we can always feed energy back into the grid, so no energy is lost. As it is a possibility to have not enough energy with an off grid setting it is smarter to go for a hybrid system. There is always the possibility of having a bigger off grid with more panels and more batteries but as it is more expensive, we would not be able to economically save money.

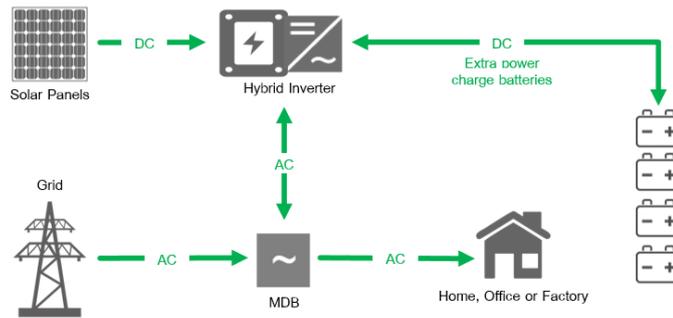


Figure 1. Hybrid System.

We also choose to use energy storage systems so that when generation is higher than production, we can ensure demand is always met when our production is low.

As mentioned, we are going to compare a house load to an office load. We are going to be analysing the electricity load curve of a single household from Switzerland [1]. As expected from a household, there is a difference between summer and winter days, and peaks in consumption rather than a steadier consumption curve more typical of offices.

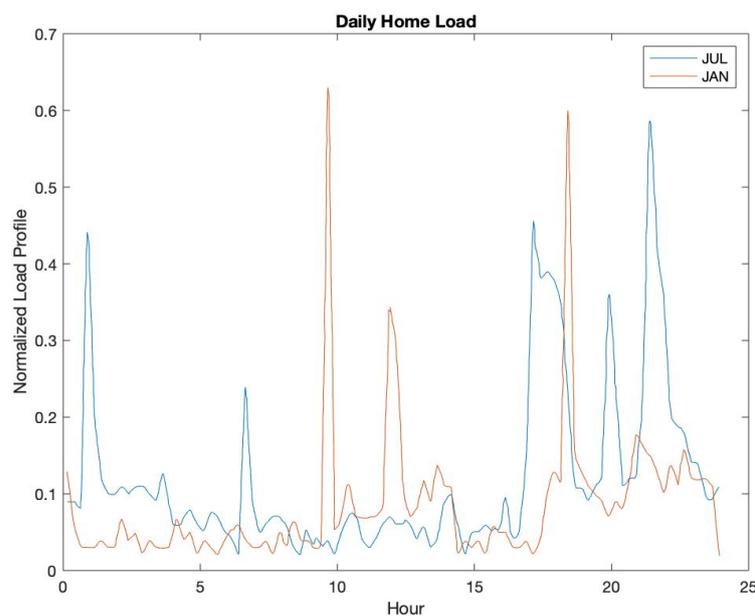


Figure 2. Load profiles in MATLAB of our Home Load.

For our office building analysis, we have chosen an office building from New Zealand [2], as also expected, we have a steady consumption along the day and a consumption differences between summer and winter.

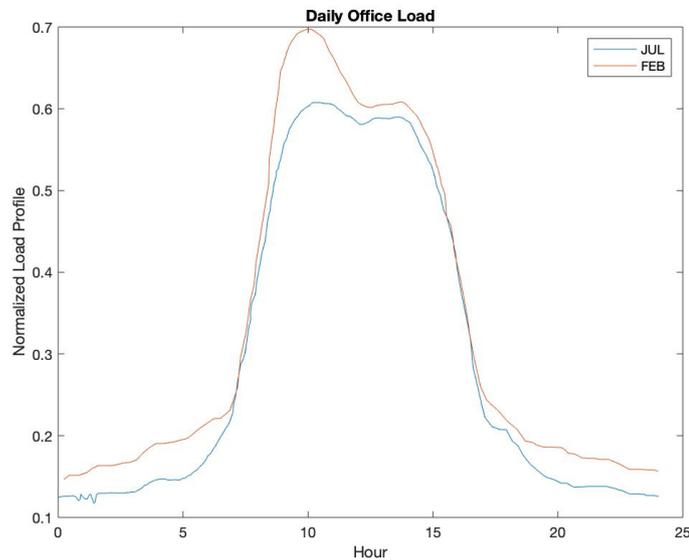


Figure 3. Load profiles in MATLAB of our Office Load.

Office loads, as previously mentioned, are generally larger in size so will therefore have a larger PV plant than Office loads.

Finally, we are going to be choosing two different locations for our analysis. We think, that as the sun irradiates differently depending on the latitude, this is going to have an effect on the energy produced, being larger the closer we get to the equator. Therefore, we want to really see if this effect is large enough to make a big difference. That is why our two locations have been Malaga and Santander.

4. Results

First thing we saw, was that there was a difference between locations, that impacted the sizes of our PV plants for the same load on different places. Confirming that the closer you get to the equator the more production you have.

Secondly, we determined that despite the difference in size in our two different load types, they both need the same size battery. This is due to two reasons, we do not have a small enough battery to be optimal for our home load, and as our office load has a consumption

curve similar to the production curve, we need less storage, and therefore our smallest battery is sufficient for both locations.

Cost analysis

We also found out, that theoretically a smaller plant should give us the most cost-effective result for our given scenarios. That is why we are going to take a closer look at overall cost to see if this is true. We are going to use the Santander Office scenario to analyse our costs.

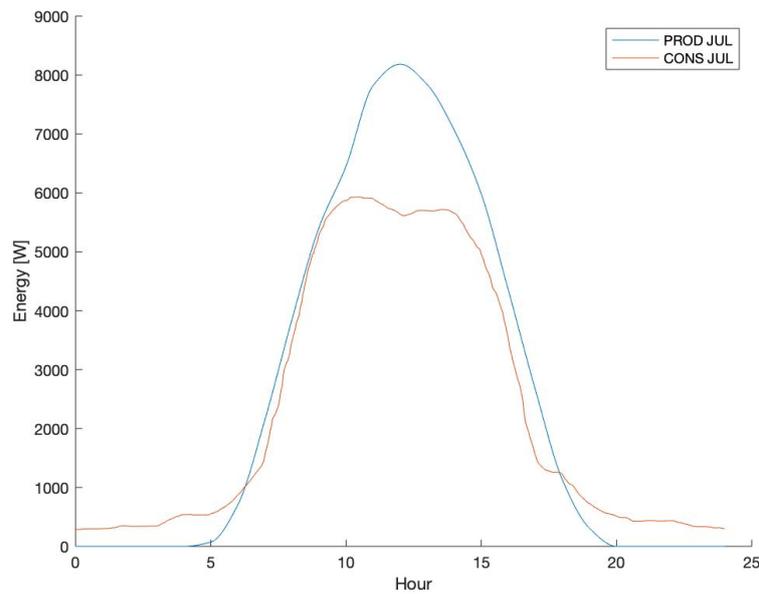


Figure 4. Santander Summer Office Load and 14kWp PV Plant

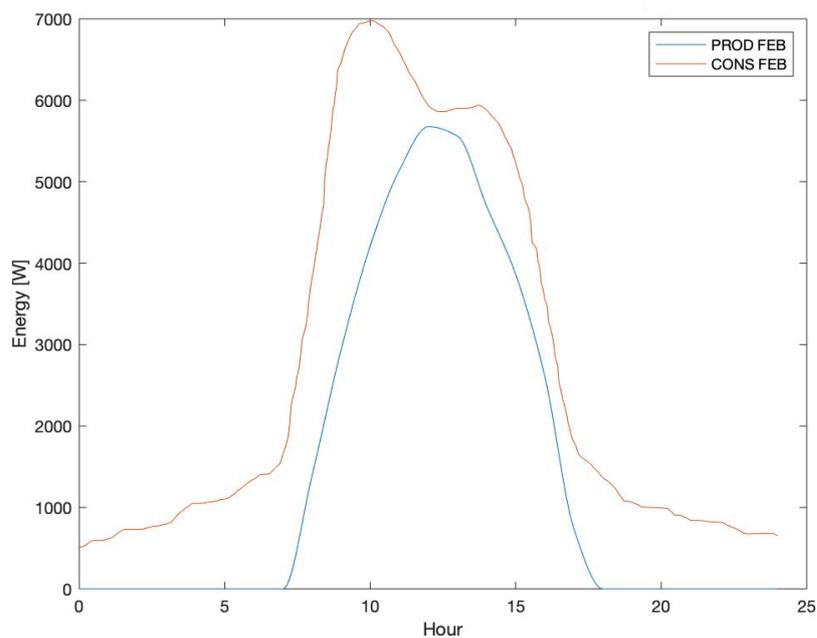


Figure 5. Santander Winter Office Load and 14kWp PV Plant

Our chosen PV plant has a 14kWp installation with a cost of 8400€ and a LG CHEM 3,3kWh battery with a cost of around 2400€. We now have to take into account that as our plant is small for more or less half of the year, we are going to need to buy electricity for the grid. With an estimation of an average price for electricity in Spain this 2021 of 0,20€/kWh we estimate given our obtained data, that if we need 29,016kWh every 24h for half of the year (182,5 days) we get a yearly cost of energy of: 1095€ a year.

With no PV plant, in our office building, we had a daily consumption of 56,01kWh in summer and 65,78kWh in Winter this will give us a yearly cost of: 14667€.

Therefore, our PV installation in total will cost around 10800€ plus a 1095€ a year of energy, we are already saving money on our first year, because these costs are lower than our annual no PV plant scenario.

5. Conclusions

1. Although a sizing criterion has not been able to be studied, we have determined certain parameters and guidelines on how to approach a given load so that it is easier to establish a cost-effective PV plant for any given load.
2. We have learned that as of right now it is cost effective to establish a PV plant, and that it is possible to save money in the short run with it. All speculations about not being a costly energy system have been proven wrong as we can see that we can easily gain back our investment.
3. Energy storage systems are proving to also be cost effective, although still expensive and having the possibility of having to change them out every few years due to aging, we have seen that are starting to be optimal in a small-scale scenario.

6. References

- [3] [1] S. Yilmaz, J. Chambers, M.K. Patel, "Comparison of clustering approaches for domestic electricity load profile characterisation - Implications for demand side management, Energy, Volume 180, 2019, Pages 665-677, ISSN 0360-5442, <https://www.sciencedirect.com/science/article/pii/S0360544219310060>
- [4] Nuria Martín-Chivelet, David Montero-Gómez, Optimizing photovoltaic self-consumption in office buildings, Energy and Buildings, Volume 150, 2017, Pages 71-80, ISSN 0378-7788, <https://www.sciencedirect.com/science/article/pii/S0378778817304796>

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CHAPTER 1. INTRODUCTION

Photovoltaic (PV) energy is a zero-emission energy source that offers substantial benefits for society, it is therefore considered a renewable energy source that, as it is inexhaustible and domestic, offers much more security than an imported energy source. Until the last decade, PVs were used in specialised low energy applications, due to its high prices. The first PV cells were produced in the 1950s and were primarily implemented in orbiting satellites. In the 70s huge improvements were made that opened a number of opportunities for terrestrial applications, PVs became a popular power source for small consumer electronics as the development for residential and commercial uses began.

Now, after many installations and some decades of improvements later, PV performances have risen considerably, allowing also for a cost reduction. This led to a flourishing off grid market for commercial and residential uses and nearly economical on-grid market, which is going to be the focus of this work.

All of this is leading us to a more developed and cost-efficient energy source, which gives us the opportunity to keep exploring how these technologies can be used daily by everyone. As mentioned above, a nearly economical on-grid market, opens the opportunity for people to have their own installation. This is why we want to explore the possibility of making these technologies more comprehensive and understandable for everyone so we can reduce the use of harmful energy sources and start using more renewable energies.

When developing and deciding to use renewable energy sources, there is a temptation to compare solar and wind energy since their development follows more or less the same curve. While in theory this is true, wind energy is mainly used in larger installations, large wind farms are more common than local installations. PV plants are more compatible with urban environments because they are more easily integrated in buildings and residential designs. This is why we will focus on solar technologies.

1.1 MOTIVATIONS

In this project we will try to establish and investigate a sizing criterion for a small PV plant used in a residential or small office environment. Having the capacity to be able to determine, given a particular installation, how big and which components our PV installation should have.

Being able to identify the context where PV can provide the best savings and make PV energy more accessible to people are our main motivations, to be able to better understand how PV plants work and how they can be used to run our households and offices in a daily basis. This would help us not only to gain quality of life but also be more environmentally friendly, which is another of our motivations. Being able to help the planet whilst saving money is a great accomplishment which we hope can be achieved in the near future.

CHAPTER 2. STATE OF PLAY

The first aspect we take into consideration when talking about implementing PV plants into daily consumption use is the strategic way to tackle how big a plant has to be for a given load, taking into account that each situation is slightly different to the rest.

In this respect, there are numerous publications that help us understand how the system works and how we can later analyse it. In 2019, S. Yilmaz, J. Chambers and M.K. Patel published a paper where they performed a rigorous assessment on household electricity demand profiles that concluded that separately each household has a very different profile but overall, they balance one another. Also, in 2017, Nuria Martín-Chivelet and David Montero-Gómez, wrote a paper on self-consumption in office buildings that helped establish load management and storage. This paper helped understand the problem at hand and gave us some possible guidelines on how to approach our main problem. This led to another important aspect of these technologies, energy storage systems. Some publications (Sylvain Quoilin, Konstantinos Kavvadias, Arnaud Mercier, Irene Pappone and Andreas Zucker, 2016), state that being able to obtain 100% self-consumption it is not at the moment realistic, and although we are able to reduce cost, Lithium-ion storage systems in particular, are far from ready for a large scale market. Others (T. Beck , H. Kondziella, G. Huard and T. Bruckner, 2015), regarding the same findings, have come to the conclusion that battery storage systems can temporarily yield good results, and therefore optimizing PV plants for a given load profile is possible.

It is possible to establish a PV system with batteries that could effectively support a given load. To make it even more effective we can have a grid connected system to help with the energy demand and possible altercations. In 2016, Kanzumba Kusakana published a paper talking about a developed model for a hybrid grid-connected and battery PV system, were an optimal scheduler for the power flow in order to be as economical as possible.

At this point, it also became important to not only have a cost-effective installation but if possible, to be able to save energy. Household electricity consumption was studied in 2010 by Aníbal de Almeida, Paula Fonseca, Barbara Schlomann and Nicolai Feilberg. Their publications focused on research about reducing wasteful consumption and responsible ways to consume, through which they obtained key contributors to power demand, information that can be used to create a more precise model and sizing criteria. Others (Yann Riffonneau; Seddik Bacha; Franck Barruel; Stephane Ploix, 2011), used dynamic programming to optimise performance and PV plants in order to reduce costs.

Finally, we take a look at the reduction of fossil fuels, which is a very important factor regarding energy consumption, as we have mentioned. It is very important to reduce, for example, CO₂ emissions, this is why some publications tackle the increasing demand of renewable energies (X. Vallve, A. Graillot, S. Gual and H. Colin, 2007), PV in particular, studying the market potential for small scale applications and analysing typical load profiles, to be able to make these technologies more available, so thanks to all of this input we are able to better understand what we want to achieve, and be able to further develop optimization methods to make it a more used energy source.

CHAPTER 3. DESCRIPTION OF THE TECHNOLOGIES

Solar energy can be harnessed in two ways. It can be used either directly to heat water to warm up buildings or for domestic use, or through photovoltaics (PVs), solar panels. These PV systems are formed up by PV cells that are interconnected to make modules. PV cells are made of light-sensitive semiconductors which can transform sunlight into an electric current. There are a some different types of solar panels:

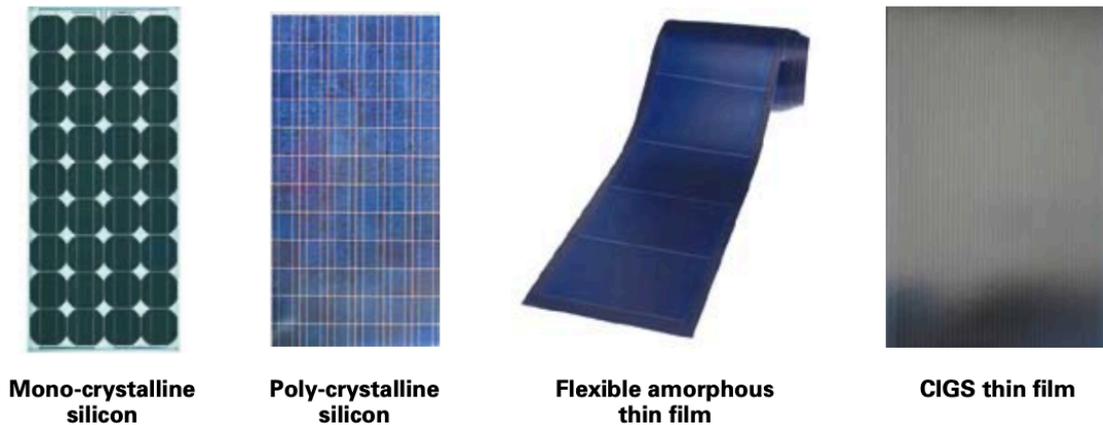


Figure 1. Different types of PV technologies. [1]

The most commonly used are crystalline silicon panels. This is due to the fact that they are more developed and are more efficient, since depending on which type of technology is used, there is a different conversion efficiency from solar light to electricity:

| Technology | Module Efficiency |
|---------------------------------------|--------------------------|
| Mono-crystalline Silicon | 12.5-15% |
| Poly-crystalline Silicon | 11-14% |
| Copper Indium Gallium Selenide (CIGS) | 10-13% |
| Cadmium Telluride (CdTe) | 9-12% |
| Amorphous Silicon (a-Si) | 5-7% |

Figure 2. Table of modular efficiencies for the different types of PV technologies. [1]

As we can see in Figure 2, for example, Amorphous silicon technology will need twice the space as crystalline silicon to produce the same amount of energy, because the module efficiency is halved for the same capacity. Crystalline silicon is not only, the most efficient of solar technologies, but also, the most developed and most used one, so it will be the technology taken into consideration for the development of our model, without having to differentiate between mono-crystalline and poly crystalline as their difference in module efficiency can be overlooked.

Another important aspect regarding PV performance is the effects of temperature. We have to take into considerations that PV cell performance declines as the temperature of the modules rise. [1]

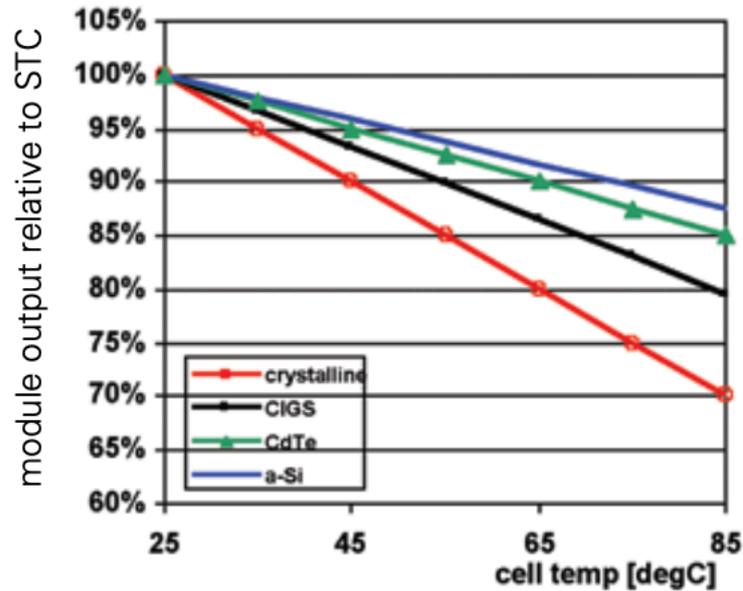


Figure 3. Effects of temperatures on the different types of PV modules. [1]

With these panels, a PV plant can be created, and electricity can be used, stored or fed into the electric grid.

PV plants have four basic components:

1. The solar panels that convert sunlight into electricity generating a direct current (DC)
2. An inverter that transforms direct current into alternating current.
3. Storage system, batteries.
4. Our load or the grid to which our plant is connected, or to both.[2]

Usually, energy storage systems for small scale loads, such as the ones we are going to study, are not used due to the inefficiency they are characterised by. But, interest in grid-scale energy storage technology has progressively increased over the last few years, and for obvious reasons. Consumer demand for improved portable electronics and electric vehicles is propelling technology forward at an unthinkable rate 20 years ago. And as Energy Storage Systems could play a bigger role in the future, we are going to implement it into our model. [3]

Energy can be stored in a variety of ways:

1. Chemically and electrochemically (ie. batteries, hydrogen, fossil fuels, and biofuels).
2. Electrically (ie. capacitors, superconducting magnetic energy storage).
3. Mechanically (ie. compressed air, hydro energy storage, and flywheels).
4. Thermally (ie. hot water/vapor, latent heat).

For our application, battery technologies make the most sense. There are a variety of them available: Lead-acid (Pb-Ac), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), sodium-sulfur (Na-S), and lithium-ion batteries. Lithium-ion type batteries have emerged as the technology of choice for electric vehicles and, to a lesser extent, as they are starting to be used, stationary battery energy storage systems. This is why we will focus on this type of batteries. The electro-chemical fundamentals of battery functioning are not of main concern in this work. [4]

CHAPTER 4. PROJECT DEFINITION

4.1 JUSTIFICATION

Over the last years, renewable energies have become more and more popular. As technologies advance, they are also becoming more affordable, all of this implies that more people are interested in powering their houses with them. If we take a closer look at PV technologies, we can see this advancements and also great number of people wanting to use them. But due to the cost and complexity of PV plants we cannot tell whether it is going to be worth it to power our homes and offices.

This is precisely this what we are trying to achieve with this work. We want to be able to establish a sizing criterion for both home and office loads, in order to maximize self-consumption of the produced energy, so that we do not oversize our plants making them more expensive and therefore not optimal, or undersize them in a way that the plants are not able to cope with the energy demand of our system. By establishing a sizing criterion, we will be able to make PV technologies more affordable for everyone.

Being able to determine the optimal size of a PV has been a major challenge for many years for researches in the field of renewable energies. As energy demand can only be estimated we can never be sure 100% on the perfect dimensions of a given load, but we can cope with these uncertainties with security measures such a battery banks for energy storage or by oversizing the plant. Being able to determine which way to go remains an unresolved problem. So, in order to help with the decision other aspects of the project must be taken into account, such as economic and environmental impacts. Being able to find the balance will be the key to not only achieving our goal but will help identify a path which can be taken to help with the growth of renewable and clean energies.

4.2 OBJECTIVES

Main objective:

- I. Establish a sizing criterion for PV plants in a small to medium scale for office buildings and households. So, we are able to spread the use of renewable energies and more precisely PV energy.

Secondary objectives:

- II. Better understand the world of renewable energies to be able to help in its development so that we can work towards a world without fossil fuels. Acquiring knowledge of how PV plants work and how we use them will help us develop critical thinking in order to decide which data is going to be useful for making precise calculations on the problem at hand.
- III. Familiarise myself with the Photovoltaic Geographical Information System (PVGIS) which we are going to use for our calculations. Learn how to use the different tools it offers in order to make better models for the problems we face so that we can obtain more precise results.

4.3 ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS

When speaking of the United Nations sustainable development goals, this project lines up perfectly with 5 of them:

- Number 7; Affordable and clean energy: helping develop a criterion to be able to install PV plants will allow more and more people to have access and use cleaner forms of energy and be able to optimise their investments.
- Number 9; Industry, innovation and infrastructure: Helping the advancement of PV energy will help us guide the world towards innovation in renewable energies and develop an industry which does not run on fossil fuels.

- Number 11; Sustainable cities and communities: Once people start using renewable energies in their homes and offices the world will be making its way to a more sustainable and environmentally friendly place.
- Number 12; Responsible consumption and production: On a daily basis we consume a great deal of resources, including energy. By analysing how much we produce and consume we can make ourselves more self-conscious on how we waste our resources being able to focus and make more responsible decisions.
- Number 13; Climate action: Clean energy means less pollution. By tackling one of the major problems regarding this problem we make a stand against harmful energies towards the environment and help promote the use of cleaner energy which will help us have a better world.

4.4 WORK METHODOLOGY

The first thing to do is obtain information on how PV plants work and search for an optimal way of establishing a criterion in order to focus on a few aspects of energy demands and productions to later on establish how our system is going to be.

Then our use case scenarios must be determined by searching for useful data regarding home and office energy load demands. So, an educated guess can be made on the subject to later compare with the results obtained in the simulations and see if they make sense.

After establishing our scenarios, using MATLAB and Photovoltaic Geographical Information System (PVGIS) calculations are made in order to establish and make a model of the PV plants depending on the different load demands obtaining enough data to be able to finally establish a sizing criteria based on our computational results and the parameters we have established earlier.

After establishing our sizing criteria for our different scenarios, conclusions can be made regarding the obtained results whilst making an extrapolation from the calculations so that the criteria established can be used for any given situation.

It is important to mention that that data due to COVID and the pandemic was not taken into account. As the data was taken from literature, and, for example, smart working can lead to a substantial change in the home load distribution, it could result in a better matched load curve with respect to production curve. However, we do not possess sufficient data to process it in a simulation.

4.5 RESOURCES

The main resource needed for this project is the use of PVGIS which gives us access to data of solar radiations and temperatures around the globe, PV potential for different technologies, letting you choose different configurations to make calculations, etc.

We also need to use MATLAB for our calculations and its tool Gabbit to be able to transform graphs into data points so we can make calculations with them in MATLAB.

CHAPTER 5. DESCRIPTION OF THE DEVELOPED MODEL

5.1 ARCHITECTURE

As we have previously mentioned in Chapter 2, our PV plant can be connected in a few different ways, that is why we can find three types of different architectures in which they can be used:

1. Grid directed. When our plant is directly connected to the grid so all the energy being produced is being consumed by someone else.
2. Grid interactive with energy storage, hybrid. The hybrid system consists on having our plant connected to both our load and to the grid. This permits us to either consume the electricity or to feed it into the grid. Also, if our load is demanding more than we are producing this excess can be covered by the grid.
3. Off grid with energy storage. No grid interaction means that all the energy needed must be produced by our plant, the excess energy can be then stored to be used in moments of less energy production.

[5]

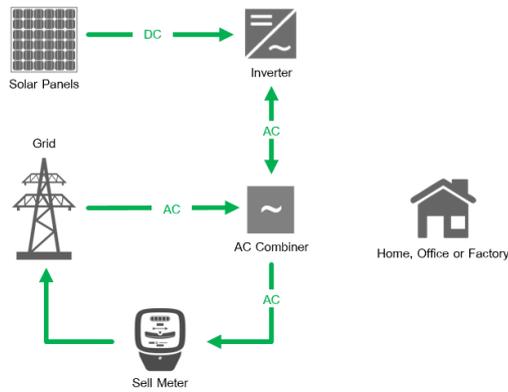


Figure 4. Grid Directed System. [6]

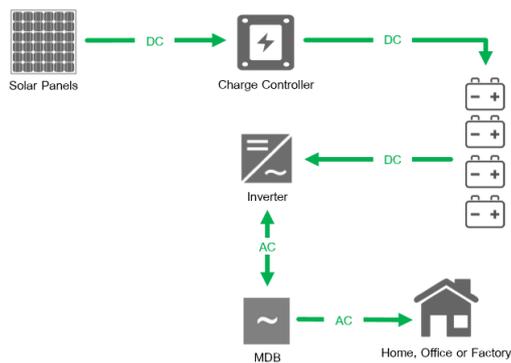


Figure 5. Off Grid System.[6]

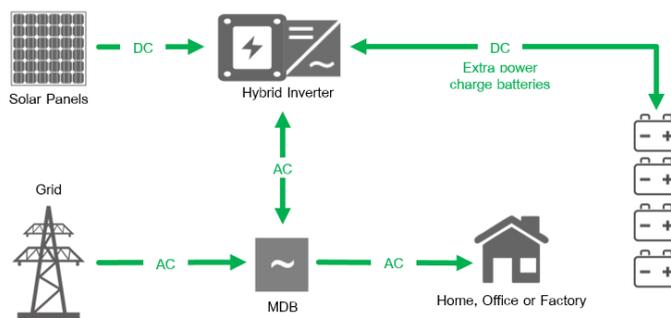


Figure 6. Hybrid System.[6]

We now have to choose which architecture is going to work better for us. We cannot use grid directed, because we need to be able to feed our load, so we have to choose an architecture that includes our load. It is smarter to go for a grid interactive architecture because if there was an instance where more energy is needed than the one we are producing or have stored, we won't be able to feed our load. And in the event that we are producing more than we need and we have our batteries full we can always feed energy back into the grid, so no energy is lost. As it is a possibility to have not enough energy with an off grid setting it is smarter to go for a hybrid system. There is always the possibility of having a bigger off grid with more panels and more batteries but as it is more expensive, we would not be able to economically save money.

We also choose to use energy storage systems so that when generation is higher than production so we can ensure demand is always met when our production is low. It makes the energy management more difficult and more complicated, so controllers are required so we are able to properly regulate our system [7].

5.2 ENERGY STORAGE SYSTEM

As mentioned, an energy storage system is required, so that we are able to store energy and discharge it in the form of electricity when needed. Storage system are formed primarily by an array of batteries, but also an inverter, a thermal management system and an electronic control system are required for the system to function. The control system, for instance, manages when the batteries need to be charged and when the loads require energy from the batteries. To coordinate the functioning, this control system also communicates with equipment outside the energy storage system. The inverter is a device that converts the electricity generated by the batteries from direct current (DC) to alternating current (AC) which is the type of current needed to run households and offices. The thermal management system regulates the entire system's temperature and prevents heat created by chemical reactions within the batteries from posing a threat to the system's performance. [8]

As previously mentioned, the type of batteries we are going to focus on are lithium-ion batteries. As we might need different types of batteries for our different PV plants and scenarios, we are going to use the following batteries offered by Tecnospot, Italian renewable energy company, for our scenarios:

Panoramica sistemi di accumulo (ioni di litio)



| Accumuli batterie agli ioni di litio | | | | | | | | | | | | | |
|--------------------------------------|-------------|----------------------|-------------------------------|-------------------------|---------|-----------------------------|---------------|-------------------------------|------------------------|-----------|-----------------------|---------------------|---|
| Produttore | Sistema | Tensione del sistema | Tipo di batteria | Capacità nominale [kWh] | DOD | Capacità utilizzabile [kWh] | Cicli di vita | Capacità batteria espandibile | Misure [L x W x H, mm] | Peso [kg] | Marchio di protezione | Montaggio | Nota |
| LG CHEM | RESU 6.4 EX | 48 V | NMC - Nickel Manganese Cobalt | 6,40 | 90% 80% | 5,76 5,12 | 6000 10000 | fino a 12,8 kWh | 406 x 165 x 664 | 60 | IP21 | su terra / a parete | |
| LG CHEM | RESU 3.3 | 48 V | NMC - Nickel Manganese Cobalt | 3,30 | 90% | 2,97 | - | fino a 13,1 kWh | 452 x 120 x 401 | 31 | IP55 | su terra / a parete | disponibile da agosto / settembre 2016 |
| LG CHEM | RESU 6.5 | 48 V | NMC - Nickel Manganese Cobalt | 6,50 | 90% | 5,85 | - | fino a 16,3 kWh | 452 x 120 x 654 | 52 | IP55 | su terra / a parete | disponibile da agosto / settembre 2016 |
| LG CHEM | RESU 10 | 48 V | NMC - Nickel Manganese Cobalt | 9,80 | 90% | 8,82 | - | fino a 19,6 kWh | 452 x 227 x 483 | 75 | IP55 | su terra / a parete | disponibile da agosto / settembre 2016 |
| LG CHEM | RESU 7H | 400 V | NMC - Nickel Manganese Cobalt | 7,00 | 95% | 6,6 | - | no | 744 x 206 x 692 | 76 | IP 55 | su terra / a parete | disponibile da settembre / ottobre 2016 |
| LG CHEM | RESU 10H | 400 V | NMC - Nickel Manganese Cobalt | 9,80 | 95% | 9,3 | - | no | 744 x 206 x 907 | 97 / 99,8 | IP 55 | su terra / a parete | disponibile da settembre / ottobre 2016 |

Figure 7. LG CHEM batteries for energy storage [9]

As we can see in Figure 7, we have different types of batteries with different nominal capacities and different percentage of usable capacity. This is important because batteries cannot be discharged completely, therefore part of the energy they have remains in it, making them have an efficiency percentage (DOD in figure 7). When a battery is needed, we will choose one of these, or a series of them, to fulfill our given requirements.

5.3 SIZING CRITERIA

Having established what is going to be achieved and the architecture that is going to be used, the next step is establishing what are going to be the parameters that are going to be studied after the simulations so that it is possible to determine, for a given case scenario, the size of our PV plant is going to be and how many batteries are going to be used in order for our system to both work and be cost effective and efficient.

There are two design constraints that we are going to focus primarily. The main problem is our peak power request, the plant needs to be able to have enough energy to maintain our

system working all the time including when most energy is being consumed. So, one the parameters we are going to take into account is peak power requested.

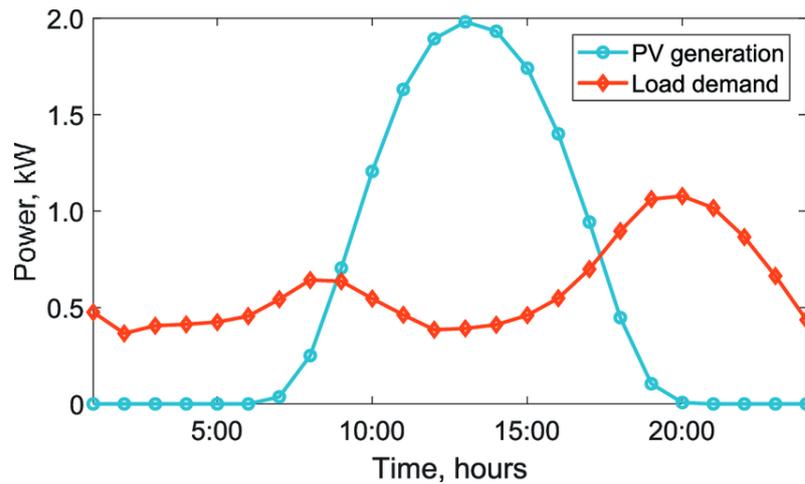


Figure 8. Graph of an average load demand and PV generation. [10]

This Graph shows us how on an average peak in demand and the peak in generation occur at different times of the day, so we have to be able to cope with these differences along the day. It is also very important to take into account the different scenarios which are going to be studied. As it will be seen in the following chapter, there is a big difference when it comes to an office load and a house. This difference is the difference in their demand curves having their peaks at different points in the day. A household resembles more the red graph in Figure 8, and an office load tends to have its peak more at the middle of the day, which will give it an advantage. As the office load has its peaks similar to the production of energy a smaller energy storage system will be needed, and household will need to store more energy to be used later in the day, more in detail of this difference will be shown further in the work.

Secondly, being able to feed our load when we do not have any energy production is very important. Photovoltaic panels provide only electrical power during the day and depending on the weather we are going to be producing more or less electricity, so these changes have to be taken into account when studying PV plants [11]. This is another reason for having batteries in our system, so we are be able to store the energy needed for every part of the

day. So, the plant has to be able to store the peak production during the day as well as producing such peak. Another thing to take into account is that if it was necessary, due to certain circumstances, power can always be taken from the grid, as we have a grid-interaction installation.

Finally, another important aspect to take into account is the time of the year, because depending on the season there will be a bigger or a smaller generation of energy.

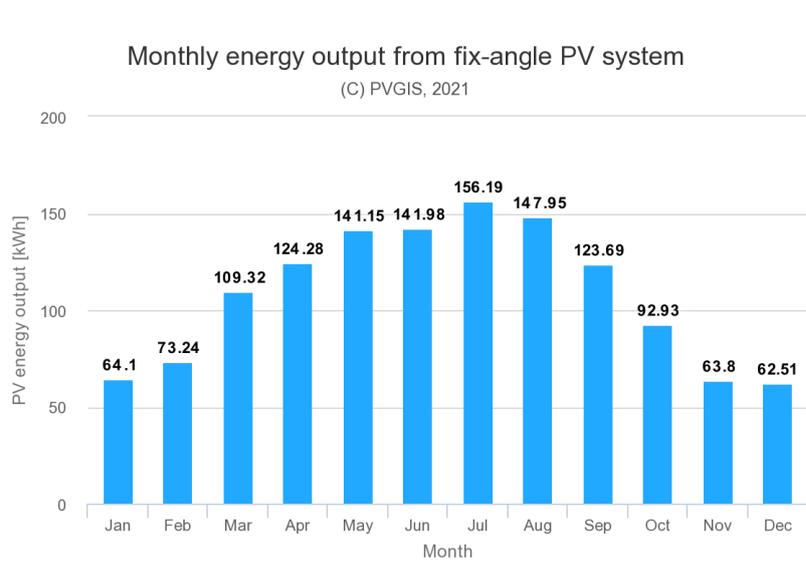


Figure 9. Graph of a monthly energy output example from a PV system. [12]

As it is shown on this graph if a PV plant is sized in order to guarantee the entire load demand is met in winter, in summer this plant is going to be oversized due to the increase in production. So a compromise has to be made between being able to produce all the demand needed when production is low and having a surplus of electricity, as our system is going to be grid-connected, the possibility of buying and selling energy is always there, so at the end of the day, the most important thing will be finding the most cost effective solution.

In order to be able to make all of this analysis, once established our scenario, having chosen location and load, we will be using the PVGIS tool to make our calculations. Thanks to PVGIS we have access to solar radiation profiles, PV potential regarding different technologies, etc. We are also able to choose the location in which to make our analysis

which will give us a more accurate understanding on how to make a sizing criterion regarding location of the plant.

5.4 USE CASE SCENARIOS

Stablishing a criteria for building PV plants for daily use is not the only objective, but also to be able to cope with the differences between an office building and a home, a comparison will be made in order to be able to take into account its differences which have been previously glanced at in the introduction, and now are going to be described.

5.4.1 HOME LOAD

The first problem we encounter when trying to merge a PV plant into a home load is its instability, because we do not have a steady consumption along the day, we encounter peaks at certain times of the day when the inhabitants consume more. Also, as people are more often in their households after work, we expect a larger consumption during the afternoon which means that most of our consumption is happening when we have low or none production, as we can see in graph 4, in the introduction, most of the production occurs during midday. All of this implies that for a home load we will be needing a bigger energy storage system to be able to store all the energy needed for the hours with more demand and less production.

Now that we have described how our household scenario, we are going to study a scenario and to be able to make an educated guess, based on our research and our data, on what our results should be.

We are going to be analysing the electricity load curve of a single household from Switzerland [13], we have chosen this particular data because it best represents the problems, we have previously mentioned. We can see, both, a difference between summer and winter days, and peaks in consumption rather than a steadier consumption curve more typical of offices.

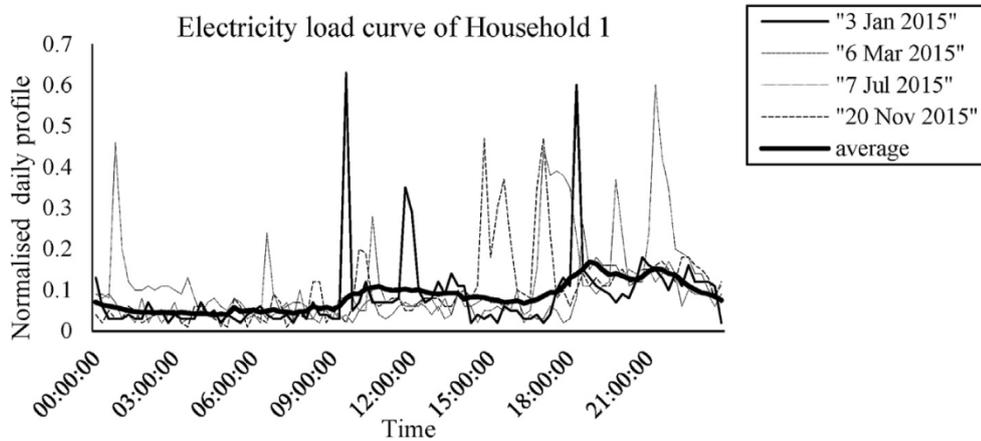


Figure 10. Electricity load curve of a single household for four different days of the year and the average curve for the year. [13]

For our calculations we have chosen to study the load profiles of the seventh of July and the third of January, to be able to compare summer and winter profiles. Thanks to MATLAB and its tool Grabit, we are able export this graph into MATLAB, so we are able to make calculations such as obtaining the overall energy consumed.

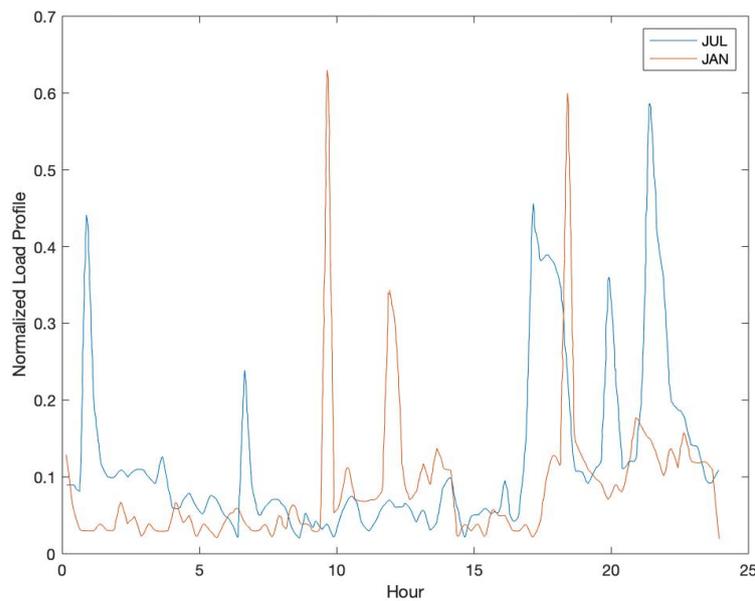


Figure 11. Load profiles in MATLAB of our Home Load

Thanks to the trapezoidal integral function we are able to obtain the nominal consumed energy for both graphs:

In January we have a normalized consumed value of 2,0523 hours. This value means that for every day we are at peak power for 2,0523 hours. And in July we have 2,8974 hours.

Having obtained this data in a normalised daily profile, it gives us the opportunity to use whatever size of load we deemed appropriate for the calculations that are going to take place. The average home load in Europe has a consumption size of 4,5 to 6kW of energy. As we want to be able to study differences between production and consumption of an average load, we have chosen to use a 5kW home load for this study. Therefore, our January and July consumption profiles are multiplied by 5kW, obtaining the load profiles that we are going to use and daily consumed energy of 10,26kWh in January and 14,487 in July.

5.4.2 OFFICE LOAD

Having an office being run by a PV plant seems more straight forward due to the fact that the peaks in energy production occur during the day when generation is also high, this will enable us to design a PV system with an smaller energy storage system because less energy will be needed in the hours of the day when production is lower. This implies that even though our consumption will be higher than our home load, due to its larger load size, we will be able to cut expenses by having a smaller energy storage system.

As we are going to establish the same criteria to the office load and the house load, we have also chosen a scenario to make our educated guess on the subject. We have chosen for our analysis an office building from New Zealand [14], we have chosen to use this data because it best represented what we think offices load profiles should look like, a steady consumption along the day and a consumption differences between summer and winter.

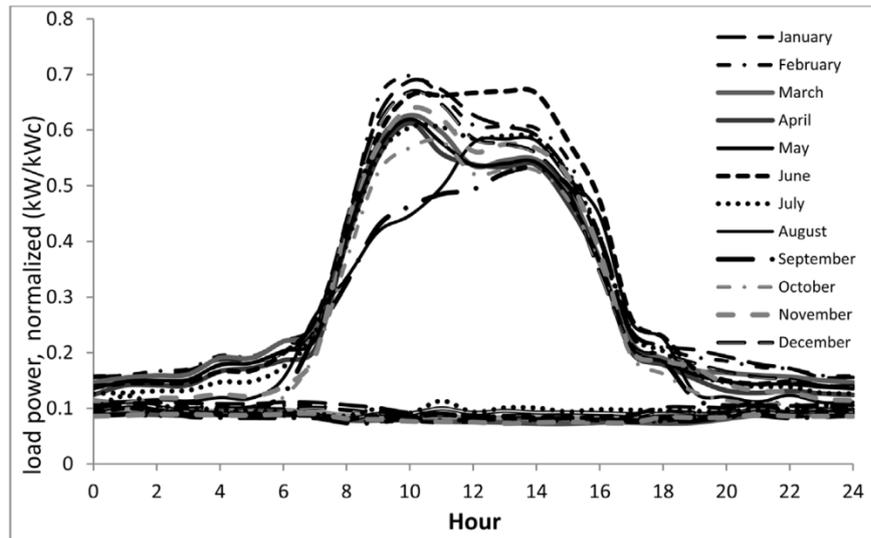


Figure 12. Monthly load profiles of an office building, at weekdays and at weekends (flat curves).[14]

As the table is hard to read, we have chosen for our analysis July and February, both for being easy to differentiate from the rest and for being in the seasons we want to compare. And thanks to MATLAB we are able to export this graph in order to make our calculations.

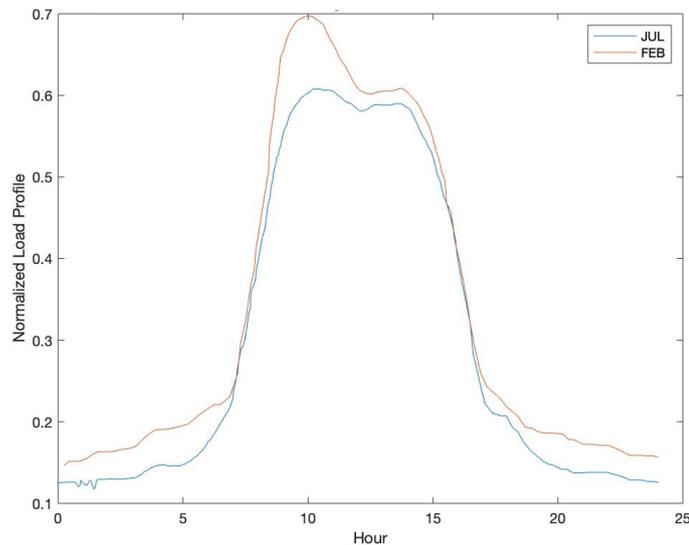


Figure 13. Load profiles in MATLAB of our Office Load

Like we did with the Home Load we are able to obtain through integration the nominal consumed energy for both winter and summer.

In July therefore, we have a normalized consumption of 5,6hours. And in January we have 6,58 hour of peak power consumption.

As well as we did in the home load, we need to stablish a size of our scenario, for offices this is trickier as there are many different possible sizes of offices raging from 9 to 21kW. We have chosen to use for our studies a 10kW size for our office.

Obtaining a consumption for July 56,01kWh and for February 65,78kWh

5.4.3 EDUCATED GUESS

| | Normalised Load [h] | Load (Office Load 10kW, Home Load 5kW) [kWh] |
|---------------------------|----------------------------|---|
| Summer Office Load | 5,601 | 56,01 |
| Winter Office Load | 6,578 | 65,78 |
| Summer House Load | 2,897 | 14,49 |
| Winter House Load | 2,052 | 10,26 |

Table 1. House and Office Load Summary

Having stablished a model and scenarios to work on, as we can see in Table 1, we are going to take a look at what is expected to help guide the simulations.

Office loads, as previously mentioned, are generally larger in size so will therefore have a larger PV plant than Office loads.

Also, in regard to energy storage, as we have seen, office loads also have a consumption curve which resembles more the production curve than the home load. This is because office hours occur primarily during the day whilst residential consumption hours have a less stablished shape primarily because as working hours end, residential consumption begins. This leads to a bigger difference between consumption and production in homes, having its

peaks sat different times of the day, therefore a bigger energy storage system will be needed to be able to cope with consumption peaks that occur while we have less to no production.

Finally, we are going to be choosing to different locations for our analysis. We choses to do this to see if location really affects energy production. We think, that as the sun irradiates differently depending on the latitude this is going to have an effect on the energy produce, being larger the closer we get to the equator. Therefore, we want to really see if this effect is large enough to make a big difference.

CHAPTER 6. SIMULATIONS

As it has already been mentioned, PVGIS is the main tool used to extract the data that is going to be later used in MATLAB.

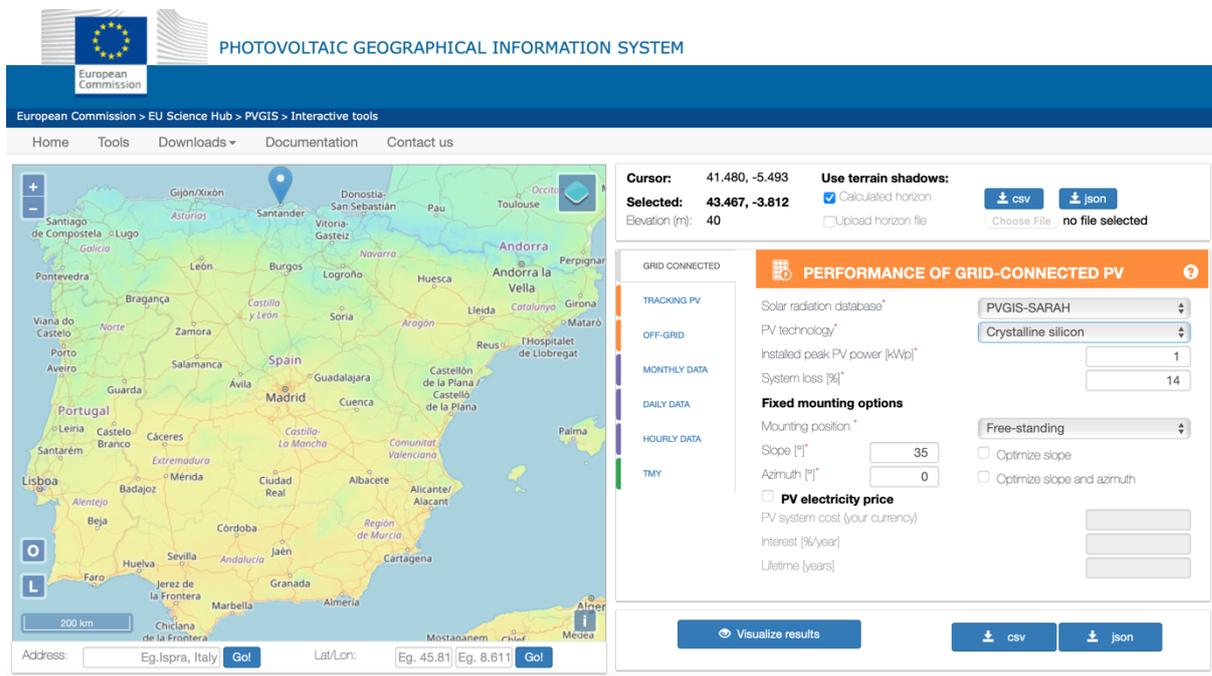


Figure 14. PVGIS main page.[12]

In Figure 14 we can see the main page of this tool. There are 7 functions on this platform but for this project only two are going to be used. The first one is the Grid Connected tab. In this tab, after establishing a location in the map, a mounting option for our panels can be established as well as a size of the plant and system losses. In this work, as average calculations are being made without a particular type of solar panel, system losses will be left at 14% which is a great average. Solar panels will be left in a free-standing position and, as the tool gives at 14% which is a great average. Solar panels will be left in a free-standing position and, as the tool gives us the possibility, the slope angle (angle in the vertical axis) will be optimized and the azimuth angle (angle in the horizontal axis, being 0° facing south.)

left in zero, because as the calculations were made, even with a 45 degree azimuth angle, the effects were similar and therefore could be discarded.

Two locations were chosen to make the simulations. These were chosen in different latitudes in order to analyse possible different results given by the location of the globe, because due to the fact that the sun does not radiate perpendicular to the earth, having different latitudes might give us different results. The locations chosen were Santander (43.467 , -3.812) in the north of Spain and Malaga (36.721 , -4.424) in the south. The distance between them should be enough to give us a good example of how different solar radiation is depending on the latitude.

6.1 PART ONE: MONTHLY ENERGY OUTPUT OF OUR PV PLANTS

The main comparison for our given scenarios and our given locations is going to be the difference between summer and winter, so we can later compare them and decide the final size of our PV plant for our scenarios. In order to do this, we can obtain, thanks to PVGIS, the monthly energy output given by a PV plant as it has been mentioned can be located wherever suits us and have the size we need. With this monthly data, an average daily summer and winter output will be obtained to compare with the consumed power of our loads in these seasons. The average daily summer output will be obtained using the months of May, June, July and August, taking into account that they each have a different number of days in them. For winter the daily average output of a given PV plant will be obtained using November, December, January and February.

6.1.1 EXAMPLE AND FIRST SIMULATION IN SANTANDER

A 1kWp (kilowatt peak) of installed power gives us the following output:

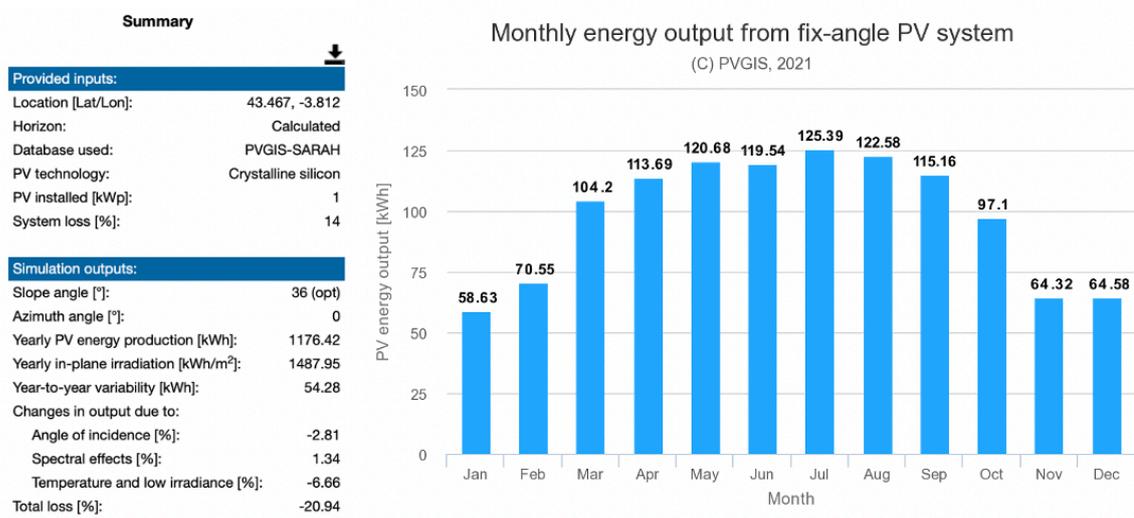


Figure 15. Monthly energy output of a 1kWp plant of installed power in Santander.[12]

With the chosen months we obtain:

- Daily Average Summer: 3,97 kWh
- Daily Average Winter: 2,16 kWh

As the size consumption of an Office and Home load have already been calculated in chapter 4.3, we know that this plant is too small for either of them. So more installed power is going to be needed.

6.1.2 SANTANDER SUMMER HOME LOAD

Our average summer home load has a daily average consumption of 14,49kWh. Therefore, to obtain this a 3,7kWp plant is needed:

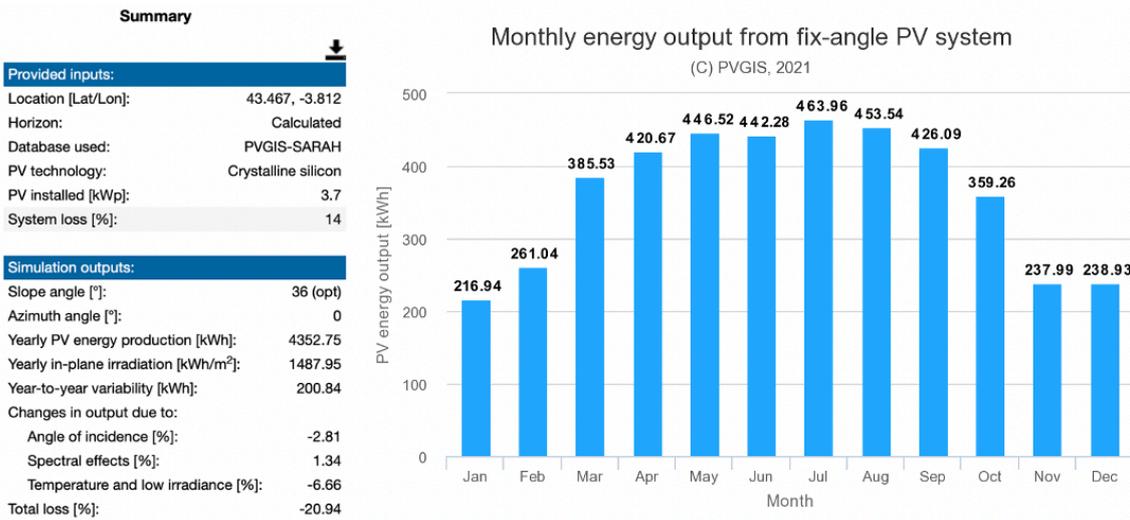


Figure 16. Monthly energy output of a 3,7kWp plant of installed power in Santander.[12]

We obtain a Daily Average Summer of 14,69kWh.

6.1.3 SANTANDER WINTER HOME LOAD

Our average winter home load has a daily average consumption of 10,26kWh. Therefore, to obtain this a 5kWp plant is needed:

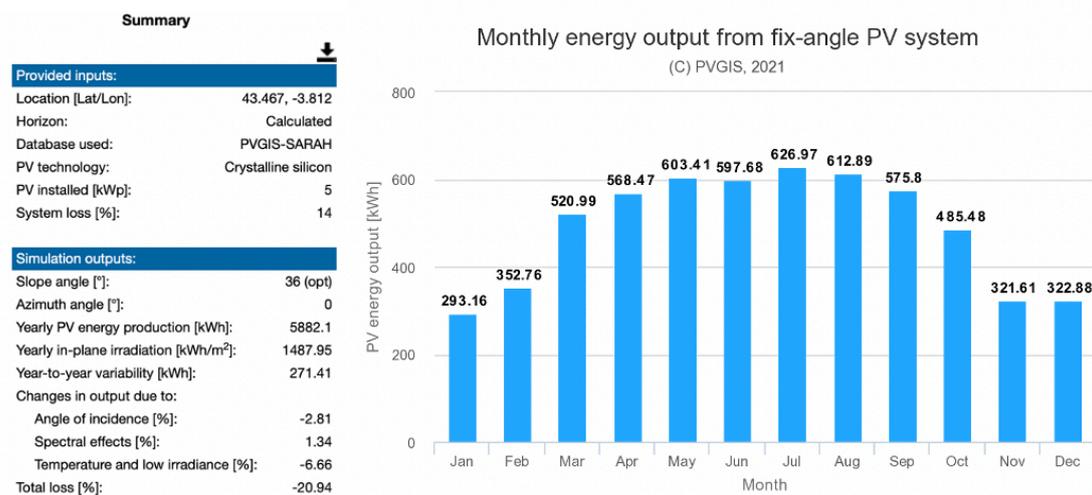


Figure 17. Monthly energy output of a 5kWp plant of installed power in Santander.[12]

We obtain a Daily Average Winter of 10,8 kWh.

6.1.4 SANTANDER SUMMER OFFICE LOAD

Our average summer office load has a daily average consumption of 56,01 kWh. Therefore, to obtain this a 14,3kWp plant is needed:

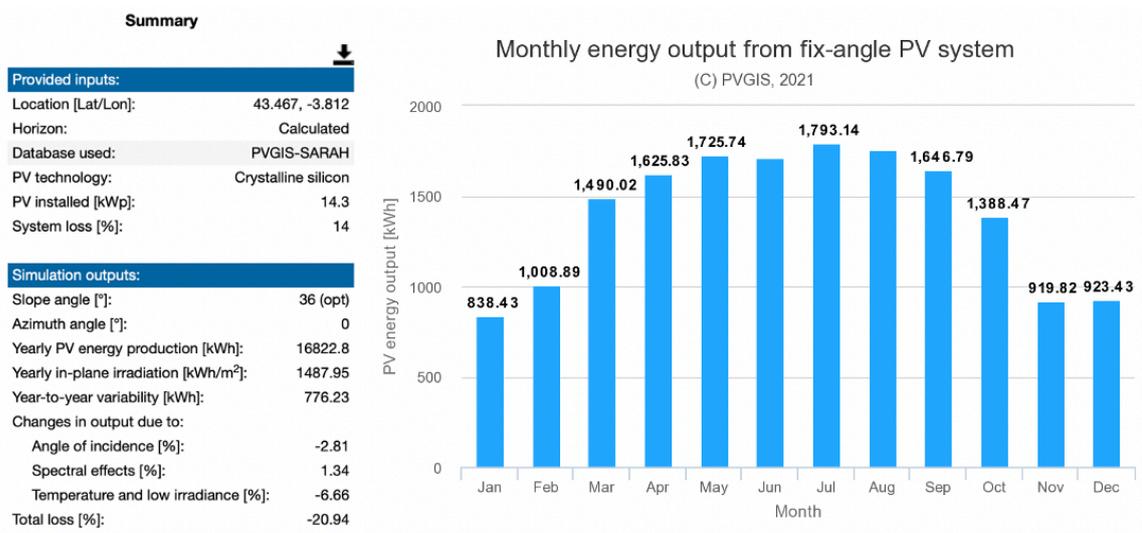


Figure 18. Monthly energy output of a 14,3kWp plant of installed power in Santander.[12]

We obtain a Daily Average Winter of 56,76kWh.

6.1.5 REST OF LOADS AND SUMMARY

The methodology is the same for the rest of the loads given the different situations. The graphs for these results are included on Appendix I.

After all of the simulations we obtain the following results:

MALAGA:

| Installed Power [kWp] | Daily Average Winter [kWh] | Daily Average Summer [kWh] | Load |
|------------------------------|-----------------------------------|-----------------------------------|------------------------|
| 2,7 | 10,42 | 14,7 | Winter and Summer Home |
| 10,3 | - | 56,05 | Summer Office |
| 17,1 | 65,95 | - | Winter Office |

Table 2. Malaga Installed Plants

SANTANDER:

| Installed Power [kWp] | Daily Average Winter [kWh] | Daily Average Summer [kWh] | Load |
|------------------------------|-----------------------------------|-----------------------------------|---------------|
| 3,7 | - | 14,69 | Summer Home |
| 5 | 10,8 | - | Winter Home |
| 14,3 | - | 56,76 | Summer Office |
| 30,5 | 65,87 | - | Winter Office |

Table 3. Santander Installed Plants

We can see a few different things while comparing tables 2 and 3. Firstly, for the same Load we can see that we always need a larger installation for Santander, this is because, as we presumed it would happen, more irradiation occurs the closer we are to the equator, and the more irradiation the smaller our plant needs to be. We can therefore conclude, as this size difference is pretty large, that latitude plays a very important role when it comes to production of energy with PVs.

If we now take a look at the Home loads for both locations, the difference between installed power needed in summer and winter is not as large as we can see in the Office loads. This means that whether we choose a bigger plant that will oversize in some part of the year or a smaller one that will make us have to buy energy from the grid, we would not be having a very big difference in size and therefore costs. This is why is going to be easier to optimise the size of a home load, when it comes to its installed power.

The opposite scenario is present in the offices loads, a big difference in size is needed to satisfy the demand for winter and summer therefore choosing an optimal size is going to be trickier as we will have to choose between having a bigger one that will makes us produce an excess of production in summer or a smaller one which will lead to the necessity of purchasing energy from the grid.

6.2 PART TWO: HOURLY PRODUCTION AND CONSUMPTION COMPARISON

Having obtained the theoretically perfect PV plant size for our individual scenarios separating in winter and summer, they now have to be studied together. As the same plant is going to be needed for summer and winter, as it has already been mentioned, the perfect plant for a given scenario in winter might be oversized for summer or vice versa, so an analysis of a given plant has to be studied for both scenarios. As we already have the given sizes for all circumstances, we can already determine if a plant is going to be able to cope with our load for both summer and winter, so in order to determine if a bigger or a smaller plant is going to be needed we are going to take a look at the hourly irradiance which can be later converted into hourly energy production. When this hourly daily energy production is compared with the hourly daily consumption we can determine if we are either consuming or producing more and how much. In term when compared both summer and winter we will be able to determine if we use a bigger or a smaller plant and also how much energy storage we are going to need. We can determine the size of our batteries by comparing peak

productions and consumptions, the biggest difference between the two, with a positive production, will determine the maximum energy we will be able to store in our batteries.

6.2.1 SIMULATION PREPARATION

In order to make a good comparison with all our data we have to make a few adjustments to our data. Thanks to the second tool we are going to use in PVGIS, hourly irradiance data, we can obtain for a given location and month the average sun irradiation. This hourly irradiation is a 24-point graph, one for each hour. Our daily load consumptions, thanks to MATLABs Grabit, has an average of 600 data points. So in order to be able to compare the hourly production which we are later going to obtain form the irradiance we are going to resample all of our hourly data , both the irradiance and the consumption, so we not only have the same number of points (600) but also we are going to make a 24h vector divided into this 600 points, that is going to be the hourly reference for all of them. This gives the opportunity to operate with the data as they will all have the same x-axis data.

In order to do this, we can use MATLAB and its shape-preserving basic fitting plot tool. Where it gives you a function for your given data points and you can insert a given x vector, in our case our auxiliary 600 point 24h vector, to convert our data points into 600 data points, holding the same information.

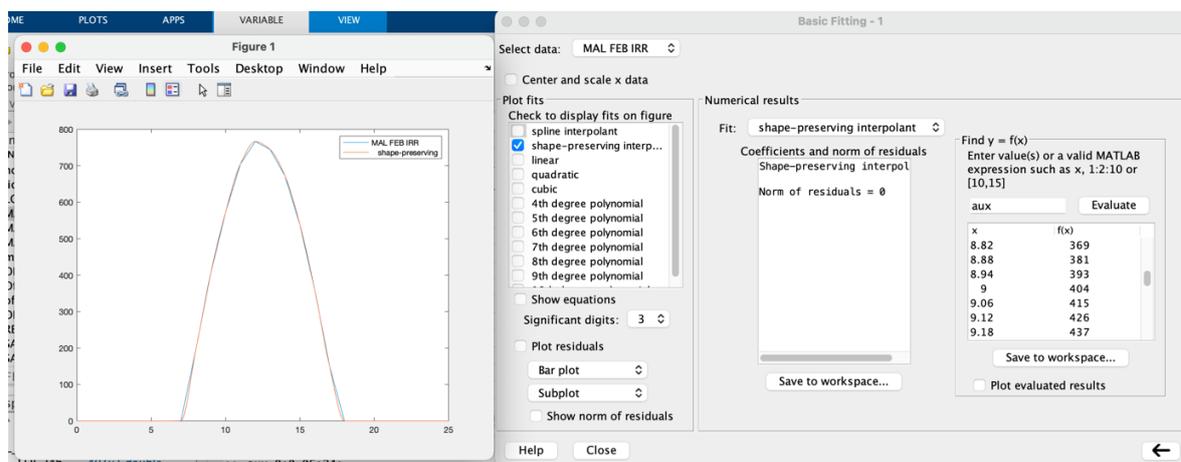


Figure 19. MATLABs shape-preserving tool.

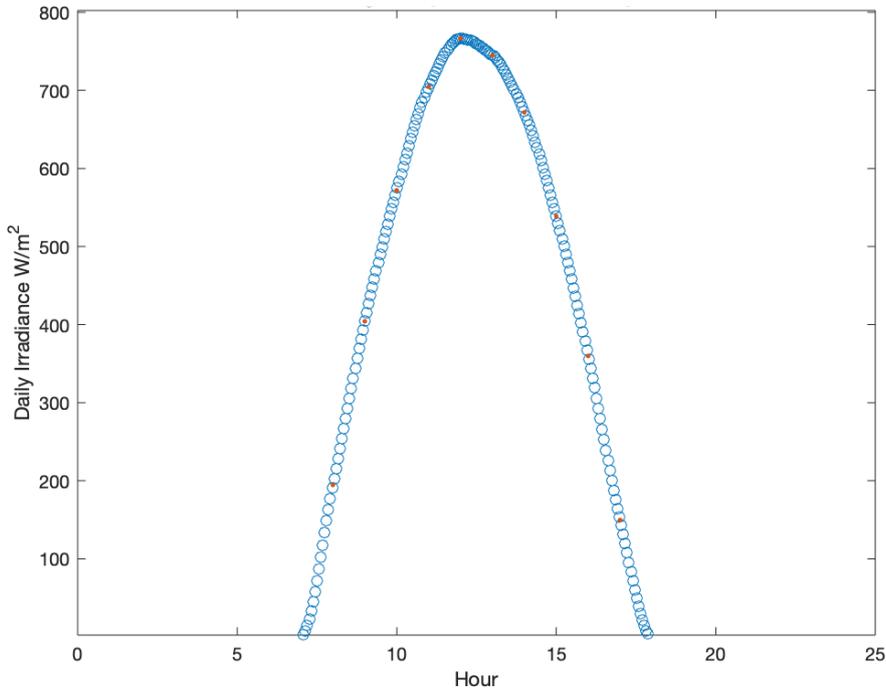


Figure 20. Malaga's Daily Irradiance in February

As we can see in this example in Figure 20, we have converted Malaga's Daily Irradiance from a 24-point vector, orange, to a 600-point vector, blue.

6.2.1.1 Irradiance to Production

The next step is to convert the Daily irradiance into production by our PV plant so it can be later compared to the daily consumption for each scenario.

Thanks to the information in PVGIS we can estimate that for every 1kWp of installed power we have 1000W of energy produced per square metre. So, we can say that we have 1square metre of Solar Panels for every 1kWp, it is important to take into account the system loss of 14% due to the conversion from solar energy to electricity. Taking into account the conversion to nominal irradiance to balance the equation, we can say that:

$$\text{Equation 1. Energy Produced [W]} = \frac{\text{Irradiance } \left[\frac{\text{W}}{\text{m}^2}\right]}{\text{Nominal Irradiance} \left[1000 \frac{\text{W}}{\text{m}^2}\right]} * 0.86 * \text{Installed power [kWp]}$$

6.2.2 SANTANDER OFFICE LOAD STUDY

6.2.2.1 Installed power of 30,5kWp

We are now going to use Santander Office Load as our main system to analyse. We are going to start analysing the biggest plant possible and work our way down to our optimal size. The biggest plant possible for this scenario was a 30,5kWp plant which gave us enough energy to cope with all of the winter consumption. But as we have previously mentioned this should be too big of a plant for summer, which would effectively make it too big of an investment for it to be viable.

With Equation 1, we obtain the following production for February and July:

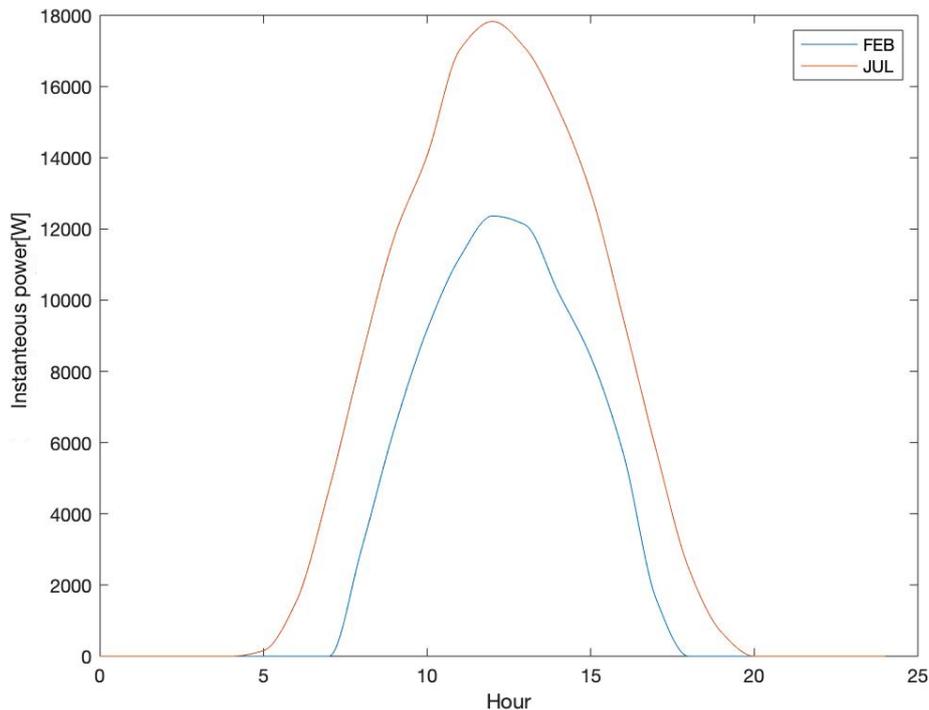


Figure 21. Santander 30kWp PV plants Office Production.

We can now separately compare them to our Winter and Office Loads to see if we are consuming or producing more:

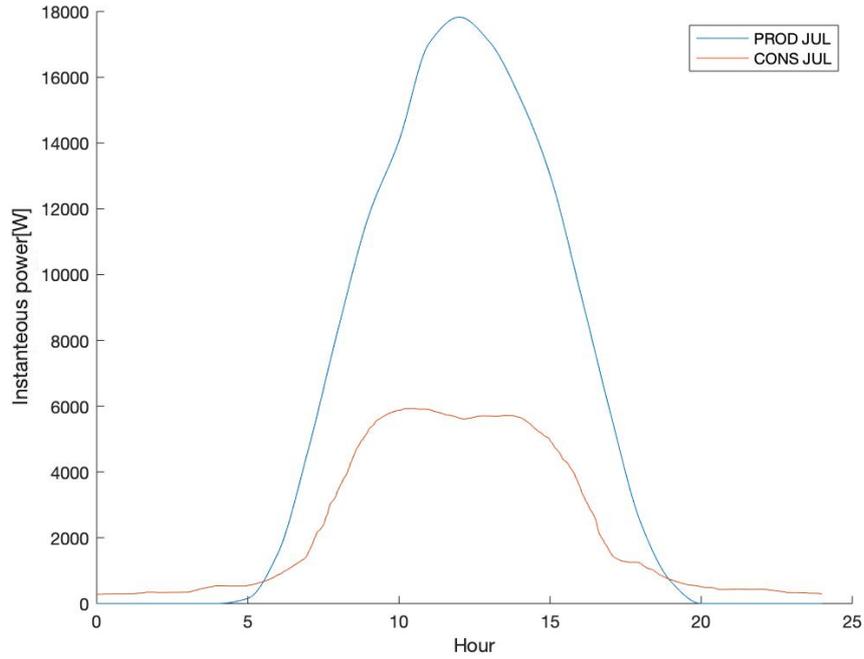


Figure 22. Santander Summer Office Load and 30kWp PV Plant

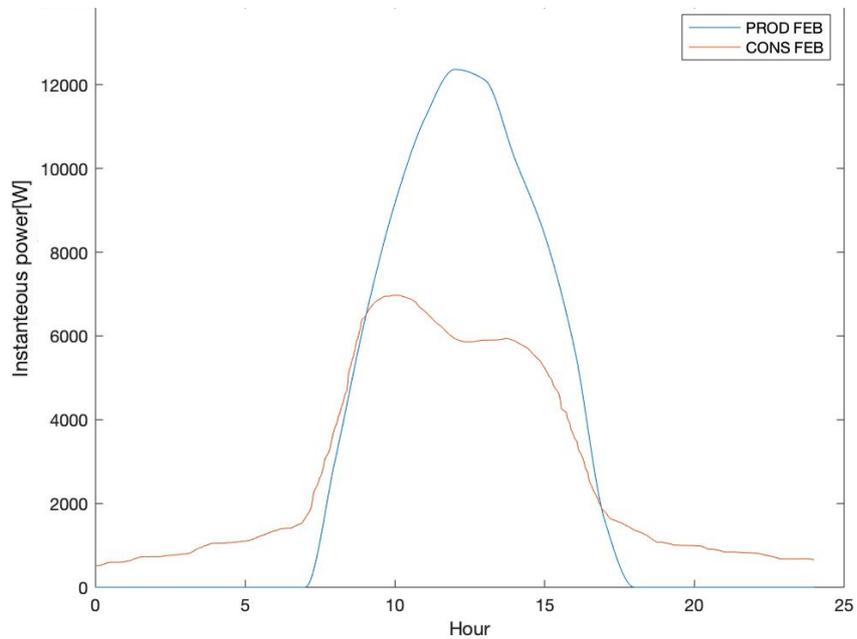


Figure 23. Santander Winter Office Load and 30kWp PV Plant

As it is shown in both figures 22 and 23, it looks like we have an overproduction in both months, which we are going to calculate how much below. We can also see that specially in July we have a very big overproduction which is going to lead to a lot of energy not being used and therefore being sent into the grid, and as it has been previously mentioned this is underproductive in terms of cost and plant size.

If we subtract one from the other and integrate the result, we can see how much we are over producing (positive value of integral) or consuming (negative).

In February we have the following: 14335Wh

And in July: 83346Wh

We therefore not only have an overproduction all year round, but as we have mentioned quite a large one specially in summer. Therefore, we have obtained a valuable conclusion. As a bigger plant is more expensive, if we have very large overproduction at least in one season of the year it is not worth it to invest in such a large PV plant as the selling of the overproduced energy will not compensate the original cost of the plant. We will dive deeper into this cost later on.

6.2.2.2 Installed power of 14kWp

As we have seen large plants seem to be a problem, as having an intermediate size plant will also give us overproduction in at least one of the seasons. If we look at tables 2 and 3 an intermediate plant between the optimal for winter and summer will generate an over production at some point, and as we have just discovered it is more efficient to try and avoid overproduction and if needed as we have a grid connected system get energy form the grid. Therefore we are now going to study the same system with an installed plant of 14kWp, which is just under the optimal for our winter plant meaning that we should avoid a big overproduction and we might end up having a bit of over consumption, but in the long rum will be more economic.

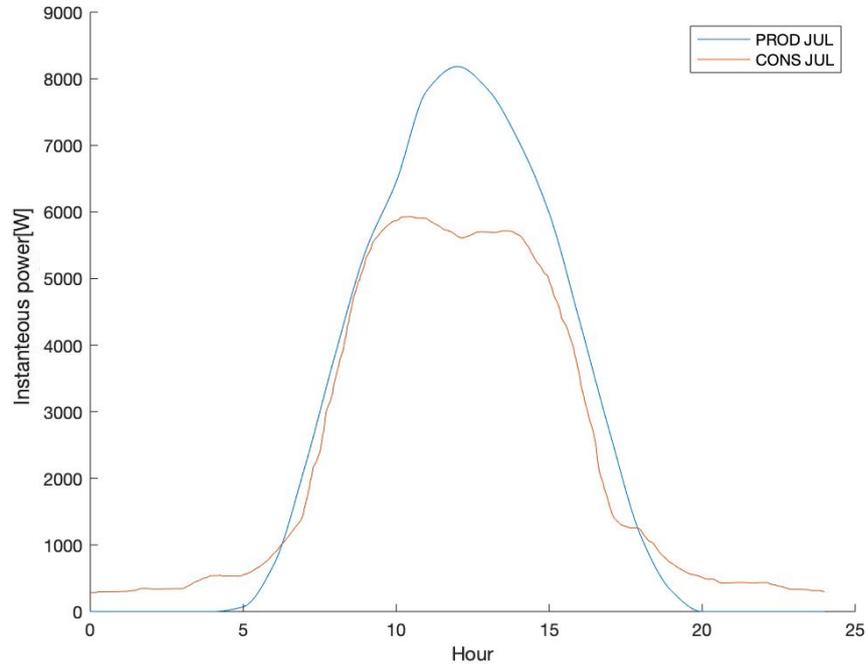


Figure 24. Santander Summer Office Load and 14kWp PV Plant

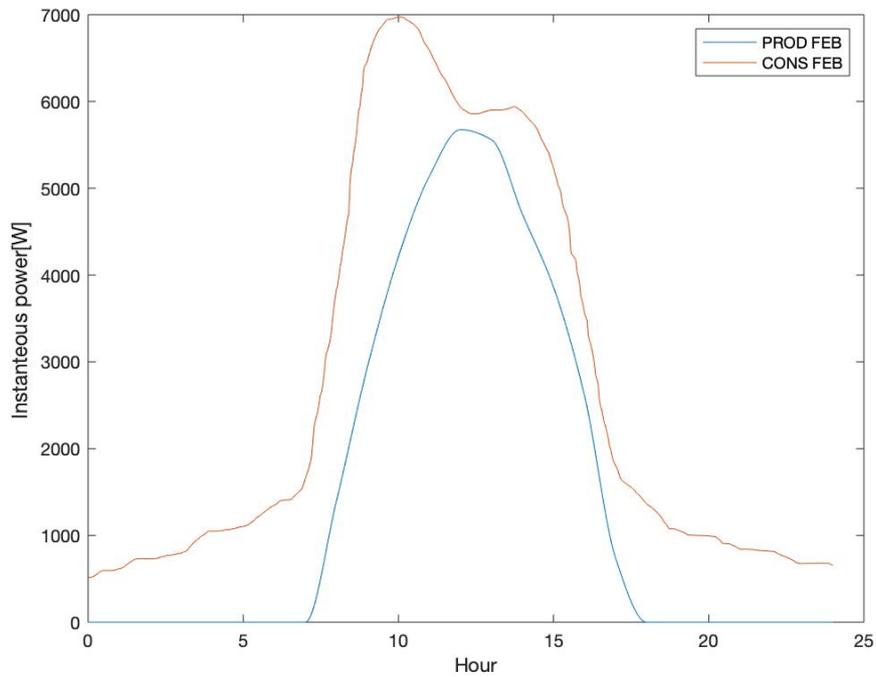


Figure 25. Santander Winter Office Load and 14kWp PV Plant

As we can see, for this plant the production curves are more similar to the consumption, as this is an office scenario, we know that production hours are similar to consumption hours.

When doing the integral of the subtraction of the graphs we obtain the following results:

In February we have a Production-Consumption of: -29061Wh over the whole day.

And in July: 7956Wh.

As previously mentioned, in winter we have more consumption than production therefore the system requires power from the grid for it to keep operating. On the other hand, in summer we just about cover the consumption which is great because it means that is very well optimized for this period. Now it is a matter of checking if it is worth it to have such overconsumption in winter with this size of a plant.

Another aspect to take into account when deciding if this plant is cost effective is our batteries for energy storage. We have already established that for winter we have an over production and we will have to take into account that energy taken from the grid. But, for summer, we can see in figure 24 that although we produce more than we consume there are hours of the day where consumption is higher, therefore we need to store energy from when we are producing more to use later on in the day. As we have already mentioned, the energy stored can only be used from one day to another, as energy in batteries will not last enough to be used in another month.

Therefore, to see our peaks where we are producing more, we have plotted the subtraction of production minus consumption during the day:

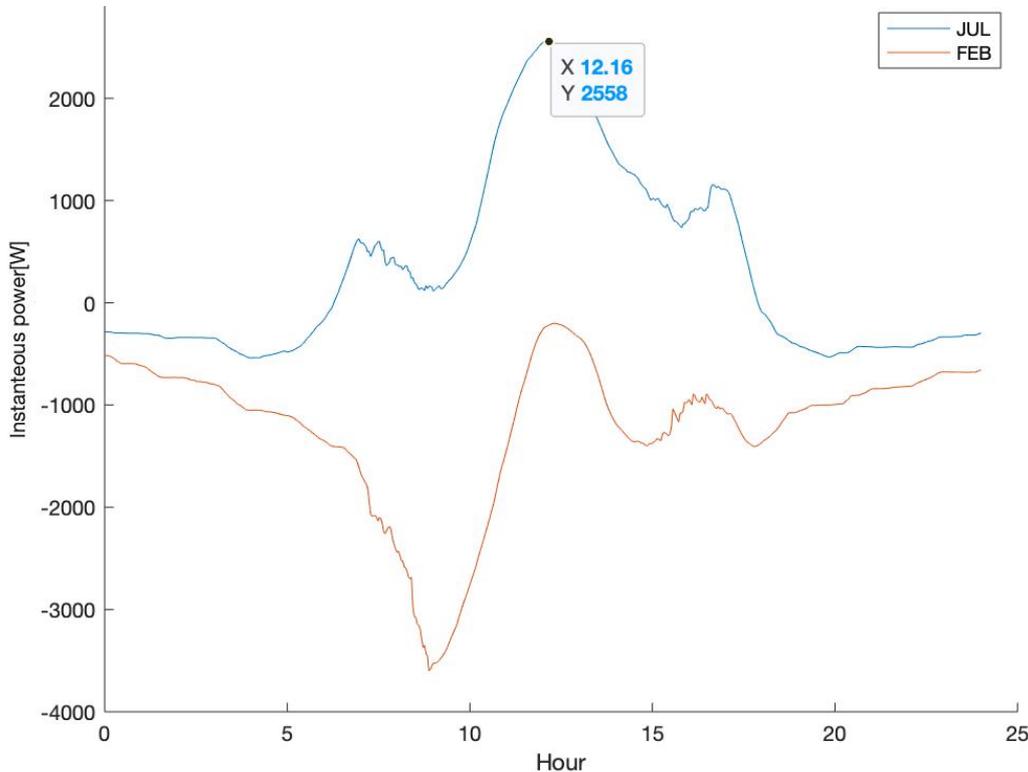


Figure 26. Santander's Production minus Consumption with a 14kWp plant

As we have already seen in figure 25, during Winter there is no point where production is higher than consumption, the orange graph does not go over zero at any point. On the other hand, we can see that during the summer there is a peak of 2558Wh at around midday of production over consumption, which means that we would be able to store as much as that peak. That amount of energy can be used later, which would be more than enough for the rest of the day as we barely have more consumption, this is completely different than home loads as we shall see. Therefore if we take a look at figure 7 (figure containing the different type of batteries we are going to use) we could install a 3,3kWh, 90%, Nickel Manganese Cobalt battery, which will give us a usable capacity of 2,97kWh for this plant giving us the possibility to store all year round our excess of production to be used later in the day. Therefore, giving us all we need to have this installation finished.

6.2.2.3 *Summary and costs*

For an Office building with a 10kWh load located in Santander, we have installed a 14kWp PV plant with a 3,3kWh Nickel Manganese Cobalt battery. This installation permits this office building to run all year round at optimal costs.

We are only taking into account the cost of the components we are going to install to make our comparisons [15]:

- Our LG CHEM 3,3kWh battery costs around 2.400€
- A 14kWp installation can be achieved through several solar panels, at an average cost of 60€ every 100Wp therefore: 8400€.

6.2.3 *SANTANDER HOME LOAD STUDY*

Having learned that a smaller plant in the long run is more beneficial in terms of cost and space, for our home load in Santander we are going to start the study with a smaller plant and see if its optimal. As we can see in Table 3 for an optimal summer consumption, we would need a 3,7kWp installation and for winter a 5kWp. So, we are going to consider using a 3,5kWp installation.

6.2.3.1 *Installed power of 3,5kWp*

As we previously did for the office load, we are going to take a look and compare production and consumption for summer and winter:

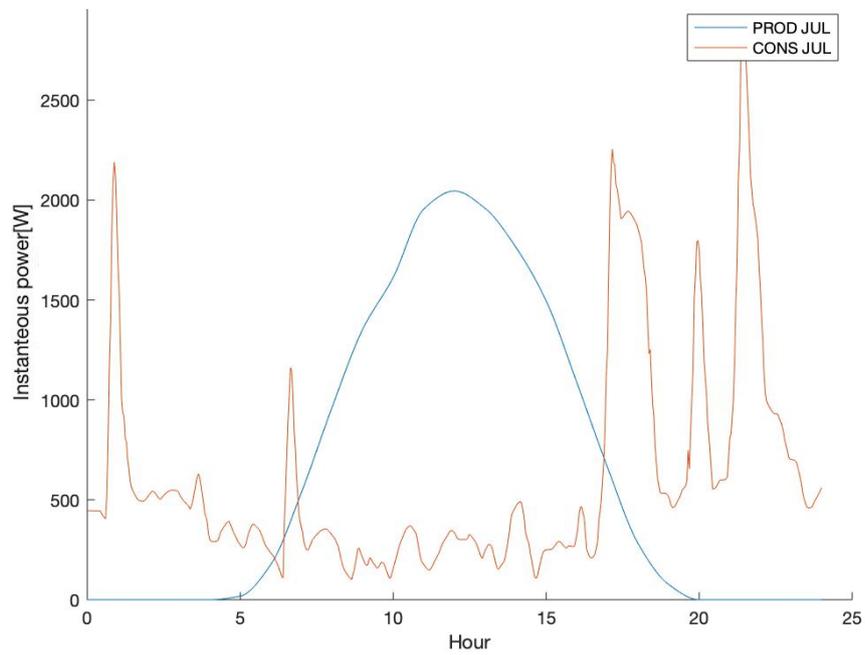


Figure 27. Santander Summer Home Load and 3,5kWp PV Plant

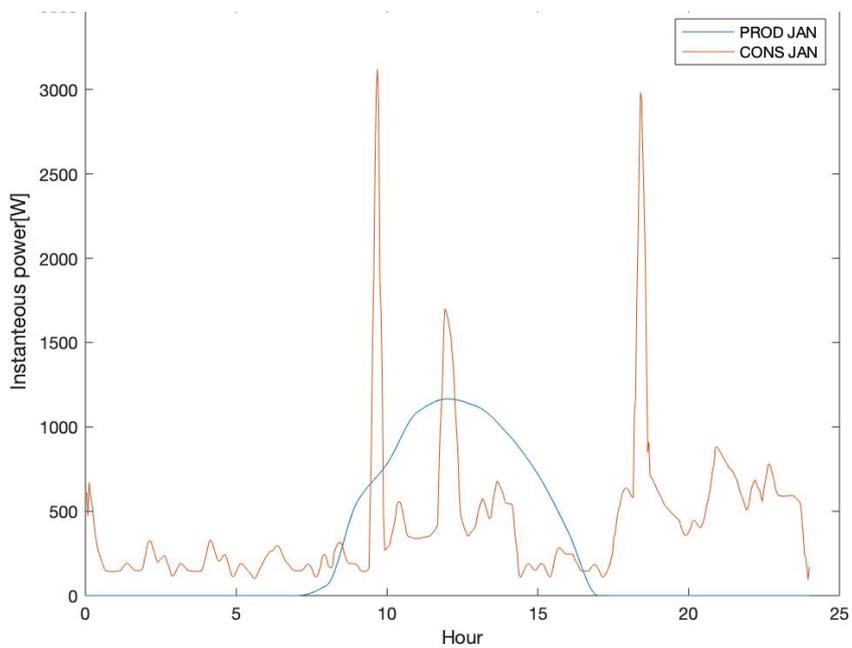


Figure 28. Santander Winter Home Load and 3,5kWp PV Plant

The main difference we can see in Figures 27 and 28, in comparison to the consumption of the Office load, is what we already knew, that the shape of the consumption is very different to the production. These means that in order to fulfill the consumption in no production hour a bigger energy storage system is going to be needed, scaled to the size of our load, as in terms of size the battery system for our office might be bigger but this is due to the fact that the load itself is bigger.

If we now integrate the subtraction of consumption minus production, we obtain the following results:

In January we have a Production-Consumption of: -3516Wh over the whole day.

And in July: 1394Wh.

This data compared to the office load is not only smaller in terms of overall consumption and production, but as a result the difference are between the seasons is narrower making it easier to stablish our plant, because an excess of consumption of 3516Wh over the winter can easily be taken from the grid without making a big difference. Therefore, this is a perfect size for our given load given that for summer we can cover the consumption and as mentioned we barely need to buy energy for the grid in winter.

To now see how big our storage system can be we can take a look at the peaks where we have more production in the already mentioned subtraction minus consumption graphs:

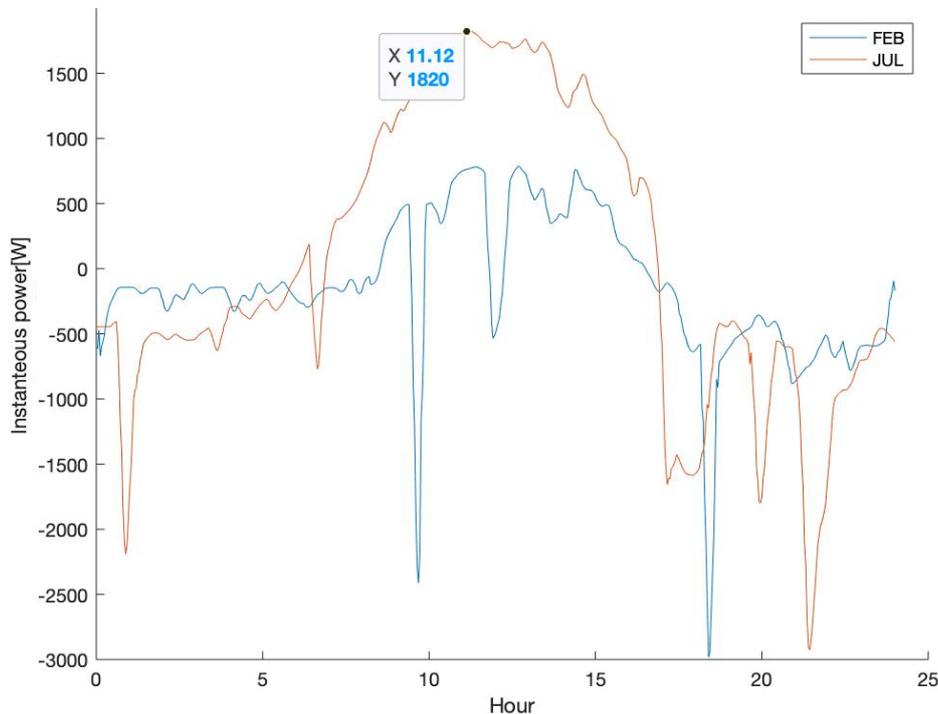


Figure 29. Santander Home Load Production minus Consumption with a 3,5kWp plant

Our biggest peak during the year, occurs during the summer at around midday, which makes sense as it is peak production hours and in household, we tend to have less consumption at this time. This peak of 1820W will give us the possibility of installing a battery of 3,3kWh, 90%, Nickel Manganese Cobalt battery, which will give us a usable capacity of 2,97kWh (Figure 7), which is the smallest one they offer, making it bigger than needed. We now have a complete installation.

6.2.3.2 Summary and costs

For a Home with a 5kWh load located in Santander, we have installed a 3,5kWp PV plant with a 3,3kWh Nickel Manganese Cobalt battery.

Our cost is:

- LG CHEM 3,3kWh battery costs around 2.400€

- A 3,5kWp installation can be achieved through several solar panels, at an average cost of 60€ every 100Wp therefore: 2100€.

6.2.4 MALAGA LOADS STUDY

For Malaga we use what we have learned what we have discovered while studying our Santander scenarios to obtain the perfect PV plants to satisfy our loads. The simulations for these studies are included on Appendix II.

After all of the simulations we obtain the following results:

6.2.4.1 Malaga Office Load

We ended up deciding to go with a 10kWp plant and a 3,3kWh, 90%, Nickel Manganese Cobalt battery.

Which give us a cost for our components of:

- LG CHEM 3,3kWh battery: 2.400€
- A 10kWp installation: 6000€

6.2.4.2 Malaga Home Load

We went with a 2,5kWp plant and a 3,3kWh, 90%, Nickel Manganese Cobalt battery.

Which give us a cost for our components of:

- LG CHEM 3,3kWh battery: 2.400€
- A 2,5kWp installation: 1500€

CHAPTER 7. ANALYSIS OF RESULTS

The first thing we can see when analysing our results, it's despite the difference in size in our two different load types, they both need the same size battery. This is due to two reasons, we do not have a small enough battery to be optimal for our home load, and as our office load has a consumption curve similar to the production curve, we need less storage, and therefore our smallest battery is sufficient for both locations.

Another aspect to point out is that the home energy storage system will undergo a higher number of partial charge/discharge cycles daily when compared against the office load, this can lead to faster ageing of batteries in the home installation scenario.

7.1 COST ANALYSIS

As we have theoretically determined a smaller plant should give us the most cost-effective result for our given scenarios. That is why we are going to take a closer look at overall cost to see if this is true. We are going to once again use the Santander Office scenario to analyse our costs.

Our chosen PV plant has a 14kWp installation with a cost of 8400€ and a LG CHEM 3,3kWh battery with a cost of around 2400€. We now have to take into account that as our plant is small for more or less half of the year, we are going to need to buy electricity for the grid. We calculated that during the winter we had an over consumption of 29016Wh, if we approximate that spring and autumn balance out the winter and summer deviations and therefore say that for half of the year, we need that amount of energy daily. Taking into account that this is an approximation to see how much it cost to run our scenario, there is also the fact that we are able to sell our excess of production that will help compensate our costs, but we want to just make an approximation because analysing a hole year of consumption is not the focus of this work.

With an average price in Spain this 2021 of 0,20€/kWh we can say that if we need 29,016kWh every 24h for half of the year (182,5 days) we get a yearly cost of energy of: 1095€ a year.

With no PV plant, as in an office building, we had a daily consumption of 56,01kWh in summer and 65,78kWh in Winter this will give us a yearly cost of: 14667€.

Therefore, our PV installation in total will cost around 10800€ plus a 1095€ a year of energy, we are already saving money on our first year, because these costs are lower than our annual no PV plant scenario.

7.2 SIZING CRITERIA ANALYSIS

Now that we have taken a look at our optimal plants for our given scenarios, it is time to take a look at establishing a sizing criterion for any given scenario. We talked about taking into consideration, in chapter 5.3, peak daily power requested for our given load, as taking into consideration the time of the year, because we have different production and finally establishing a battery system.

We can see given the result on chapter 6.2, that peak power requested can give us a sense of how big our plant is going to be, as installation are sized in kWp. But we cannot determine the size of our plant with just this number, because as we have also found out, latitude is very important, and the closer to the equator the more you can produce with a given plant. Therefore, we saw that for a given load in two different locations we had different PV plant sizes.

We have also seen that time of the year varies our production, but we could not obtain information that helped establish a criterion for any given scenario, only that a smaller plant it more economical, given that overproduction in certain seasons of the year is not optimal.

And finally, establishing a battery system turned out to depend completely on the given load and its consumption, given that the size of our storage system depends on the peaks during

the day where production is higher than consumption, we cannot establish any correlations between different scenarios.

We can therefore say that at this time it is not possible to establish a sizing criterion for a given scenario given that there are many factors to take into account. But we have made enough research to have a better knowledge on how to do it. We have learned differences between office and household loads, how to take into consideration different production that occurs all year round and have seen that battery systems can be viable on a PV plant system.

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CHAPTER 8. CONCLUSIONS

In this work we have studied photovoltaic plants with energy storage that can be implemented in small size office or homes. In particular, a comparison has been made between the two types of load trying to establish a sizing criterion for any given load profile.

The most important conclusions that we have obtained are:

1. Although a general sizing criterion has not been able to be established, we have determined certain parameters and guidelines on how to approach a given load so that it is easier to establish a cost-effective PV plant for any given load.
2. We have learned that for a Mediterranean Country it is cost effective to establish a PV plant, and that it is possible to save money in the short run with it. All speculations about not being a costly energy system have been proven wrong as we can see that we can easily gain back our investment. It is also important to point out that there are other expenses that have not been taken into account such as paperwork, installation costs or design, but that still make our plant cost effective.
3. Energy storage system are proving to also be cost effective, although still expensive and having the possibility of having to change them out every few years due to aging, we have seen that are starting to be optimal in a small-scale scenario.
4. It is better to have a smaller plant and have to buy energy from the grid from time to time than to have a larger plant with overproduction because the cost of that investment is going to be too high, also the footprint of installation of PV plants can be a limiting factor, in urban areas there is less space for an installation.

CHAPTER 9. BIBLIOGRAPHY

- [1] Handbook for Solar Photovoltaic (PV) Systems – Building and Construction Authority – Singapore Government Agency – URL: https://www.ema.gov.sg/cmsmedia/Renewable_Energy/Solar_Photovoltiac_Systems/Handbook_for_Solar_PV.pdf
- [2] *How PV Solar Plants Work? A Beginners Guide - Solar DAO*. (2018, June 13). Solar DAO. <https://medium.com/@solar.dao/how-pv-solar-plants-work-a-beginners-guide-79f085b8ee88>
- [3] Energy Storage World Market Report - Energy Storage World Forum - URL: https://www.eqmagpro.com/wp-content/uploads/2017/01/Energy_Storage_World_Markets_Report_2014-2020.compressed.pdf
- [4] Pelzer, D. (2019). *A Modular Framework for Optimizing Grid Integration of Mobile and Stationary Energy Storage in Smart Grids* (1st ed. 2019 ed.). Springer Vieweg.
- [5] Zipp, K. (2015, October 29). *What are some common types of solar PV and storage installations?* Solar Power World. <https://www.solarpowerworldonline.com/2015/10/what-are-some-common-types-of-solar-pv-and-storage-installations/>
- [6] Types of Solar Systems – ENMAX – URL: <http://www.enmax.co.th/en/types-of-solar-systems/>
- [7] K. Kusakana, "Optimal operation control of a grid-connected photovoltaic-battery hybrid system," 2016 IEEE PES PowerAfrica, 2016, pp. 239-244, doi: 10.1109/PowerAfrica.2016.7556608.
- [8] Yuksel, A. (2020, February 28). *Energy IQ: What is stationary energy storage and how energy storage works.* Cummins Inc. <https://www.cummins.com/news/2020/02/28/energy-iq-what-stationary-energy-storage-and-how-energy-storage-works>
- [9] Tecnospot - Li-ion energy storage systems - (2016 workshop accompanying material).

- [10] Average daily PV generation and load profile of a typical SA household for 2015. – Research Gate – URL: https://www.researchgate.net/figure/Average-daily-PV-generation-and-load-profile-of-a-typical-SA-household-for-2015_fig2_334312997
- [11] H. Kanchev, D. Lu, F. Colas, V. Lazarov and B. Francois, "Energy Management and Operational Planning of a Microgrid With a PV-Based Active Generator for Smart Grid Applications," in *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4583-4592, Oct. 2011, doi: 10.1109/TIE.2011.2119451.
- [12] Photovoltaic Geographical Information System (PVGIS) - EU Science Hub - European Commission - URL: <https://ec.europa.eu/jrc/en/pvgis>
- [13] S. Yilmaz, J. Chambers, M.K. Patel, "Comparison of clustering approaches for domestic electricity load profile characterisation - Implications for demand side management, *Energy*, Volume 180, 2019, Pages 665-677, ISSN 0360-5442, <https://www.sciencedirect.com/science/article/pii/S0360544219310060>
- [14] Nuria Martín-Chivelet, David Montero-Gómez, Optimizing photovoltaic self-consumption in office buildings, *Energy and Buildings*, Volume 150, 2017, Pages 71-80, ISSN 0378-7788, <https://www.sciencedirect.com/science/article/pii/S0378778817304796>
- [15] Europe Solar Store – URL: <https://www.europe-solarstore.com>
- [16] X. Vallve, A. Graillot, S. Gual and H. Colin, "Micro storage and demand side management in distributed PV grid-connected installations," *2007 9th International Conference on Electrical Power Quality and Utilisation*, 2007, pp. 1-6, doi: 10.1109/EPQU.2007.4424208.
- [17] Y. Riffonneau, S. Bacha, F. Barruel and S. Ploix, "Optimal Power Flow Management for Grid Connected PV Systems With Batteries," in *IEEE Transactions on Sustainable Energy*, vol. 2, no. 3, pp. 309-320, July 2011, doi: 10.1109/TSTE.2011.2114901.
- [18] T. Beck, H. Kondziella, G. Huard, T. Bruckner, Assessing the influence of the temporal resolution of electrical load and PV generation profiles on self-consumption and sizing of PV-battery systems, *Applied Energy*, Volume 173, 2016, Pages 331-342, ISSN 0306-2619, <https://www.sciencedirect.com/science/article/pii/S0306261916305104>

- [19] Sylvain Quoilin, Konstantinos Kavvadias, Arnaud Mercier, Irene Pappone, Andreas Zucker, Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment, *Applied Energy*, Volume 182, 2016, Pages 58-67, ISSN 0306-2619, <https://www.sciencedirect.com/science/article/pii/S0306261916311643>
- [20] Aníbal de Almeida, Paula Fonseca, Barbara Schlomann, Nicolai Feilberg, Characterization of the household electricity consumption in the EU, potential energy savings and specific policy recommendations, *Energy and Buildings*, Volume 43, Issue 8, 2011, Pages 1884-1894, ISSN 0378-7788, <https://www.sciencedirect.com/science/article/pii/S0378778811001058>

APPENDIX I

SANTANDER WINTER OFFICE LOAD

Our average winter office load has a daily average consumption of 65,78 kWh. Therefore, to obtain this a 30,5kWp plant is needed:

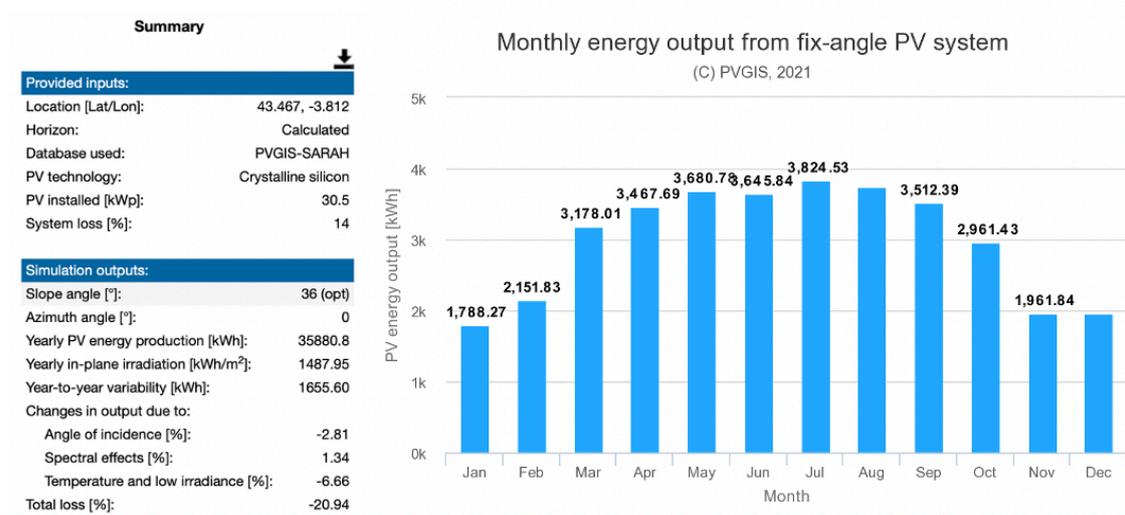


Figure 30. Monthly energy output of a 30,5kWp plant of installed power in Santander.[12]

We obtain a Daily Average Winter of 65,87 kWh.

MALAGA SUMMER AND WINTER HOME LOAD

Our average winter home load has a daily average consumption of 10,26 kWh and our summer home load of 14,49kWh. Therefore, to obtain both of them a 2,7kWp plant is needed:

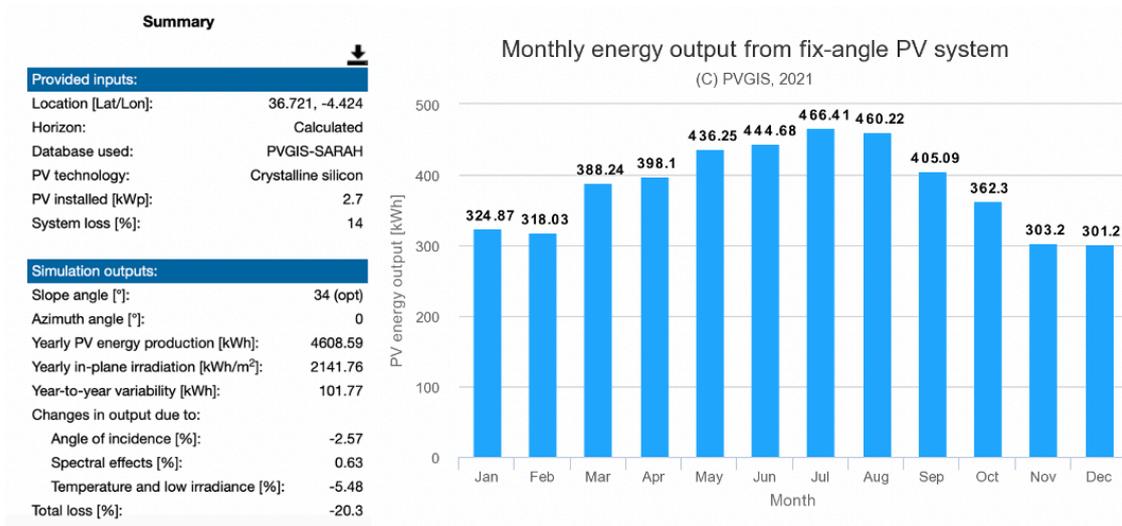


Figure 31. Monthly energy output of a 2,7kWp plant of installed power in Malaga.[12]

We obtain a Daily Average Winter of 10,42 kWh and a Daily Average Summer of 14,7kWh.

MALAGA SUMMER OFFICE LOAD

Our average summer office load has a daily average consumption of 56,01 kWh. Therefore, to obtain this a 10,3kWp plant is needed:

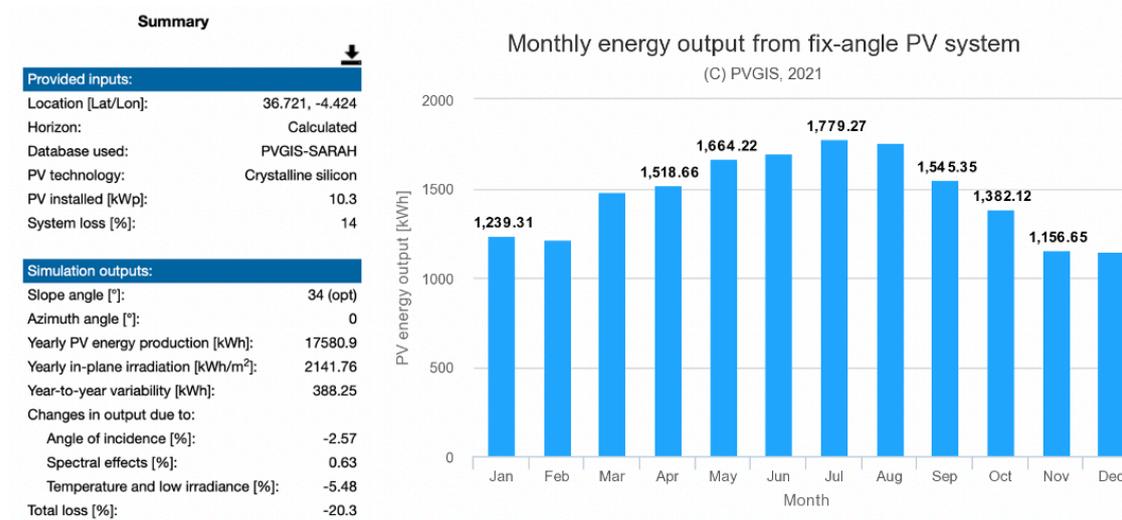


Figure 32. Monthly energy output of a 10,3kWp plant of installed power in Malaga.[12]

We obtain a Daily Average Summer of 56,05 kWh.

MALAGA WINTER OFFICE LOAD

Our average winter office load has a daily average consumption of 65,78 kWh. Therefore, to obtain this a 17,1kWp plant is needed:

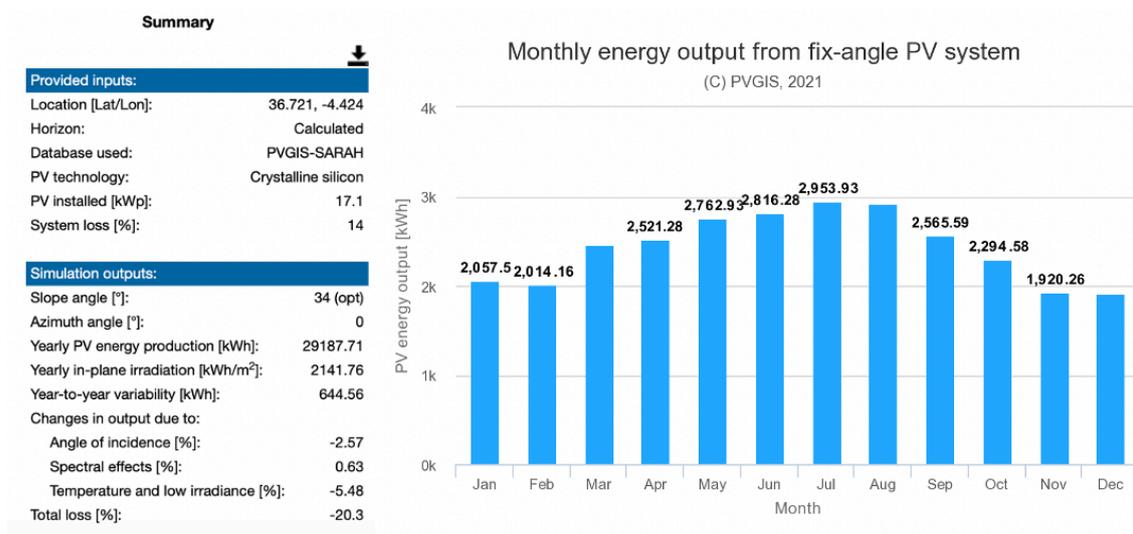


Figure 33. Monthly energy output of a 30,5kWp plant of installed power in Malaga. [12]

We obtain a Daily Average Winter of 65,95 kWh.

APPENDIX II

MALAGA OFFICE LOAD STUDY

Following the same analysis, we did for Santander we have installed a 10kWp plant for our office building in Malaga.

Installed power of 10kWp

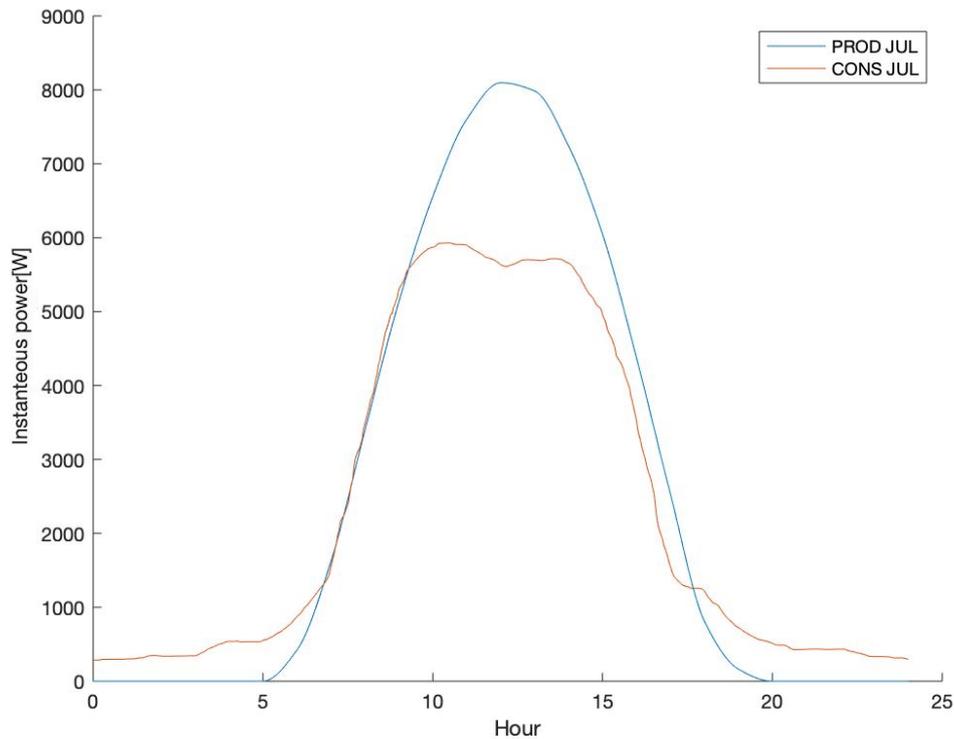


Figure 34. Malaga Summer Office Load and 10kWp PV Plant

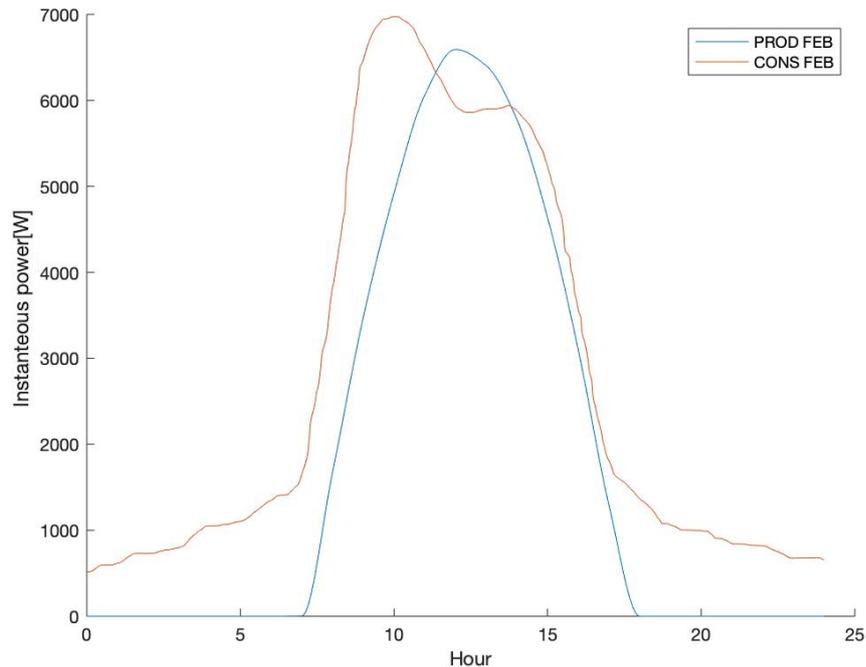


Figure 35. Malagas Winter Office Load and 10kWp PV Plant

By taking a look at figures 34 and 35 it seems that a correct size has been chosen following that we want to obtain the minim possible plant that permits us to be cost effective. Taking a look at further data we can see how we did.

By integrating the subtraction of consumption minus production, we obtain the following results:

In February we have a Production-Consumption of: -21962Wh over the whole day.

And in July: 5949Wh.

As expected, an excess of consumption in winter and a excess of production in summer. Although the excess of consumption in winter seems very big in comparison with summer, we obtained similar result for our office building in Santander, therefore we can say that this plant could perfectly work in this scenario.

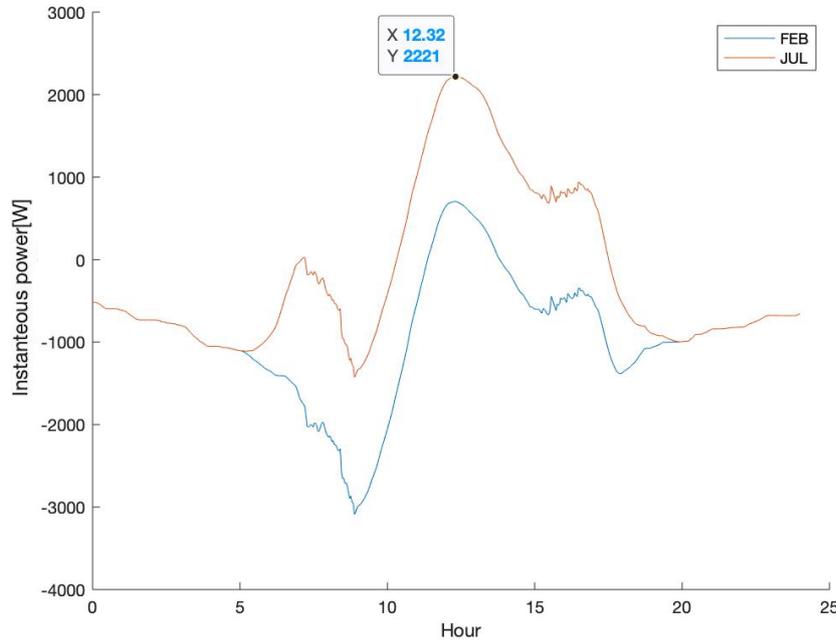


Figure 36. Malagas Production minus Consumption with a 10kWp plant

In order to now decide which energy storage system, we can use we take a look at the peaks of over production in Figure 36. We can see that we obtain similar results than in our Santander Office building, therefore the same battery system can be used: a 3,3kWh, 90%, Nickel Manganese Cobalt battery, which will give us a usable capacity of 2,97kWh (Figure 7).

MALAGA HOME LOAD STUDY

For our Home Load in Malaga we follow the same rules as before, therefore we are going to try to study a 2,5kWp plant in our scenario:

Installed power of 2,5kWp

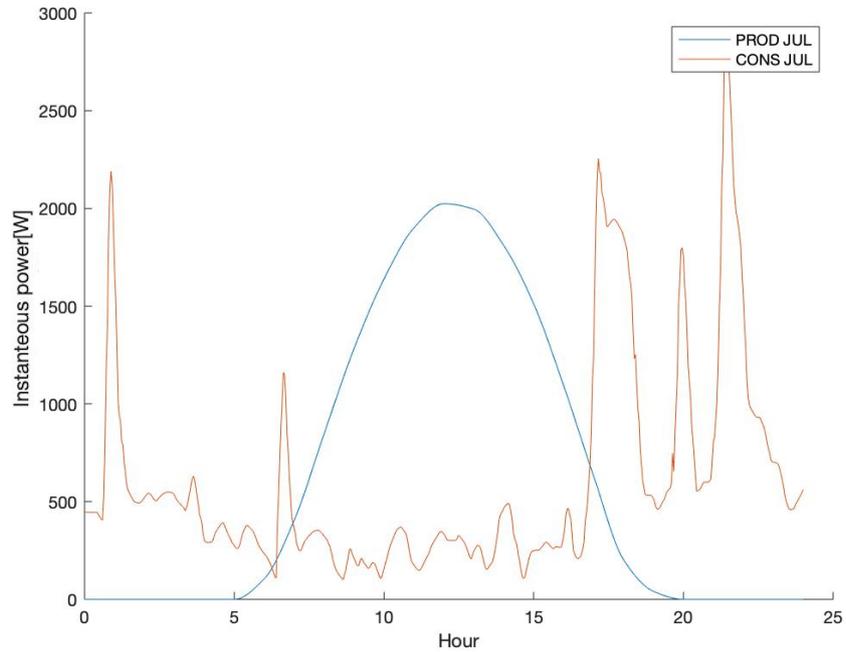


Figure 37. Malaga Summer Home Load and 2,5kWp PV Plant

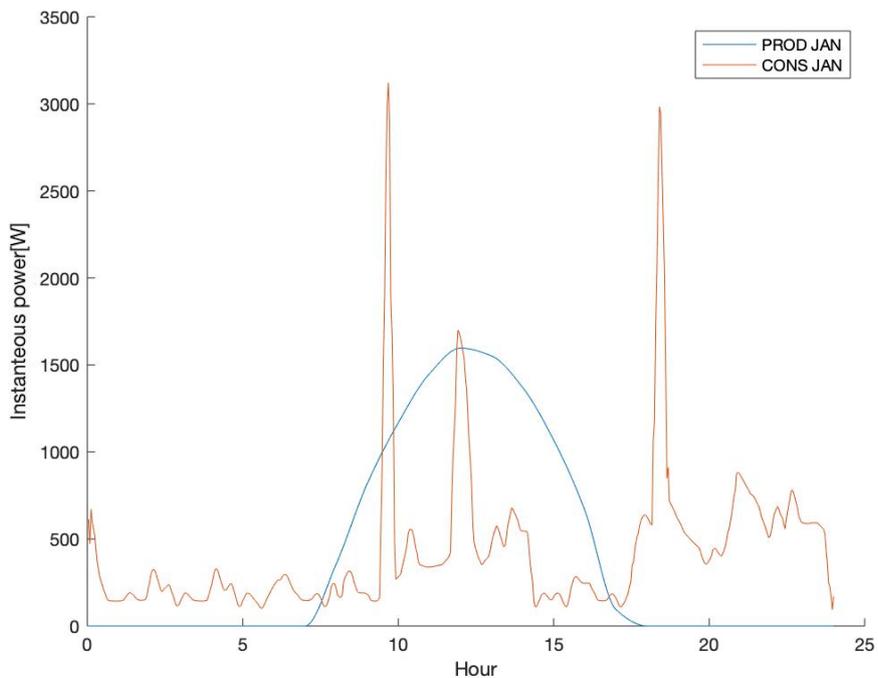


Figure 38. Malaga Winter Home Load and 2,5kWp PV Plant

If we now integrate the subtraction of consumption minus production, we obtain the following results:

In January we have a Production-Consumption of: -211Wh over the whole day.

And in July: 892Wh.

With this data, our plant fits perfectly with this load as we barely have over production or consumption all year round, this was bound to happen due to the fact that, as we could see in Table 2, the same optimal PV plant size was used for both winter and summer in our Malaga Office building.

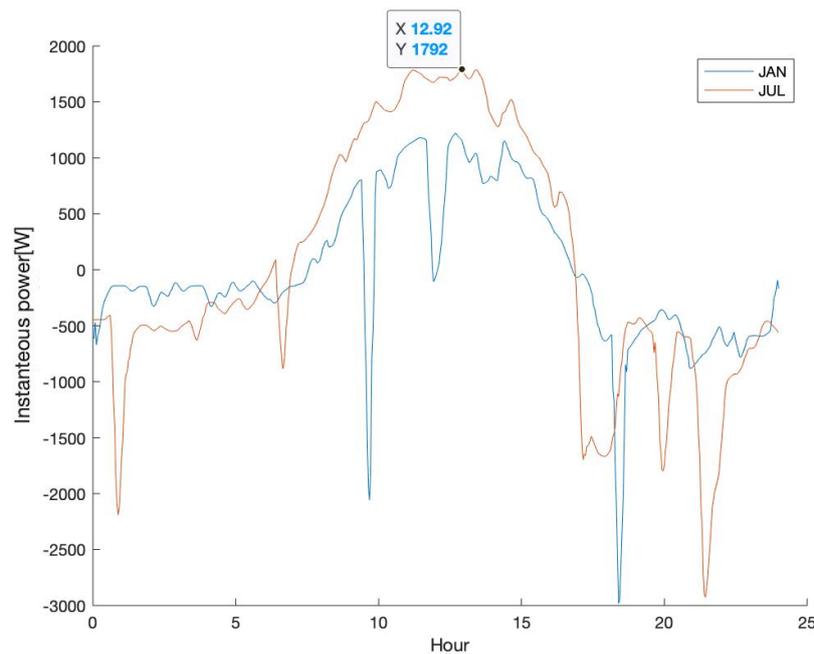


Figure 39. Malagas Production minus Consumption with a 2,5kWp plant

In order to now decide which energy storage system, we can use, we take a look at the peaks of over production in Figure 39. As it happened with the Household in Santander our biggest excess of production is lower than the smallest battery, we have available therefore we can use the same one: 3,3kWh, 90%, Nickel Manganese Cobalt battery, which will give us a usable capacity of 2,97kWh. Which we can see is the same battery for all of our 4 scenarios.