Master's thesis

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Investment Analysis for Residential Storage and PV Systems under Spanish Grid Tariffs

Master's thesis in Electric Power Engineering
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Project thesis
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Abstract

The elimination of the so-called solar-tax in Spain at the end of 2018, which had earlier made investment in residential PV systems unattractive, has opened a new horizon for self-consumption and thereby providing an opportunity for households to reduce energy costs. This thesis presents an investment analysis to determine the optimal size of a grid-connected energy storage/PV system that minimizes the electricity bill in Spanish households. The problem is formulated as a linear programming optimization and implemented in Python. The study considers two models, one stochastic and one deterministic, which perform annual simulations for three households with different annual load consumption patterns. Real data from solar radiation, spot prices and load consumption are provided for the modelling. Results show that it is more cost-effective to invest in PV systems rather than in battery storage and up to 23% reduction in the annual electricity costs can be achieved in the best case scenario. Moreover, a sensitivity analysis on energy storage prices is carried out, which mainly affects households with high energy consumption.

Keywords— Optimal sizing, energy storage, solar power, stochastic optimization, electricity bill.

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In first place, I want to grate Jay and Sigurd for having faith on me during the realization of the thesis until the end. There is a quote that says "Do not limit your challenges, challenge your limits". In that sense, they really knew how to push me towards my limits so I could overcome them.

In second place, I want to say that I am grateful for this three years I spent in Trondheim. I first came as a exchange student from Spain and ended up as a master student at NTNU. During this period, I got to meet many different people from all over the world and learn fantastic lessons about life, which made me grow not only professionally but also personally. Same as good moments do not last long, now my time in Trondheim has come to an end and it is time to change and face new challenges in life.

Lastly, but not less important I want to express my gratitude to my lovely parents, Gabriel and Guadalupe, and my little sister Alba for taking care of me no matter what. On the other hand, to my best friend Gabriel and to my friends Dario, Miguel, Pablo and Alfonso, who have been always there despite the distance.

Adrián Cruz Castro.

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Abbreviations

- H1 = Household 1
- H2 = Household 2
- H3 = Household 3
- PV = Photovoltaic
- REE = Red Eléctrica de España
- EDP = Energías de Portugal
- kWh = Kilowatt hour
- kW = Kilowatt
- W = Watts
- MW = Megawatt
- MWh = Megawatt hour
- TWh = Terawatt hour
- € = Euros
- $ = Dolars
- Batt = Battery
- km = Kilometers
- BNEF = Bloomberg New Energy Finance
- ToU = Time of use
- CO2 = Carbon dioxide
- OMIP = Operador del mercado Ibérico - Polo Portugués
- OMIE = Operador del mercado Ibérico - Polo Español
- PVPC = Precio Voluntario al Pequeño Consumidor
- VAT = Value added tax
- DHA/S = Time discrimination A/S
- DP = Discrimination periods
- EV = Electric vehicle
- NCA = Nickel cobalt aluminium oxide
- NMC = Nickel manganese cobalt oxide
- HEMS = Home energy management systems

Contents

1 Introduction

1.1 Background

Facts as decarbonization, climate change and generation through renewable sources put the electric sector in a constant transition, which may end up having an impact on the market in the following years. There are already many companies working in new energy projects in order to catch the new market opportunities.

A good example of this transition is the PV technology, which is raising as one of the most efficient and effective renewable resources at a household level. Its implementation brings to homeowners an increase in their electricity bill savings and less grid dependence. However, as many other renewable sources, it is weather dependent. Solar panels gather energy from sunlight, meaning solar energy is usually available during periods of the day when the household requires few energy consumption.

Therefore, the use of an energy storage technology in combination with a PV technology is often considered to store the energy surplus produced by the solar panels to use it when needed. This synergy of technologies not only helps to increase the flexibility of PV production, but also to reduce the electricity bill costs. Although there are studies as [9] and [10] that claim investing in energy storage for individual households might not be cost-effective nowadays, the truth is that it is a matter of time. In 2010, battery prices were around 1100$/kWh$ and they dropped 87% reaching 156kWh in 2019. According to [1], It is expected that the average price becomes close to 100$/kWh$ for 2023 and below that price by 2025. In fact, according to the senior energy storage analyst of BNEF, James Frith, the more battery prices fall, the higher the value buyers will obtain than they do today. Figure [1.1] shows the prediction of this analyst.

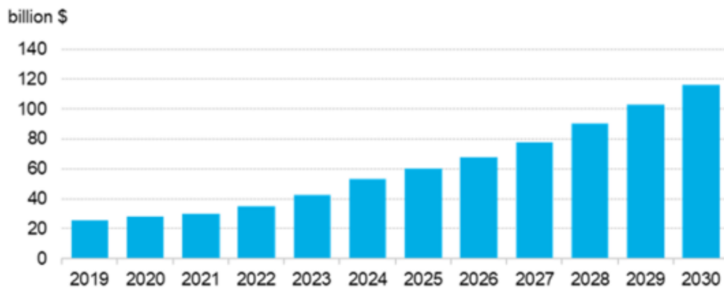


Figure 1.1: Annual lithium-ion battery market size [1]

Whenever batteries gets cheaper, the electrification of more sectors will carry out, and it is here where end-consumers come into play. Nowadays, there are many households paying considerable high electric bills, although it is true that this depends on the country where it is consumed. In Spain, citizens pay a higher price for electricity than the majority of the European countries. Based on [11], Spain is the 4th country with the most expensive electricity of Europe, following Denmark, Germany and Ireland. Due to this fact, an optimal energy management to pair and schedule PV and batteries might reduce considerably the electricity bill of households in Spain under ToU and feed-in tariffs if implemented effectively, as the electricity purchases when prices are the highest (On-peak periods) can be avoided. In addition, energy surplus from the PV can be sold to the grid, which may help to reduce even more the bill and recover the investment faster.

Although Spain has huge potential in solar production due to its geographical location, countries as Germany or United Kingdom, which have lower potential, have higher solar capacity. In 2019, while Spain had 9.233 MW of PV capacity, Germany and United Kingdom solar capacity reached 49.016 MW and 13.616 MW respectively [12]. This scenario is expected to change in the following years as the solar tax law was abolished at the end of 2018 [13], commonly know in Spain as "Impuesto al sol", which established a tax over each energy unit produced by PV technologies ands did not allow to sell solar energy to the grid for small consumers, among others. This law has been limiting the development of solar systems at a household level, since it made their investment not attractive economically speaking. This change in regulation opened a window towards self-consumption and energy cost savings in Spain.

With the purpose of researching and analyzing the new horizon in Spain in terms of energy self-consumption, this thesis develops an investment analysis to assess the optimal size of PV and battery technologies that minimizes the electricity bill for individual households under a ToU Spanish tariff.

1.2 Motivation and scope

Assessing about the optimal size of PV and battery technologies that minimizes the electricity bill is an incentive to promote the installation of green energies that helps to reduce the C02 footprint and to develop the self-consumption of electricity in Spain. Spain has a good geographical location in terms of solar radiation, thus a high PV contribution is expected. However, the influence of the battery and its possible interactions with PV systems is unknown, as yet there has been no investigation of the possible impacts in households belonging to the Spanish low-voltage grid.

Nevertheless, it is not enough to size PV and battery to get price reductions in the electricity bill, but also to schedule correctly their operation. Solar panels only produce energy during the sunshine hours, meaning the PV energy is only available during those hours unless a battery stores that energy for a later use. Batteries can store energy from the PV or from the grid when electricity prices are low, and then use that energy to cover the energy demand when electricity prices become high. In addition, once the energy demand is fulfill, this energy can be sold to the grid, which may help to recover the investment faster. Therefore, a proper scheduling is also necessary to operate batteries and PV systems efficiently so that electricity bills can be better minimize. A way to model optimal sizing and scheduling of energy technologies is linear programming, and this thesis makes use of it to face an investment analysis problem grounded on a electricity bill minimization in Spain.

This study is based on a municipality located at the outskirts of Madrid, from where annual consumption data of three different households are collected. Each of them has the capability to include energy storage and PV systems. Since the future is uncertain, historical data of solar radiation and electricity prices from the same municipality are also included in order to predict future tendencies of these data, so that dimensioning can be size accordingly. The programming language is Python, which develops two linear programming models to solve the problem, one stochastic and one deterministic. Both models are created with an optimization algorithm that finds the optimal size and management of batteries and PV systems that minimize the total annual costs for each household, considering electricity bill and investment costs. The analysis period is 25 years while considering a discount rate of 5%. At the end, a sensitivity analysis is included to determine the impact of battery prices over the investment decisions.

1.3 Problem definition

This research will attempt to answer the following questions:

- *Is it cost-effective to invest in PV and energy storage technologies in order to reduce the domestic electricity bill for households of the low voltage Spanish grid under a TOU tariff after the abolition of the so-called "Impuesto al sol" law? What optimal size minimizes the domestic electricity bill? How big is this bill reduction in comparison with no making any investment? And how much savings will house owners make?*
- *Usually, an investment analysis is carried out based on predictions about the future. How far would sizing predictions differ from the actual real ones that minimizes costs the most?*
- *How energy storage prices influence the investment decisions? What impacts does it has over the domestic electricity bill?*

1.4 Outline

The remainder of this thesis is divided into six sections. Chapter 2 presents a literature review about previous researches in similar topics relevant to this thesis. Chapter 3 introduces the modelling and the two simulation models used in the case studies. Chapter 4 presents the results of the simulation cases. The discussion about the results is presented in Chapter 5 and the conclusions of the research in Chapter 6.

2
Literature review

2.1 The Spanish Electric System

There are already many the studies performed about the electricity bill reduction under the support of photovoltaic systems and batteries as [14], [15] and many other researches already mentioned. However, there are not so many that combine it with the new energy regulations in Spain.

Since this thesis deals with electricity tariffs in Spain, it is necessary to give first an overview of how the Spanish electric system is and how its power markets works. There exists four big activities inside the Spanish electric sector: generation, transmission, distribution and commercialization.

2.1.1 Generation

The generation is considered to be very diverse (see table 2.1), meaning that it is composed by a mix of several energy technologies, being the wind and hydro the two renewable sources with more influence. Equally, the combined cycle power plants together with the nuclear plants reach almost half of the total energy mix. It is important to clarify that these last technologies mentioned are not the ones that contribute more energy to the grid, but the ones that has more MW installed. In any case, since each power plant has a different efficiency, it is usually the nuclear energy the one that contributes the most to the Spanish grid.

Table 2.1: Generation structure in Spain [2]

Technology	**Generation in 2019**
Hydro	9.0%
Wind	20.6%
Solar	3.5%
Thermo Solar	2.0%
Other Renewables	1.7%
Nuclear	21.2%
Coal	5.0%
Oil and Gas	2.2%
Combine Cycle	21.9%
Cogeneration	11.4%
Other no Renewables	1.5%

The maximum instantaneous power demanded in 2019 was around 40,455 GW and the power installed 110,266 GW, in other words, the electric system is oversized. Thus, if all power plants worked at their total capacity, they would be able to supply double the maximum demand. Regarding the total generation in 2019, Spain produced around 264,8 TWh. Besides, Spain it is also a country that imports and exports energy with its neighbours, France and Portugal. The balance in 2019 ended up in 6,6 TWh imported.

2.1.2 Transport

This is an activity regulated and controlled by a single system operator called REE, who is in charge of the electric grid of the whole country. The Spanish grid reached 44457 km in 2019.

REE is the organism whose main duty is to ensure the maintenance and the correct use of the electric grid, as well as the monitoring of the power production of the power plants. They also manage the energy transport from the generation plants till the conversion points to low voltage grids. As it can be seen in the map below, Spain is a country that has an electric grid very spread out in all its territory, being the areas of Madrid, Barcelona, Basque country and Galicia the points with higher consumption.

Figure 2.1: Map of the Spanish electric grid from 2016 [2]

2.1.3 Distribution

This phase is controlled by five big companies, which are in charge of assuring the use, maintenance and operation of the electric grid from the low voltage grid till end-users. These companies are Endesa, Iberdrola, Gas Natural Fenosa, EDP y Viesgo.

The picture below shows the distribution of these companies all over the country. Endesa manages the areas of Cataluña, Aragon, and both the Canary and the Balearic islands. A great part of the center and east of Spain is covered by Iberdrola. Gas Natural owns another area in the center and the whole Galicia area. Finally, EDP and Viesgo take over of the north.

Figure 2.2: Map of the distribution areas [3]

2.1.4 Commercialization

This is one of the most meaningful stages, since it covers the buying and selling activity of energy packages handled by the market operators OMIP and OMIE.

OMIP is a regulated market operator that provides a trading platform for energy derivatives products, known as futures, where energy prices change for many different periods in time. It acts in a similar way as the stock market. This market usually deals with higher prices and volumes of energy, but with a greater stability.

OMIE is another market operator in charge of setting the electricity prices hourly and it does it through three market processes, a day-ahead market, an intraday market and an continuous intraday market.

- **The day-ahead market.** It establishes the energy price for the next 24 hours of the next day. This process takes place every single day of the year at 12:00pm. The system is known as an "electric pool". Every day the government ask for an specific amount of watts to the electric companies so that all consumers get the electricity they demand. The electricity companies reply with a supply, which starts with the cheapest energies, mainly renewables, and ended up with the most expensive ones, which are usually the most polluting energies, as coal. The last energy source that enters the market is the one that sets the energy price. However, this evaluation also needs a technical validity, in which the system operator is involved. This one has to assure that the market results are possible from a grid perspective (e.g. the capacity of the network is not congested).
- **The intraday market.** This market acts as a tool that allows to adjust the production and consumption predictions and make changes on the

day-ahead output in order to balance the generation and demand. These needs tend to show up more often because of a higher capacity of renewable energy, which is very variable and sporadic. This changes in production and consumption are also sent to the system operator, so that its balance processes can be programmed.

- **The continuous intraday market.** It is based on a common computer system on real time that monitors all the different intraday markets just like the different system operators from several countries in order to communicate the available interconnection capacities in between the borders. In the case of Spain, the continuous intrday market allows buying and selling with other markets beyond France and Portugal borders. However, this is only possible when the connection line between countries is not saturated in one of the ways and/or the electricity price is the same or similar.

2.2 Types of Markets in Spain

Spain offers to consumers two ways of buying electricity from the grid, either through the so-called PVPC Market or the Free Market.

2.2.1 PVPC or Regulated Market

PVPC is a market modality only available for consumers with an installed power below 10kW. This market fixes the electricity price hourly during the whole year based on the supply and demand between producers and consumers. The price is regulated by the Government and by the five distribution companies mentioned above.

2.2.2 Free Market

This modality is offered to all consumers regardless of their installed power and in this case, the consumer agrees with the company a fix price, meaning he will always know exactly how much the kWh will cost. Since the government is not involve in this market, each company competes for the best management possible of the energy packages to satisfy their demand. There are almost 100 different companies in this market.

2.3 Electricity bill in Spain

Electricity bills in Spain are complex and their price depends on several features, especially for those who participate on the PVPC market, since they do not have a fix energy price as it happens in the free market. In this subsection, it is intended to show in detail how the electricity bills in the regulated market are elaborated.

There are 5 concepts with which electricity bills are build up [16] [7]:

- **Power installed.** This is the maximum power that can be consumed simultaneously. When this power is exceeded, the meter disconnects the household from the power grid, leaving it without electricity supply.

  The price is calculated by multiplying the installed power by the capacity price set by the electricity company chosen. The higher the capacity the higher this price is. The price per kW depends on the contract signed with the electric company. It is usually between 0.11-0.13 €/kW·days.

  $$PowerInstalled = P_{cap} \cdot p_{cap} \cdot N^{\circ}days \tag{2.1}$$

  Where,

  - P_{cap} =Power chosen in kW
  - p_{cap} =Power price in €/kW·days
  - $N^{\circ}days$ =Billing period in days

- **Energy consumed.** It represents the total number of kW consumed during the billing period and its price calculation is given by equation (2.2). It is important to mentioned that this price is build up by two terms, the cost of producing electricity and the grid-access costs. These two costs are explained in detailed in section 2.4.

  Previous to 2018, there were to types of billing for the energy consumed part based on the type of metering device installed at the household. In case of an analog meter, the amount of energy consumed is multiply by the average price of energy during the billing period, see equation (2.3). On the other side, for those consumers with a smart meter installed at their homes, the price was elaborated as it is done today, by multiplying the hourly energy consumed by the corresponding price at that same moment, given by the PVPC market and published in the system operator (REE) webpage daily.

  Nevertheless, it is assumed every household has a smart meter installed nowadays, since the Government launched a law in 2012 "Orden IET/290/2012" published in [17], where it was established that analog meters must be substitute by smart meters before the 31st of December 2018.

Consumers with smart meter

$$EnergyConsumed = \sum_{h}^{hours} E_{cons}^{h} \cdot (p_E^h + T_{grid}^h) \quad (2.2)$$

Consumers with analog meter

$$EnergyConsumed = E_{cons}^{Total} \cdot (p_E^{Avg} + T_{grid}^{Avg}) \quad (2.3)$$

Where,

- E_{cons}^{h} =Energy consumed per hour in kWh
- p_{cons}^{h} =Energy price per hour in €/kWh
- T_{grid}^{h} =Grid-access toll price per hour in €/kWh
- E_{cons}^{Total} =Total energy consumed during the billing period in kWh
- p_{cons}^{h} =Average energy price of the billing period in €/kWh
- T_{grid}^{h} = Average grid-access toll price during the billing period in €/kWh

- **Electricity tax.** It is a tax for electricity established on January 1st 2015 (5,1127%). This percentage is multiply by the resultant cost from the installed power and energy consumed.

- **Control and measurement equipment.** It is the monthly cost for the measuring equipment of the household. The price depends on the equipment installed.

Table 2.2: Monthly cost based on the meter installed [7]

Type of meter	Price(€)/month
Regular meter without remote management	0.54
Regular meter with ToU without remote management	1.11
One phase smart meter with remote management availability	0.81
Three phase smart meter with remote management availability	1.36

- **IVA tax.** It is a type of value-added tax. This one is applied on the sum of all previous concepts (21%).

2.4 Low voltage electricity access rates

As mentioned before, in all electricity bills there is a term called grid-access costs, although they are also known as electricity access rates. This term represents the costs for the transport and distribution of energy through the grid from the generation to the supplying points. These costs are independent from electricity consumption and differ based on the power installed, on the discrimination period and on the voltage level with which energy is supplied, leading to different types of tariffs [18]. This thesis wants to focus on the low voltage level grids, as it represents the most common scenario for domestic consumers in Spain. Table 2.3 shows all the possible low grid-access tariffs among which consumers can choose the one that economically suits the most for their electrical consumption pattern and power installed.

There are two factors with which access rates tariffs are made in the Spanish system:

- **Contracted power:** Consumers with a power installed below 10 kW will have a 2.0 access rate. Those between 10 kW and 15kW will have a 2.1 access rate and powers above 15 kW will have 3.0 access rates, as long as they belong to the low voltage grid. The higher the access rate number the higher the price consumers will have to pay.
- **Time discrimination:** All powers displayed in table 2.3 have a "last name" depending on whether they have time discrimination or not. Tariffs with A at the end do not have any time discrimination, meaning they will always see a very similar electricity price regardless of the time of the day. Tariffs ending in DHA have two time discrimination periods, known as peak and off-peak. DHS tariffs are made for those with EVs at home and it is divided into three different time periods during the day (peak, off-peak and mid-peak). The only exception is tariff 3.0 A, which always has three periods.

Table 2.3: Power installed range and discrimination periods for low voltage tariffs

Grid-access tariffs	**Voltage level**	**Power installed**	**DP**
Tariff 2.0 A	1kV	1-10 kW	1 period
Tariff 2.0 DHA	1kV	1-10 kW	2 periods
Tariff 2.0 DHS	1kV	1-10 kW	3 periods
Tariff 2.1 A	1kV	10-15 kW	1 period
Tariff 2.1 DHA	1kV	10-15 kW	2 periods
Tariff 2.1 DHS	1kV	10-15 kW	3 periods
Tariff 3.0 A	1kV	15kW	3 periods

From all grid-access tariffs mentioned above, this research only takes tariff 2.0 DHA under study. The scope of this project tries to give insight about the optimal size of solar panels and batteries that minimizes the electricity bill of the vast majority of consumers in Spain. Therefore, It has been assumed that regular consumers are between powers of 1 to 10 kW and subjected to two discrimination periods, since the EV technology is still far to be considered in Spain. Thus, tariff 2.0 DHA is the perfect candidate.

Peak and off-peaks in 2.0 DHA rate vary based on the time of the year. There are two timetables adapted to the time change in Spain, a summer timetable and a winter timetable, see picture 2.3. During winter, the peak hours (when the electricity price is most expensive) are between 12pm to 22pm and the valley hours (when electricity price is cheaper) are from 22 at night to 12pm next day. Summer timetable has the same time extension, but with one hour shift. Picture 2.4 shows graphically the electricity market price that a consumer sees under a tariff 2.0 DHA in a regular day where the two discrimination times can be distinguished.

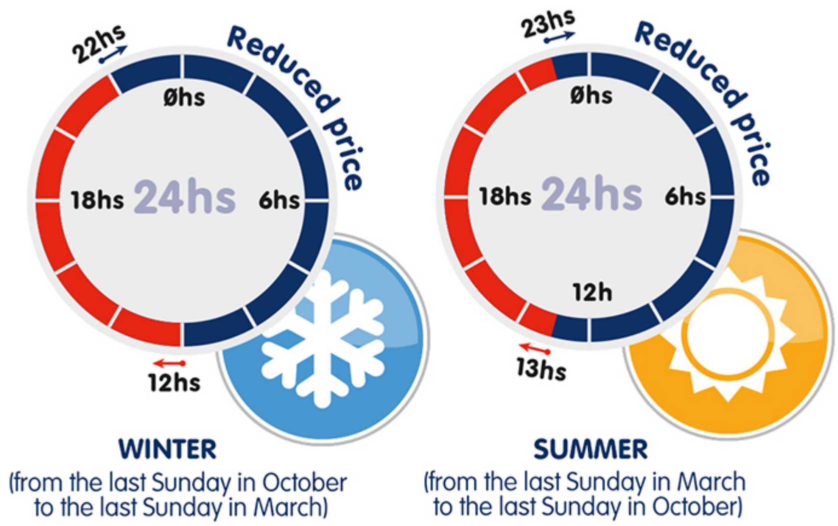


Figure 2.3: 2.0 DHA grid-access rate timetable [4]

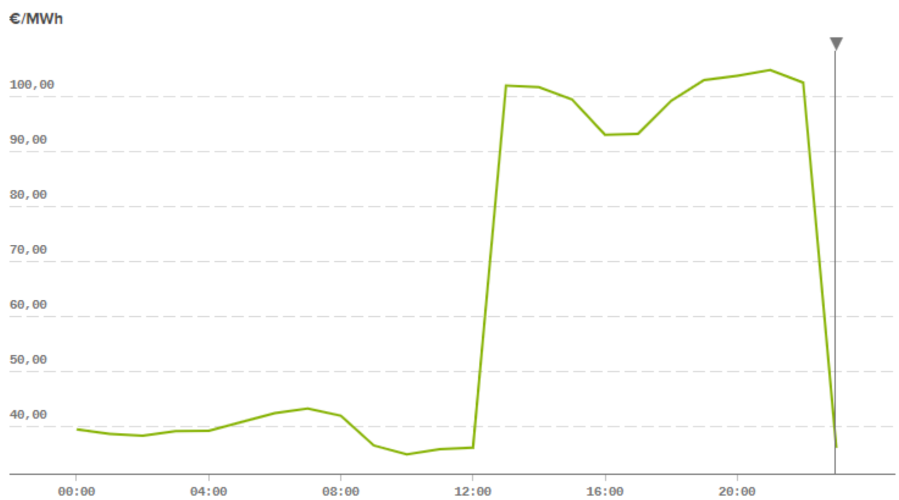


Figure 2.4: Hourly PVPC price for 2.0 DHA in a regular day [2]

2.5 Energy storage and PV systems

2.5.1 Batteries

One essential part of this study is to identify which type of battery suits the best in terms of price, lifetime and energy density, based on the work carried out from preceding studies.

According to [8], lithium-ion and lead-acid are the most common battery types used in combination with solar systems. Studies as [19] (lithium-ion battery) or [20] (lead acid) are some examples, although there are studies as [21] that chose a different alternative as NCA and NMC batteries. However, among all batteries, lithium-ion is at the end the one with bigger market share due to its high usable capacity and long lifespan. It terms of price, lead-acid is cheaper in the short-term, but lithium-ion is a better option if future replacements are considered in the long term, see table 2.4.

Table 2.4: Comparison between different battery types with the same storage capacity [8]

Characteristics	Lead-Acid Battery	Lithium-Ion Battery
Preliminary cost	2000	4000
Storage capacity	4 kWh	4 kWh
Depth of Discharge (DoD)	50%	90%
Life Cycle	1,800	4,000
Cost/ kWh / Cycle	0.556	0.278

The lifespan is also an important factor to consider. Solar battery lifespan is usually between 5 to 7.5 years for lead-acid types and 11-15 years for lithium-ion types, meaning they need to be replaced at least once to match with the solar panel lifetime, which is around 25-30 years. Moreover, during their lifetime, batteries do not keep the same capabilities as when they were brand new, they experience what is known as degradation or ageing process, which influences the economical and technical performance of batteries. Some researchers included these ageing factors into their energy storage models [20], [22], [23].

Regarding prices, battery costs vary widely depending on the manufacturer, region, brand, etc. Usually, this is a factor difficult to establish and at the same time very important since it influences the sizing modelling in a high extent. Figure 2.5 presents some battery costs chosen in recent studies.

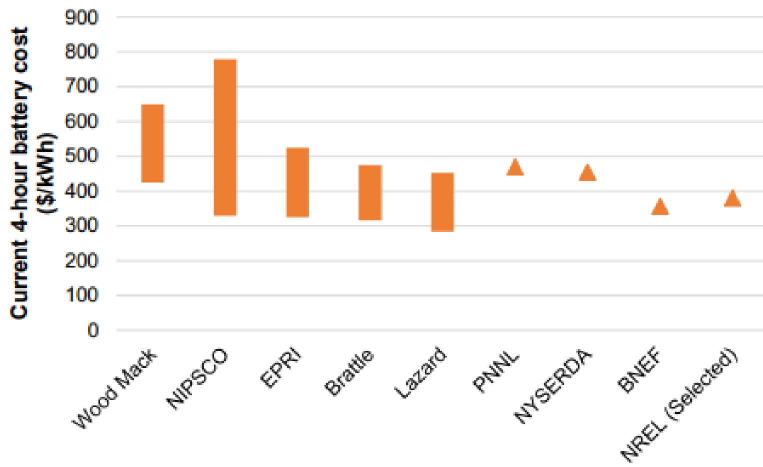


Figure 2.5: Current battery storage costs from studies published in 2018 and in 2019 [5]

In this thesis the battery type chosen to size is a lithium-ion as future costs are considered for the investment analysis. Furthermore, the ageing of the battery is neglected, meaning the battery will always have its initial storage capacity until it is no longer useful from a economical point of view. In terms of price, the optimal sizing is carried out with an initial battery cost of 500€/kWh.

2.5.2 Solar panels

Similarly to previous section and as part of this thesis, it is also important to give insight about how solar panels features are implemented in previous researches in order to find the ones that fits better to the modelling of this study.

There exist a belief claming that policrystalline cell perform better than monocrystalline in places with high temperatures. However, studies as [24] have proved that policrystalline panels always reach a higher cell temperature than monocrystalline ones. This mentioned study consisted on testing the efficiency degree of photovoltaic conversion of three different types of solar panels, among them the monocrystalline and policrystalline ones. Some of this results concluded that after all, policrystalline cells present higher conversion efficiency even under high temperatures. From the two main types of solar panels, it is clear that at the end the choice depends on what is more valuable for the consumer, either prices or performance. In case the consumer needs low prices, then policrystalline panels may be an option. On the contrary, if the performance is the matter of choice regardless of the price, monocrystalline panel is the perfect candidate.

Temperature as in many other electrical appliances plays a big role in terms of efficiency. Spain is a country that experiences relatively high temperatures, especially during the summer months, where ambient temperatures may reach 38ºC easily. According to [25] temperature is a very important fact to consider when choosing a solar panel, since solar module efficiency decreases as temperature increases once the solar cells are above 25ºC. Some papers have taken this factor into account by considering ambient temperature as a variable in the solar production equation [26], [19], [22]. However, others have carried out their results by fixing the efficiency of solar panels also achieving competent results [20], [27], [28].

Similarly to energy storage, solar panel costs differ by aspects like manufacturer or region among others. A recent report from the Lawrence Berkeley National Laboratory, a department of Energy managed by University of California, has researched about the solar installation costs variations from different regions in USA [6] with a national median price around 1,6$/W installed. Figure 2.6 displays some of these values in a bar plot. On the other hand, some research papers as [20] and [28] set a installation cost of 1,4$/W and 1,2$/W respectively, whereas studies as [27] decided to establish a range from 1,01$/W to 1,84$/W in their sizing models instead.

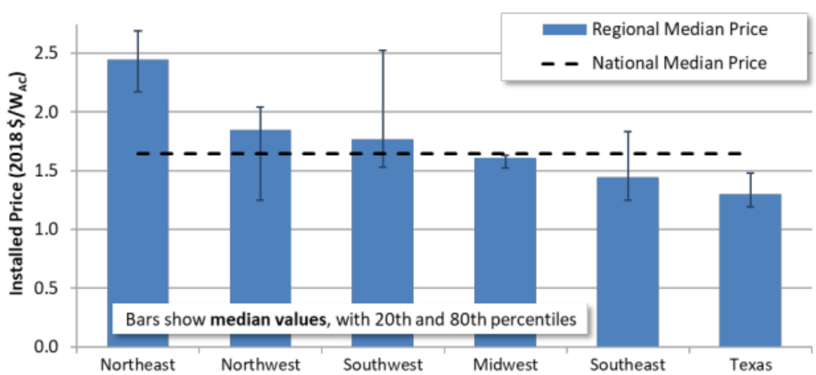


Figure 2.6: Median Installed PV Price by Region in 2018 in USA [6]

As this research focuses for consumers located in Spain, which is considered as a warm country and by knowing the huge impact that high temperatures have over solar cells, the modelling of this study considers a monocrystalline panel, whose features are described in the modelling section. However, temperature is not considered for the analysis. Instead, a fixed efficiency for the solar panels is assumed. In terms of costs, the average price in Spain varies from 0,9€/W to 1,45€/W according to [29] and [30]. Considering previous papers and reports assumptions a cost of 1,2€/W is assumed for the modelling in this thesis.

2.6 Optimal sizing

Optimal sizing is a topic widely researched in the energy sector with several applications, not only in coupling energy storage with PV for residential applications, as this thesis does, but also in large-scale projects with other coupling combinations (PV-battery-wind, PV-battery-diesel) [31] [32] [33].

Studies about optimal sizing has been handle mainly with a technical and a economical approach, which is usually taken as separate aim. An analysis assessing the best-suited battery technology depending on size in combination with PV was proposed in [21] to check the impact of on self-consumption, demand load-shifting and avoidance of PV curtailment while considering economic factors of electricity prices. The study in [27] presents a technical and an economical study of PV and energy storage sizing in five Australian apartment buildings. The study shows the benefits of applying shared energy storage and solar generation for peak shaving, self-consumption, and peak demand by comparing financial costs and electricity bills with different grid tariffs. Optimal PV size combined with storage and energy demand in residential buildings rooftops was obtained in [34] to maximize self-sufficient and to reduce the net load variance without considering economic impacts. [35] presents an optimal operation strategy and sizing of a PV system and a energy storage able to reduce annual electricity bills of a household taking into account investment costs. In [36], PV sizing considering storage is analyzed based on cost optimization, regardless technical perspective.

In order to size energy storage and PV systems, researchers usually choose to size the PV first and then they proceed to optimally size the energy storage [37], [38], [39]. This methodology normally brings low benefits economically speaking. There are also some other studies as in [36], which decided to try a different strategy by sizing the battery in first place.

It is clear that the sizing of PV and storage differs depending on the approach given. On the one hand, if the approach is technical, a real overview of the most efficient achievable results and decisions about sizing will be obtained, but this often leads to non-profitable ideal situations. On the other hand, an economical approach may be successful on achieving good results in terms of profit, but its expansion is limited by physical boundaries. In this thesis, the sizing of PV and battery systems is done from an economical perspective and unlike other studies the sizing technique will be on the optimization program to decide which technology should be sized first.

2.7 Energy management

In order to achieve a reasonable reduction in the energy bill by sizing optimally energy storage and PV, it is also necessary to develop optimal scheduling strategies to efficiently manage and monitor generation, electricity consumption and storage of a household, in order words, an optimal energy management.

Some researches have been dealing in the development of home energy management systems (HEMS) [40] with several household appliances. Applications of HEMS for devices with thermal storage is one the most hot research topics in this field as [41] discuss. However, with the huge renewable penetration incoming HEMS is starting to be applied to flexible appliances in previous years as energy storage in [35] where a sizing and a scheduling of a battery is performed in combination with PV systems, Plug-in Hybrid Electric Cars discuss in [42], which optimally schedules an electric vehicle, an electric water heater and a rooftop PV system in order to reduce daily household costs, or wind turbines and solar panels as in [43].

The main aim of an energy management is to minimize electricity bill costs. Usually, when HEMS is performed in a household one of the most common optimization activities done in recent studies is load shifting, i.e. to schedule high consumption devices in low-cost hours as presented in [44]. This thesis implements HEMS to optimally schedule the operation of the energy storage and PV systems that helps to reduce the electricity bill without considering load shifting.

2.8 Optimization and programming techniques

This section gives insight about the optimization methods used to face the problem established in the modelling section of this thesis. It also gives some insight about the optimization techniques that previous works carried out.

When it comes to develop a sizing modelling that requires knowledge about future prices, load demand and some other unpredictable data as the expected solar production for the following years, it often leads to uncertainties. Therefore, it is important to make accurate predictions in order to avoid oversizing. Nowadays, there are already many different optimization algorithms methods able to solve linear and non-linear sizing problems and perform predictions very fast. The genetic algorithm [26], particle swarm optimization technique [45] and mixed integer linear programming [34] are some of those algorithms used in several researches among others.

Similarly to [46], this thesis deals with two different types of models in order to determine the optimal size and scheduling strategy for PV and energy storage systems to minimize electricity bills, one deterministic and one stochastic model. A model is deterministic when the development of future states of a system are not based on estimations, i.e. it will always produce the same output as all variables from the initial state are known. On the other hand, in a stochastic model there are random variables that vary generally with time, which means the output of an stochastic model is determined by the estimation of variables often based on probability distributions. Since future electricity consumption, energy prices and solar radiation is unknown, an stochastic model is developed to handle this uncertainty. On the contrary, the deterministic model is made as a way to simulate a real case scenario whose main aim is to answer one of the research questions proposed for this thesis, "How far are predictions from reality?", by making a comparison with the stochastic model.

These two models are solved by linear programming where the objective functions and the constraints are linear. The programming language used for this research is Python. Python is an open source that works with packages that help to expand the possibilities and functions of the desired model. Pyomo is one of those packages and it was chosen to provide the optimization function as a tool to solve the problem that this thesis sets out.

Some programming languages make use of a solver to solve their optimization problems. Among all solvers, Gurobi Optimizer was used for solving the models presented in the modelling section of this thesis. Gurobi is a commercial product that allows to solve linear programming optimization problems. A license is required to be able to work with Gurobi and in this case the academic license was obtained [47].

2.9 Economic planning principles

For an investment of any type it is necessary to carry out an economical analysis in order to assess the costs and revenues of it in the long term. In this section some of the basic economical terms used in this thesis are explained below according to [48].

2.9.1 The Time Value of Money

The term "time value of money" is a concept stating that they money available in the present is worth more than the same amount in a future, due to its interest earning potential capacity. This fact has to be taken into account in any economical planning, especially if it is based on a long term horizon. As a consequence of the time value of money and as a way to interpret it, the following concepts shows up.

- **Present value and annuity**. Present value is a concept used to convert future costs and revenues to the present. On the contrary, annuity is used to convert a fixed price in the present into an equivalent series of annual amounts during the time horizon. The annuity equation is presented below.

$$\epsilon_{n,r} = \frac{r}{1-(1+r)^{-n}} \tag{2.4}$$

  , where

  - n = number of years
  - r = discount rate

- **Project Lifetime and Analysis Time Horizon**. Project lifetime is the time period over which project costs occur. There are two types, the technical lifetime and the economic lifetime.

  - *The technical lifetime.* It is the total period of time over which a component can technically perform its functions. In other words, the total time that a machine or facility works before it must be replaced.
  - *The economic lifetime.* It is the total period of time over which a component is expected to be useful economically speaking. The economic lifetime of a component could be different than its technical lifetime, but never longer than it.

- **Salvage value**. The salvage value is the remaining value of an asset or component when time horizon of the analysis is shorter than the lifetime of the asset or component. One of the ways to take this value into account is by linear depreciation. Equation 2.5 shows how the salvage value of an asset is calculated.

$$F_t = \frac{n-t}{n} \cdot F_0 \tag{2.5}$$

,where

- F_0= Asset's initial costs
- F_t = Asset value at the end of the year t
- n = Assumed lifetime

- **Net benefit**. In every economic analysis of a project, where a project means an upgrade or an implementation of an asset, the present value of costs and benefits from both, the reference case and the project that wants to be implemented, are considered. The net benefit is an economic concept that represents the difference between those two present values. When this difference is higher than zero, means in general terms that the project is worth to invest in. The net benefit is defined below.

$$NB = F_{ref} + O_{ref} - (F_P + O_P) \tag{2.6}$$

,where

- F_{ref} = Present value of the fixed costs of the reference case
- F_P = Present value of the fixed costs of the project
- O_{ref} = Present value of the operational costs of the reference case
- O_P = Present value of the operational costs of the project

3
Modelling

This chapter intends to give detailed explanation about the simulation setup done for the creation of scenarios.

3.1 Problem definition

This thesis is based on an investment analysis to asses the optimal sizing of solar panels and batteries that minimizes the domestic electricity bill under a Spanish grid tariff. The abolition of the solar tax in 2019 could have opened a new horizon in electricity self-consumption. This research aims to give an objective review about the electricity self-consumption in Spanish households with a range of power installed between 1kW and 10kW, where the big majority of households are.

In order to carry out the analysis, three households with different electrical consumption and power installed were selected from a municipality at the outskirts of Madrid, named Boadilla del Monte. Each of them able to include batteries and solar production. The optimization programs finds the optimal size of PV and batteries, as well as the optimal way to control them, to minimize the total annual electricity bill and the annual investment costs for each of the households. The analysis is based on a 25 years investment period considering a discount rate of 5%

The problem is faced with two different models, one deterministic and one stochastic as described in section 4. As a consequence there are two objective functions, which are described with detailed in 5.5.

The models were coded with Python with an extension package for the optimization, called Pyomo and solved by Gurobi, a linear programming solver, on a Dell Latitude E6230 computer with Intel Core i5-3340M at 2,7 GHz and 8GB of RAM.

3.2 Model features

This section will give insight about the two different models performed in this study and their main features.

3.2.1 Stochastic model

The stochastic model uses historical data from previous years to predict the outcome of 2019. The optimization program seeks the best solution of each decision on solar and battery size in each possible scenario of 2019. Then, it applies the probability of occurrence of each scenario to find the most probable and optimal solution that should be taken in order to minimize the bill.

It has been collected 5 years of solar radiation, 4 years of spot prices and 3 possible cyclical consumption profiles for each household. That makes 60 possible scenarios. It was assumed each scenario has an equal probability of 1/60.

3.2.2 Deterministic model

Unlike the stochastic model, the deterministic model has perfect information of 2019, meaning it does not have to make any predictions. Therefore, the optimization program finds the best solution possible for the outcome of 2019. The recreation of this scenario has the purpose to show the loss of profit due to the presence of uncertainty by comparing its results with the ones of the stochastic model.

3.3 Household modelling

This section will show the modelling for each of the households. The household is designed as an entity connected to the power grid and it is based on an energy balance, where the household is able not only to import, but also to export energy to the grid. These energy imports and exports depend on the activity of the appliances, the PV system and the battery, and on the energy consumption. Equation 3.1 and equation 3.2 represent the energy balance in the deterministic and stochastic model respectively for each of the households.

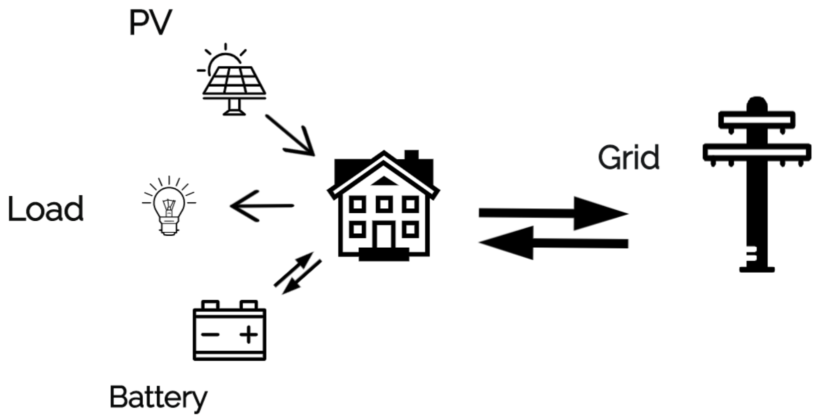


Figure 3.1: Visualization of energy flow for a household with its appliances and load consumption.

- Deterministic

$$P_t^{buy} - P_t^{sell} = P_t^{load} + P_t^{ch} - P_t^{dis} - P_t^{PVprod} \tag{3.1}$$

- Stochastic

$$P_{t,s}^{buy} - P_{t,s}^{sell} = P_{t,s}^{load} + P_{t,s}^{ch} - P_{t,s}^{dis} - P_{t,s}^{PVprod} \tag{3.2}$$

Where,

- P_t^{buy} = *Energy bought from the grid at time t*
- $P_{t,s}^{buy}$ = *Energy bought from the grid at time t in scenario s*
- P_t^{sell} = *Energy sold to the grid at time t*
- $P_{t,s}^{sell}$ = *Energy sold to the grid at time t in scenario s*
- P_t^{load} = *Energy consumption at time t*
- $P_{t,s}^{load}$ = *Energy consumption at time t in scenario s*
- P_t^{ch} = *Battery charging power at time t*
- $P_{t,s}^{ch}$ = *Battery charging power at time t in scenario s*
- P_t^{dis} = *Battery discharging power at time t*
- $P_{t,s}^{dis}$ = *Battery discharging power at time t in scenario s*
- $P_{t,s}^{PVprod}$ = *PV power production at time t in scenario s*

3.4 Modelling of Appliances

This section will give information about the main features and assumptions of the two possible appliances present in the models, which are the solar panels and the batteries.

3.4.1 PV system

PV systems generated in this model are composed of identical solar panels, in particular by monocrystaline panels of 320W with an efficiency of 19%. These panels have no limits in space, meaning that the algorithm finds the size of the solar installation that minimizes the electricity bill regardless of the available roof space.

Regarding costs, a 1,2€/W is assumed to represent the solar installation costs in the simulations. On the other hand, the lifetime of the PV panels is assumed to be 25 years, which means solar modules do not have to be replaced during the analysis period.
Table 3.1 summarizes all the features and parameters mentioned.

Table 3.1: PV designed values

PV design parameters	**Value**
Type	Monocrystalline
Rated power (W/panel)	320
Efficiency (%)	19
Area (m2/panel)	1,6866
System capacity (kW)	Variable
Installation costs (€/W)	1,2
Lifetime (years)	25

The PV production is simulated in the models by the following equations:

- Deterministic

$$PV_t^{prod} = Qrad_t \cdot A^{panel} \cdot \frac{Size^{solar}}{P^{PVpanel}} \cdot \eta^{PVPanel} \tag{3.3}$$

- Stochastic

$$PV_{t,s}^{prod} = Qrad_{t,s} \cdot A^{panel} \cdot \frac{Size^{solar}}{P^{PVpanel}} \cdot \eta^{PVPanel} \tag{3.4}$$

where,

- PV_t^{prod} = *PV production at time t*
- $PV_{t,s}^{prod}$ = *PV production at time t in scenario s*

- $Qrad_t$ = *Solar radiation at time t*
- $Qrad_{t,s}$ = *Solar radiation at time t in scenario s*
- A^{panel} = *Solar panel area*
- $Size^{solar}$ = *Solar system size*
- $P^{PVpanel}$ = *Power rated of solar panel*
- $\eta^{PVPanel}$ = *Solar panel efficiency*

3.4.2 Batteries

The batteries generated in this model are composed by lithium-ion batteries with a round trip efficiency of 90%. The optimal capacity of the battery is decided by the optimization program in kWh. On the other hand, the charging/discharging power has been set to a maximum allowable of 7 kW.

As stated in literature section, the lifetime of a lithium-ion battery is usually between 11-15 years. For this thesis it has been assumed a battery lifetime of 15 years, which implies that the battery has to be replaced once and the new battery will still have a value at the end of period for the analysis. This fact is represented by the salvage value and the discounted value of the reinvestment in the objective function.

Concerning costs, an initial price of 500€/kWh is assumed as a starting point in the first simulations. Later on, this price is changed in order to perform a sensitivity analysis and test out its influence over the investment.

Similarly to PV modelling, a table summarizing the main features and parameters for the battery simulation is provided below.

Table 3.2: Battery modelling parameters

Battery design parameters	Value
Type	Lithium-ion
Capacity (kWh)	Variable
Round trip efficiency (%)	90
Maximum charge/discharge rate (kW)	7
Initial SOC (kWh)	0
Minimum SOC (kWh)	0
Installation costs (€/kWh)	500
Lifetime (years)	15

The battery behaviour is simulated in each of the models differently by the following equations and set of constrains:

- Deterministic model

$$SOC_t = SOC_{t-1} + b_t^{ch} \cdot \eta_{ch} - \frac{b_t^{dis}}{\eta_{dis}} \tag{3.5}$$

Equation 3.5 is only valid under the following conditions:

$$\begin{gathered}\text{At } t = 0, SOC_t = SOC_{initial} \\ b_t^{ch} < P_{max} \\ b_t^{dis} < P_{max} \\ P_{max} <= 7kW \\ P_{max} <= B_{cap} \\ SOC_{min} < SOC_t < B_{cap}\end{gathered}$$

- Stochastic model

$$SOC_{t,s} = SOC_{t-1,s} + b_{t,s}^{ch} \cdot \eta_{ch} - \frac{b_{t,s}^{dis}}{\eta_{dis}} \tag{3.6}$$

Equation 3.6 is only valid under the following conditions:

$$\begin{gathered}\text{At } t = 0, SOC_{t,s} = SOC_{initial} \\ b_{t,s}^{ch} < P_{max} \\ b_{t,s}^{dis} < P_{max} \\ P_{max} <= 7kW \\ P_{max} <= B_{cap} \\ SOC_{min} < SOC_{t,s} < B_{cap}\end{gathered}$$

where,

- SOC_t = *Battery SOC at time t*
- $SOC_{t,s}$ = *Battery SOC at time t in scenario s*
- SOC_{t-1} = *Battery SOC at time t-1*
- $SOC_{t-1,s}$ = *Battery SOC at time t-1 in scenario s*
- b_t^{ch} = *Battery charging power at time t*
- $b_{t,s}^{ch}$ = *Battery charging power at time t in scenario s*
- b_t^{dis} = *Battery discharging power at time t*

- $b_{t,s}^{dis}$ = *Battery discharging power at time t in scenario s*
- η_{ch} = *Battery charging efficiency*
- η_{dis} = *Battery discharging efficiency*
- $SOC_{initial}$ = *Battery initial SOC*
- P_{max} = *Battery maximum charging power*
- SOC_{min} = *Battery minimum SOC*
- B_{cap} = *Battery capacity*

3.5 Data sets

In this section, data used in the modelling of this research is presented.

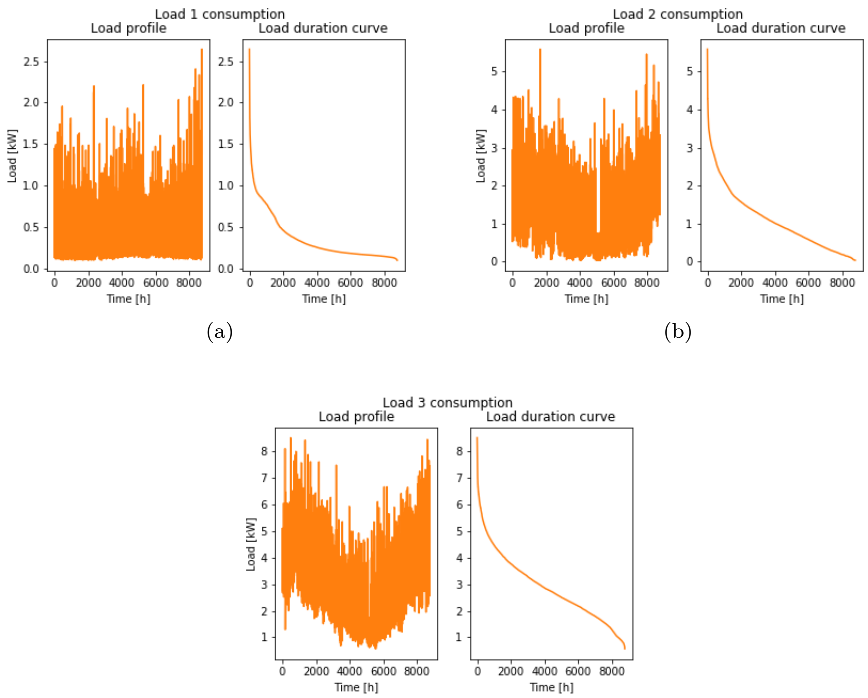
3.5.1 Load data

As it was stated, the electrical load consumption of three different households of the same municipality were obtained for the modelling. A small load (household 1), a medium-average load (household 2) and a high load (household 3), each of them participating in the regulated market or PVPC. These electrical loads are real data measured during the year 2019 and are necessary for two main reasons. On the one hand, they are useful to illustrate a general idea of the electrical consumption patterns of an average household in Spain. On the other hand, they are useful to simulate the deterministic model and compare its results with results from the stochastic model, which are based on predictions that estimate the outcome of 2019.

2019 hourly load data plots from the three households are presented below together with their respective load duration curves and table 3.3 shows its main features in terms of power and annual energy consumed.

Table 3.3: 2019 load profile features

	Power installed	**Annual consumption**
Load 1	4.4 kW	3192.05 kWh
Load 2	6 kW	9526.53 kWh
Load 3	10 kW	25332.72 kWh



(a) (b)

(c)

Figure 3.2: Hourly electrical consumption and duration curve during 2019. (a), (b) and (c) represents household 1, household 2 and household 3 respectively.

For this research, only real hourly load data from 2019 were possible to get, in other words, the hourly consumption from past years is unknown. In order to tackle this lack of data, it is assumed that the electrical consumption from each household ranges $\pm 10\%$ over the years on a random basis. Normally, consumers have a cyclical consumption profile over the years, meaning some years the consumption is a bit higher and in some others a bit less.

Therefore, in order to replicate this behaviour, two additional load consumption scenarios were created for each of the households, a higher one and a smaller one, based on the real one. Firstly, 10% of the total annual consumption of 2019 was computed for each of the households. Then, this amount was divided by 8760h in order to obtain the equivalent of that ten percent per hour. Finally, this amount per hour was summed and subtracted to each hour of the 2019 consumption to obtain the two additional scenarios. This way, each household of the model has the possibility to adopt three different load scenarios with the same probability of occurrence for the next year. Table 3.4 and graph 3.3 gives an example of these assumptions taken for a better understanding.

Table 3.4: Data used to create additional load profiles for each household

Household	2019 total consumption	10 %	Inc./Dec. per hour
Household 1	3192 kWh	319.2 kWh	± 0.036 kWh/h
Household 2	9526.53 kWh	952.65 kWh	± 0.11 kWh/h
Household 3	25332.72 kWh	2533.28 kWh	± 0.29 kWh/h

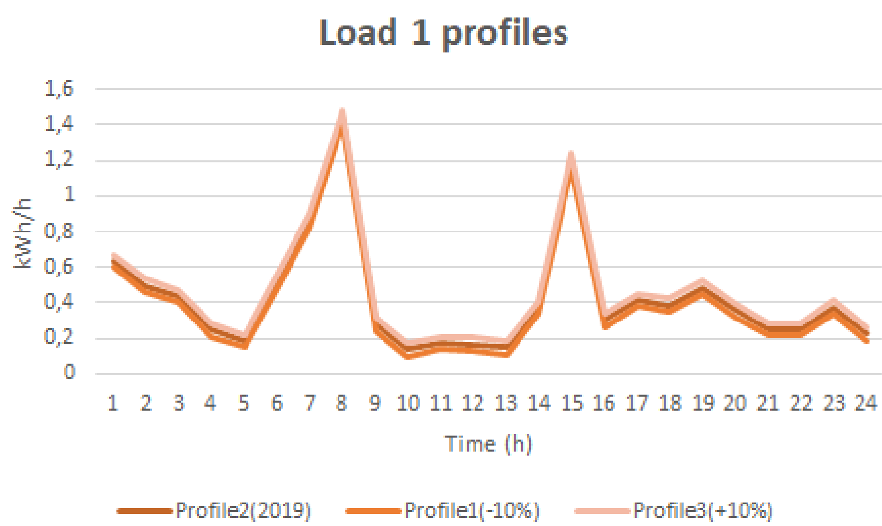


Figure 3.3: Possible load scenarios of household 1 during a regular day of May

3.5.2 Spot price

The term spot price in electricity indicates the current price of electricity in the market. Usually, its price comes apart from the grid tariff,but in the case of Spain, especially for consumers in the regulated market, the grid tariff is included in the spot price. As it was explained in previous sections, the grid tariff used in this research is the 2.0 DHA, which has two discrimination periods. Electricity prices vary over the years and thus, historical data from spot prices were collected from the system operator webpage [2], in particular from 2015 to 2019 inclusive. The years between 2015 to 2018 were used to estimate the spot prices of 2019 in the stochastic model. On the other hand, 2019 spot prices were used in the deterministic model.

3.5.3 Buyback price

This thesis uses the name "buyback price" to refer to the price for exporting domestic energy surplus into the grid, in other words, the amount in euros that an individual consumer gets for selling his excess of energy produced to the electric companies. Just like electricity price fluctuates over the year, so does the buyback price.

This option of selling the excess of domestic energy to the electric companies was not possible in Spain until 2019 due to the law and regulations that existed before. Therefore, only real buybuck prices from 2019 are known. According to the system operator, REE [2], these prices can never get higher than the spot price, where the grid tariff is also included. Since this model contains historical data from the spot prices and not from the buyback, the algorithm might have inconsistencies when optimizing in case of using 2019 buyback prices as buyback prices for previous years, as there may be situations where the buyback price could get higher than the spot price.

In order to avoid optimization issues, it was assumed a fixed buyback price of 0.04€/kWh for the stochastic model, which never surpasses the spot price in any of the data used for the simulation and it represents the average buyback price of 2019.

3.5.4 Solar radiation

The energy that a solar panel produces depends on the solar radiation. Solar energy is a non controllable source of power due to weather uncertainty and due to the fact that the sun is not always sunning. However, in order to reduce this uncertainty, historical data of solar radiation for Boadilla del Monte is collected from 2014 to 2018 for the stochastic model [49]. Figure 3.4 shows the solar radiation for one day of may in different years, from where it can be seen that solar radiation varies across days within a year. Therefore, the algorithm establishes that the hourly radiation of 2019 is a random variable whose value is estimated by the probabilities and tendencies from historical data. All years are considered with the same probability of occurrence.
For the deterministic model, real solar radiation data from 2019 were collected.

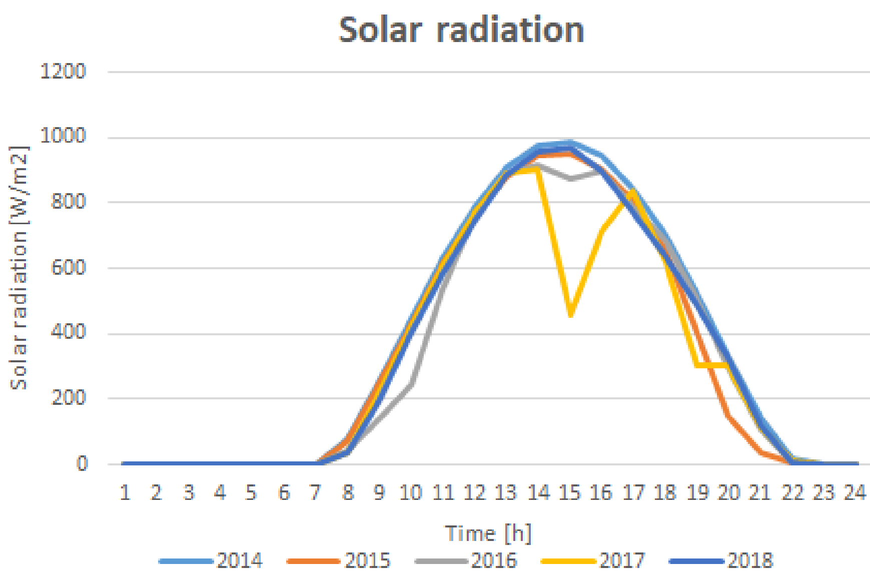


Figure 3.4: Hourly solar radiation during a day of May, Boadilla del Monte, Madrid

3.6 Objective function

The objective function seeks to minimize the annual electricity bill and the annual investment costs by choosing the optimal size of batteries and PV. In other words, the objective function is composed by two terms, the net costs for buying and selling energy and the corresponding annuity for the investment of the batteries and solar panels. As the power installed and the taxes costs are considered fixed prices that depend on the household electric installation, the resultant cost for the energy sold and bought is the only variable cost that determines how the electricity bill will look like at the end. Thus, the reason why the power installed and taxes are not included in the objective although they are illustrated in the results.

There are two objective functions build up for the simulations, one for the deterministic model and the other one for the stochastic model.

1. **Objective function for the deterministic model**

$$min \sum_t (e_t^{imp} \cdot C_t^{spot}) - \sum_t (e_t^{ext} \cdot C_t^{buyback}) + Size^{solar} \cdot p^{solar} \cdot Ann_{n,r}$$
$$+ Size^{batt} \cdot p^{batt} \cdot Ann_{n,r} \cdot (1 + (1+r)^{-n} - \frac{2n-N}{n} \cdot (1+r)^{-N}) \tag{3.7}$$

where,

- e_t^{imp} = Grid import in time t [kWh/h]
- e_t^{ext} = Grid export in time t [kWh/h]
- $C_t^{buyback}$ = Selling price in time t [kWh/h]
- C_t^{spot} = Spot price + grid tariff price in time t [€/kWh]
- $Size^{solar}$ = Optimal size of the PV system
- $Size^{batt}$ = Optimal battery size
- p^{solar} = Price per W of solar panel installed
- p^{batt} = Price per kWh of battery capacity
- $Ann_{n,r}$ = Annuity term given by equation 2.4
- r = Discount rate
- n = Battery lifetime
- N = Analysis time period
- $(1+r)^{-n}$ = Represents the discounted value of the battery reinvestment
- $\frac{2n-N}{n} \cdot (1+r)^{-N}$ = Represents the battery savage value

2. **Objective function for the stochastic model**

$$min \sum_t \sum_s \pi_s \cdot (e_{t,s}^{imp} \cdot C_{t,s}^{spot}) - \sum_t \sum_s \pi_s \cdot (e_{t,s}^{ext} \cdot C_t^{buyback})$$
$$+ Size^{solar} \cdot p^{solar} \cdot Ann_{n,r} \tag{3.8}$$
$$+ Size^{batt} \cdot p^{batt} \cdot Ann_{n,r} \cdot (1 + (1+r)^{-n} - \frac{2n-N}{n} \cdot (1+r)^{-N})$$

where,

- π_s = Scenario probability
- $e_{t,s}^{imp}$ = Grid import in scenario s during time t [kWh/h]
- e_t^{ext} = Grid export in scenario s during time t [kWh/h]
- $C_t^{buyback}$ = Selling price in time t[kWh/h]
- C_t^{spot} = Spot price + grid tariff price in scenario s during time t[€/kWh]

3.7 Case Scenarios

This section presents the three case studies developed in this thesis.

3.7.1 No Appliances case

It is considered the reference case, where the annual consumption and costs that consumer pays without making any investment are reflected. It is named reference case because it is useful to compare and asses the impact of the cases where the investment is carried out.

3.7.2 Investment based on predictions with historical data

This case-scenario is focused on the stochastic model shown before, which pretends to find the closest decision to the ideal one in terms of PV and battery sizing based on historical data. Data from 2014 to 2018 are used to predict the outcome of 2019.

3.7.3 Investment when there is a perfect knowledge of data

In order to check the accuracy of the predictions made in case scenario 2, this case scenario is based on an ideal case where the investment is done under a perfect knowledge of the unknown data during 2019. This way, the optimization algorithm finds the best solution possible that minimizes the electricity bill from 2019, and at the same time, it is useful to check how far the predictions made in the previous scenario are from reality. Unlike case scenario 2, this case is a product of the deterministic model presented above.

4
Results

This chapters presents the results obtained from the simulation models and from the sensitivity analysis in the form of tables and 3D-plots.

4.1 Optimal size assessment

This section contains tables where the optimal size of solar panels and batteries are displayed for each of the households in the different case scenarios. It also includes the total cost of the investment taken and the annual investment costs, i.e. the annual cost as a result of dividing the investment in a series of equal payments during 25 years.

Table 4.1: Optimal size for household 1

Scenario	Case scenario 2	Case scenario 3
Battery size (kWh)	0	0
Solar system size (kW)	3,65	1,33

Table 4.2: Optimal size for household 2

Scenario	Case scenario 2	Case scenario 3
Battery size (kWh)	0	0
Solar system size (kW)	4,43	6,16

Table 4.3: Optimal size for household 3

Scenario	Case scenario 2	Case scenario 3
Battery size (kWh)	0	0
Solar system size (kW)	11,2	11,16

4.2 Break-up of costs

This section shows in tables 4.4, 4.5 and 4.6 the break-up of annual costs for each household in the different scenarios, which is summarize for a better look in figure 4.1. The break-up of prices is divided into 4 terms explained below.

- *Electricity price.* It represents the annual costs for the energy consumed of the household. When this term gets negative numbers it means the household has covered its whole electricity costs and received additional income for selling energy.
- *Bill before taxes.* It is the sum of the electricity price plus the price paid for the power installed of the household annually without taxes.
- *Bill after taxes.* It represent the total electricity bill that the household owner will pay annually after applying taxes.
- *Total annual costs.* It is the sum of the last term mentioned and the price the household owner has to pay for the annual investment costs during 25 years.

Table 4.4: Break up of prices for Load 1

Scenario	Case scenario 1	Case scenario 2	Case scenario 3
Electricity price	292,69€	156,61€	-70,47€
Bill before taxes	505,96€	369,88€	213,28€
Bill after taxes	655,28€	482,20€	283,02€
Total annual costs	655,28€	595,55€	523,36€

Table 4.5: Break up of prices for Load 2

Scenario	Case scenario 1	Case scenario 2	Case scenario 3
Electricity price	889,62€	436,49€	197,95€
Bill before taxes	1180,45€	727,33€	488,78€
Bill after taxes	1513,13€	936,82€	633,43€
Total annual costs	1513,13€	1.314,07€	1.158,14€

Table 4.6: Break up of prices for Load 3

Scenario	Case scenario 1	Case scenario 2	Case scenario 3
Electricity price	2.385,78€	1.153,46€	979,72€
Bill before taxes	2.870,50€	1.638,18€	1.464,44€
Bill after taxes	3.662,64€	2.095,31€	1.874,33€
Total annual costs	3.662,64€	3.049,35€	2.824,19€

Figure 4.1 illustrates in a float chart a comparison of the total annual costs between scenarios and between households and figure 4.2 shows in percentage the impact of the investment on the total annual costs. The reduction in percentage is done with respect to the reference case (scenario 1). Table 4.7 displays the expected total savings that each household will make after 25 years when considering the annual costs from case scenario 2.

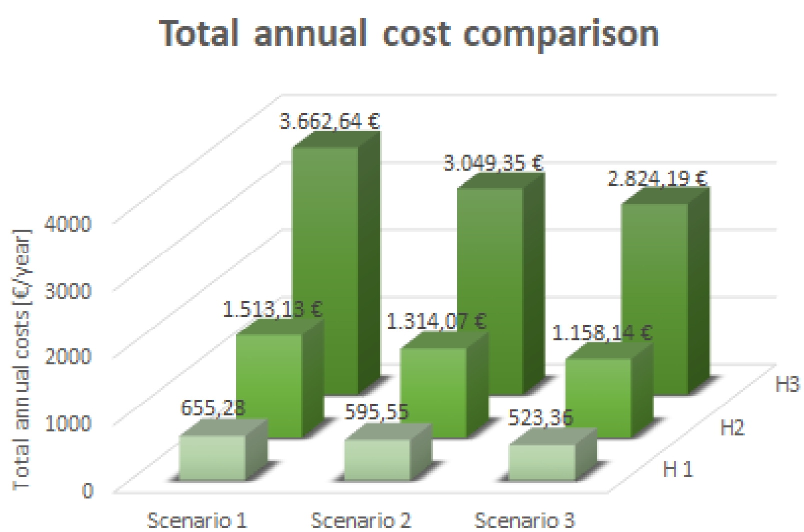


Figure 4.1: Total annual cost comparison

Table 4.7: Total expected savings after 25 years for each household when forecasting

Households	Total expected savings
H1	1.493,25€
H2	4.976,5€
H3	15.332,25€

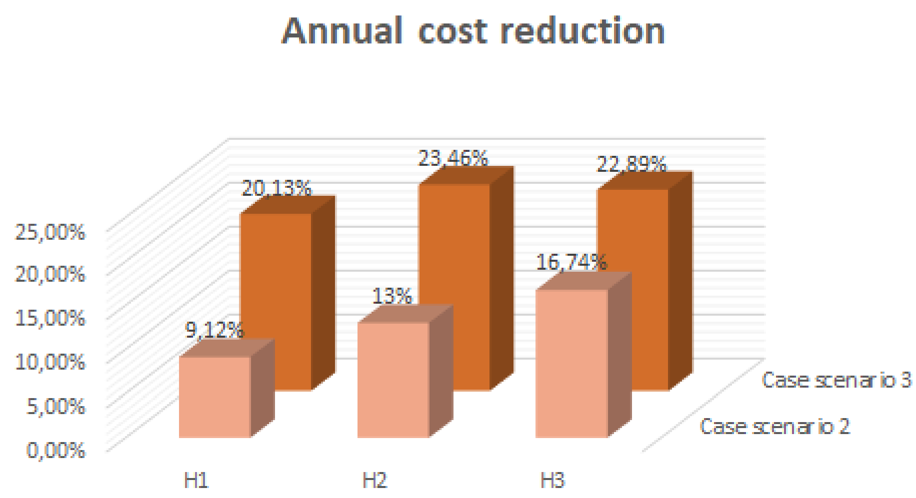


Figure 4.2: Reduction in percentage of the total annual costs for each scenario and for each household

4.3 Sensitivity Analysis

A sensitivity analysis based on the battery price is done in this section for the two models simulated. The first three 3D-plots represent the deterministic model and the three next ones the stochastic. At the end, there is a table summarizing the battery threshold cost at which changes occur. The aim is to see the influence that battery prices have over the investment decisions and their impact over the total annual costs that answer some of the research questions.

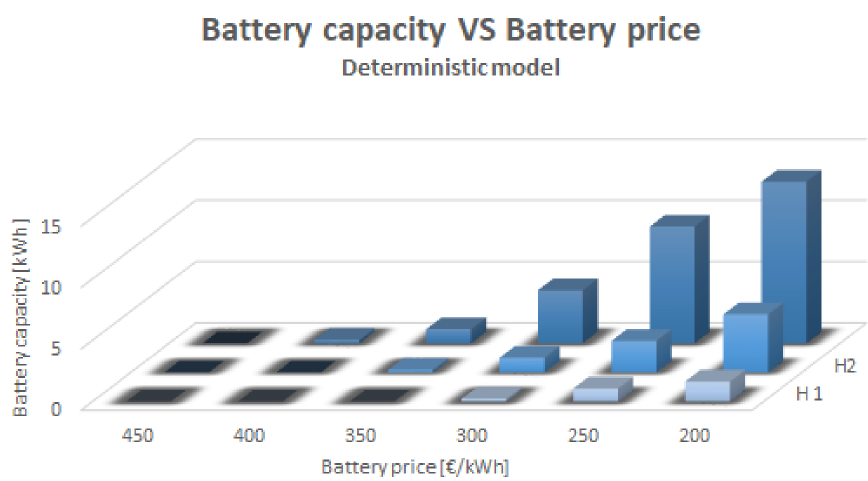


Figure 4.3: Optimal battery capacity when battery prices change based on a deterministic model

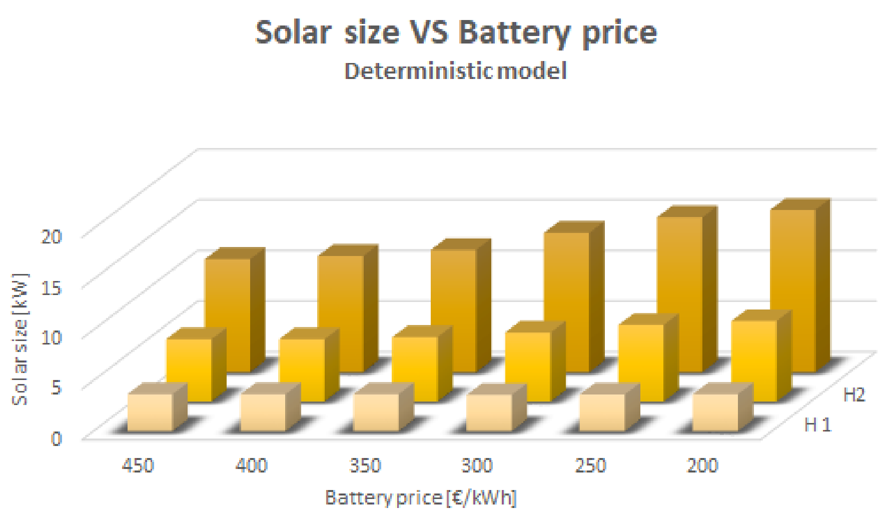


Figure 4.4: Optimal solar system size when battery prices change based on a deterministic model

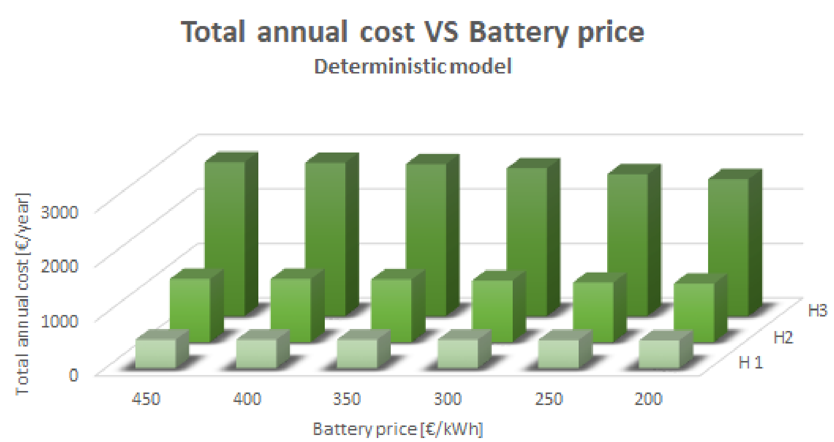


Figure 4.5: Annual total costs when battery prices change based on a deterministic model

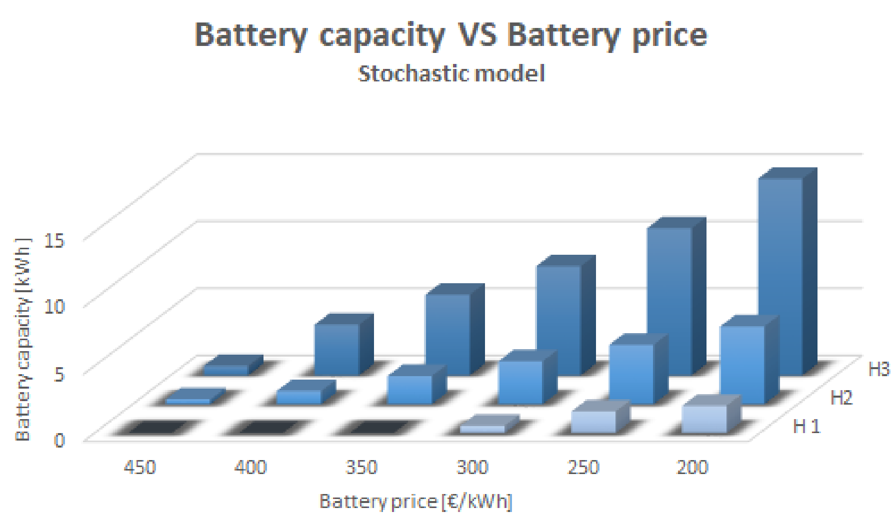


Figure 4.6: Optimal battery capacity when battery prices change based on a stochastic model

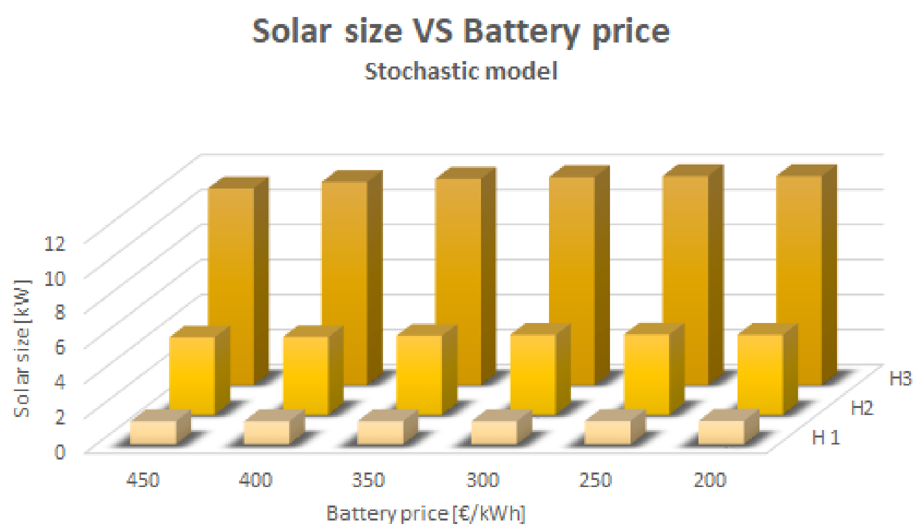


Figure 4.7: Optimal solar system size when battery prices change based on a stochastic model

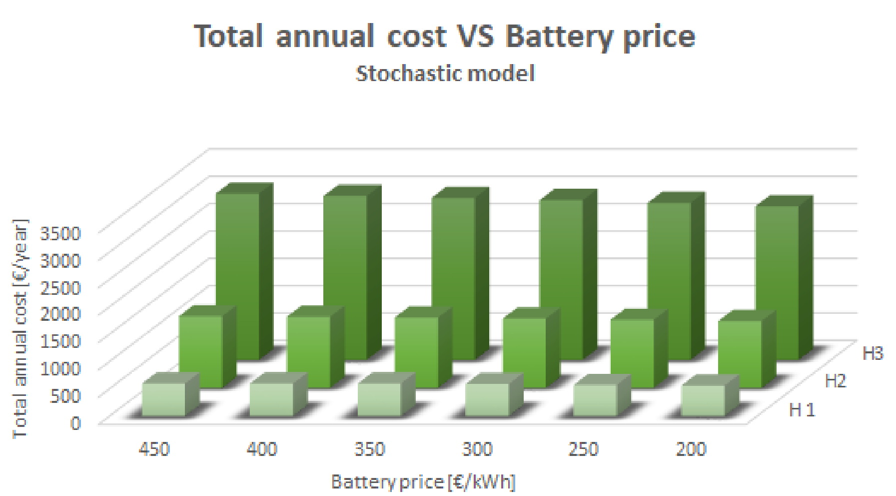


Figure 4.8: Annual total costs when battery prices change based on a stochastic model

Table 4.8: Battery cost threshold at which optimal sizing changes based on previous 3D-plots

Term	Households	Deterministic model	Stochastic model
Battery investment at	H3	350€/kWh	400€/kWh
	H2	300€/kWh	350€/kWh
	H1	250€/kWh	250€/kWh
Increase PV system size at	H3	300€/kWh	None
	H2	250€/kWh	None
	H1	None	None
Total annual cost reduction at	H3	250€/kWh	250€/kWh
	H2	None	None
	H1	None	None

5 Discussion

5.1 Discussion of results

Results from tables 4.1, 4.2 and 4.3 show that for a battery price of 500€/kWh the optimization program decides to invest only in solar panels in order to reduce the electricity bill in each of the cases, i.e. PV systems are more cost-effective than batteries in Spain. This is reasonable since Spain have a very good geographical location in terms of solar radiation and PV costs are relatively more economical than batteries considering the longer useful lifetime. In terms of dimensions, the larger the power installed and the energy consumed of a household the larger the size of the PV system as it was expected. While a small household needs between 3,65 kW to 1,33 kW of PV installation to face its consumption and reduce its bill costs, a big household needs between 11,2 kW and 11,16 kW.

Regarding the accuracy of predictions from case 2 with respect case 3, almost a perfect prediction in terms of size was only achieved for household 3 with the stochastic model, whereas for households 1 and 2 the difference in PV size was approximately 2kW down and up respectively, which is the equivalent of installing between 6 to 7 solar panels of 320W each, more or less. This might means that the higher the consumption of a house the less is the sizing impact from uncertainty over the years.

Figure 4.1 shows that all households manage to get yearly savings by investing in PV in comparison with the annual electricity bill costs when no investment is carried out. Despite this, the investment in energy appliances to reduce the electricity bill has different influence depending on the household energy consumption. While household 1 is expected to get only 1.493,25€ savings after 25 years under a stochastic approach, household 2 and 3 savings are expected to be 4.976,5€ and 15.332,25€ respectively, as table 4.7 displayed. However, at the end, they all manage to achieve more than 20% reduction for the best case scenario in terms of proportion as it can be seen from figure 4.2. On the other hand, considered as a good approach in this thesis, shows that under uncertainty the annual cost reduction ranges from 9,12% to almost a 17%, which means each household experiences around 10% more expensive annual costs and less savings with respect to the ideal case when forecasting, in general terms.

Results from figures 4.3 and 4.6 shows that while battery prices are above 350€ in the deterministic model and above 400€ in the stochastic, it is not cost-effective to invest on a battery in any of the households. Nevertheless, once battery prices are below those values, household 2 and household 3 are the only ones where a battery might be worth to invest in to maximize savings when battery prices go down, since household 1 shows very a small battery size even when battery prices are the cheapest.

Regarding the influence of battery prices over PV size, it really depends on the accuracy of predictions. Results displayed in figure 4.4 show that household 2 and 3 decide to invest in more PV size in order to maximize savings when there is a perfect knowledge of data and battery prices reach 300€/kWh, whereas in figure 4.7 households decide not to invest in PV size at all even though battery prices go down when the optimization is based on predictions.

In general terms, total annual costs are not very sensitive to a reduction in battery prices as figures 4.5 and 4.8 illustrate. Even though a battery implies an storage to save the solar energy and use it when is most convenient, which is translated into a higher reduction in electricity prices, at the end the investment costs are also higher, since one extra energy resource has to be considered. However, some considerable reduction can be appreciated in household 3 when battery costs reach 250€/kWh, which gives to think that batteries start to be efficiency when dealing with households or buildings with high energy consumption.

5.2 Further work

This section will discuss possible aspects that might have changed the outcome of this thesis as well as future work related with the study presented in this research.

Only real data from 2019 was obtained for the energy consumption of the households, while information about other sources as solar radiation or spot prices were collected from several years. This gives a limitation to predict a most accurate trend for the possible future energy consumption fluctuations, which might influence results to some extent, since they are projected over a 25 years investment.

As it was mentioned in the modelling section, this thesis do not consider a physical boundaries for the PV system installation, it only focuses on the total size of the installation that minimizes the electricity bill. This might be a reason why the optimization program decides to invest in PV mainly. Probably, if some limitations in space for the PV systems were considered, batteries would have gained importance.

Since this thesis is based on a 25 years investment, prices and savings may vary in a future from the ones estimated here, especially because the electrical consumption increases over the years as the world electrification grows. This may change predictions completely. However, nowadays there are more and more research about the so-called term machine learning, which consist on developing algorithms that let computers learn by themselves in general terms. This might be implemented in order to predict with higher accuracy this continuous increment of the energy consumption, which is suggested as future work for this thesis.

6
Conclusion

In this chapter, conclusions from the results and discussion part are discussed and research questions answered.

This thesis has focused in an investment analysis over 25 years to find the optimal sizing of PV systems and batteries that minimize the electricity bill in residential buildings of Spain. Big data collection about solar radiation, electricity prices and electrical consumptions have been used in order to estimate their future tendencies, so dimensioning can be size accordingly. Through a stochastic optimization, annual costs for three different households have been obtained including in them the electricity bill and the equivalent investment costs. The results obtained have been compared with a reference case, where the annual costs corresponding with no making any investment are represented, and with a deterministic model, which represented the most ideal results possible to obtain in case a perfect knowledge of all variables from 2019 were known. Finally, a sensitivity analysis was carried out in order to assess how dimensioning would be affected when battery costs go down. All this work enables to answer the research questions described at the beginning of this thesis, which are shown below.

The research questions are:

- **Is it cost-effective to invest in PV and energy storage technologies in order to reduce the domestic electricity bill for households of the low voltage Spanish grid under a TOU tariff after the abolition of the so-called "Impuesto al sol" law? What optimal size minimizes the domestic electricity bill? And how big is this bill reduction in comparison with no making any investment? How much savings will house owners make?**

  At the moment, It is only cost-effective to invest in PV systems rather than in a energy storage. Batteries are still expensive and the geographical location of Spain makes PV systems good candidates to minimize the bill. However, results have shown that for households with large energy consumption a battery investment might be reasonable to invest in when battery prices go down.

  The optimal size varies depending on the household energy consumption. For households with low energy consumption the optimal PV installation size ranges between 1,33 kW and 3,65 kW, for medium energy consumption between 4,43 kW and 6,16 kW and for large energy consumption around 11,2 kW. Investing in PV systems might bring up to 23% annual bill reduction in the best case scenario and savings from 1.500€ up to 15.300€ after 25 years.

- **Usually, an investment analysis is carried out based on predictions about the future. How far would sizing predictions differ from the actual real ones that minimizes costs the most?**

  When predictions are performed under a stochastic linear programming approach, around 10% more expensive annual costs and less savings are experienced. However, It has also been seen that predictions becomes more accurate when forecasting for higher energy consumption households, i.e. the higher the consumption the less error in predictions.

- **How energy storage prices influence the investment decisions? What impacts does it has over the domestic electricity bill?**

  When battery prices go down some investment in energy storage shows up, while PV systems remains barely affected by this change in terms of size. However, this investment in energy storage do not make a considerable reduction in the electricity bill at the end, only in households with a high energy consumption a noticeable reduction is achieved.

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