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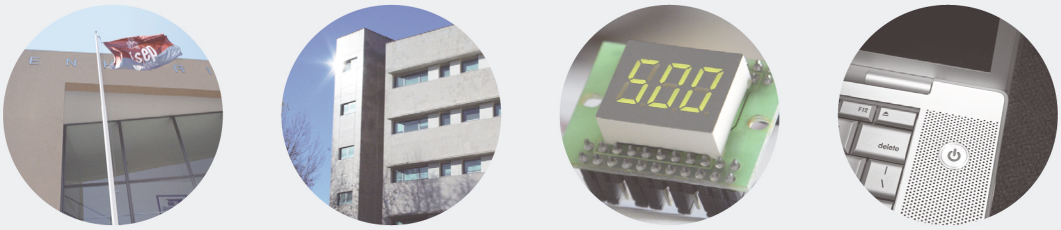
MESTRADO EM ENGENHARIA ELECTROTÉCNICA - SISTEMAS ELÉCTRICOS DE ENERGIA



Produção Renovável em Edifícios Residenciais: Nova abordagem de autoconsumo

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Renewable Energy Production in Residential Buildings

New Approach to Self-Consumption

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“I cry a lot but I am so productive, it’s an art”

– Taylor Swift

Resumo

O aumento do consumo global de energia tem levado a uma crescente preocupação no que diz respeito às fontes de produção de energia utilizadas e aos impactos que estas têm a nível ambiental. Sendo o setor energético um dos setores com maiores emissões de gases de efeito de estufa, este setor necessita que sejam tomadas medidas de forma a atingir maior sustentabilidade contribuindo para a descarbonização do setor e para a transição energética.

Desta forma, as energias renováveis têm ganho cada vez mais importância face às fontes de energia tradicionais não renováveis, havendo grandes esforços e investimentos em centrais hídricas, solares e eólicas. Uma vez que as energias renováveis não se prendem apenas à forma centralizada de produção de energia, mas também à forma descentralizada de produção, a energia solar fotovoltaica é das que mais facilmente pode ser implementada sendo que não necessita de tão grande espaço disponível para a integração da sua tecnologia. Devido à facilidade de implementação, a produção descentralizada torna-se mais fácil, podendo também ser apoiada através de unidades de produção para autoconsumo que, interligadas com a rede de distribuição de energia, poderão injetar os seus excedentes na rede, fazendo com que haja maior disponibilidade de energia proveniente de fontes renováveis.

De forma a encorajar a produção de energia solar fotovoltaica e injeção de excedentes na rede, a nível residencial, o caso de estudo proposto tem por base a injeção de energia na rede quando existir excedentes na produção e, mais tarde, quando o consumidor necessitar de energia proveniente da rede, terá a mesma quantidade de energia que foi injetada, a um preço reduzido em comparação com o preço normal praticado. Através desta proposta, a venda de excedentes à rede poderá tornar-se mais vantajosa do que através dos contratos de venda de excedentes atualmente praticados.

Para desenvolver o estudo e obter resultados, foram criados dois cenários principais. Um, onde a energia injetada na rede não entra para o cálculo dos custos de energia e outro onde a energia injetada é tida em conta para a aplicação da tarifa bonificada na energia consumida proveniente da rede. Através dos resultados obtidos perante a comparação dos dois cenários, tendo-se obtido, no melhor resultado, 33% de poupança, é demonstrado que o proposto pode ser uma boa forma de venda de excedentes à rede.

Os casos de estudo foram realizados com suporte a bases de dados reais (dados de consumo e produção), pelo que conferem aos resultados um cariz realístico.

Palavras-chave: Autoconsumo, energias renováveis, energia solar fotovoltaica, produção de energia.

Abstract

The increase in global energy consumption has led to a growing concern regarding the sources of energy production used and their environmental impacts. As the energy sector is one of the sectors with the highest greenhouse gas emissions, measures need to be taken to achieve greater sustainability, contributing to the decarbonization of the sector and the energy transition.

Therefore, renewable energies have become increasingly important compared to traditional non-renewable energy sources, with significant efforts and investments in hydroelectric, solar and wind power plants. Since renewable energies are not limited to centralized forms of energy production, but also include decentralized production, photovoltaic solar energy is one of the most easily implementable options, requiring less space for technology integration. Due to its ease of implementation, decentralized production becomes more feasible, and it can also be supported through self-consumption production units which, when interconnected with the energy distribution grid, can inject their surpluses into the grid, increasing the availability of energy from renewable sources.

In order to encourage the production of photovoltaic solar energy and the injection of surpluses into the grid at a residential level, the proposed case study is based on injecting energy into the grid when there are surpluses in production and, later, when the consumer needs energy from the grid, they will have the same amount of energy that was injected at a reduced price compared to the normal price charged. Through this proposal, the sale of surpluses to the grid could become more advantageous than with the current surplus sales contracts.

To develop the study and obtain results, two main scenarios were created. One scenario considers that the energy injected into the grid is not included in the calculation of energy costs, and the other scenario considers the injected energy for the application of a discounted tariff on the energy consumed from the grid. The results obtained by comparing the two scenarios demonstrates that the proposed method can be a good way to sell surpluses to the grid, since the best result obtained was of 33% savings.

The case studies were carried out using databases from real systems (consumption and production data), which made the results realistic.

Keywords: Energy production, renewable energies, self-consumption, solar photovoltaic energy.

Acknowledgments

The conclusion of this master's degree was only possible thanks to the unconditional support of several people to whom I extend my heartfelt thanks.

To my family, for all their support and encouragement. To my parents and my brother, for always believing in me even when I didn't, for their efforts, and for all the affection they give me.

To my friends, who have been with me over the past few years, who always manage to make me relax and detach from what's going on around me, and who, without knowing it, were essential in maintaining the balance between what needs to be taken very seriously and what doesn't.

To my mentor, Sérgio Ramos, to whom I express my gratitude for the guidance, patience, effort, and dedication. All the support was fundamental for the execution and completion of this work.

And finally, to God, for granting me health, strength, and resilience to overcome all the challenges faced throughout this journey.

To everyone who, in some way, contributed to the realization of this thesis, my deepest thanks.

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Acronyms

List of acronyms

AC	Alternating Current
CGIE	Costs of General Economic Interest
DC	Direct Current
DOE	Dynamic Operating Envelopes
ERSE	Energy Services Regulatory Authority
EC	European Commission
ESS	Energy Storage Systems
EU	European Union
EV	Electrical Vehicles
GHG	Greenhouse Gas
GMS	Grid Management System
IRR	Internal Rate of Return
LV	Low Voltage
NECP2030	National Energy and Climate Plan 2030
NPV	Net Present Value
O&M	Operation and maintenance
PI	Profitability Index
PV	Photovoltaic
RES	Renewable Energy Sources
TEDSEE	Dissertação/ Estágio
UPAC	Production Units for Self-consumption
VAT	Value Added Tax

1 Introduction

This chapter presents an introductory framework, the motivation for developing this thesis, as well as its main objectives.

1.1 Context

The climate crises and global warming demand that we take decisive measures to decarbonize our social, economic, and environmental practices. Therefore, sustainability and deep decarbonization are the urgent goals for energy transition.

Renewable energies play a crucial role in achieving more sustainable and environmentally friendly energy generation. In Europe, there have been significant investments in clean energy sources, such as solar, wind and hydro, to reduce dependence on fossil fuels and reduce greenhouse gas emissions. In addition, governments initiatives have been encouraging the generation of renewable energy, promoting the installation of centralized solar and wind farms and the installation of smaller fields at residential and industrial level for self-consumption, as well as supporting research and innovation in this sector.

Nowadays, photovoltaic (PV) systems are seen as one of the main promising sources of renewable energy, making them play a very important role in decarbonization of the electricity generation system.

This dissertation presents a new approach to residential self-consumption. Currently, prosumers inject their surpluses into the grid and need a surplus sales contract to have that energy repaid. In the new approach, prosumers inject their surpluses into the grid with no charge and, when and if they need energy from the grid, they get it at a reduced price, paying only for the use of the grids since they continue to be used and its maintenance is extremely important.

Through the results from the case study, the best annual savings obtained by applying this new approach was €1 045.81, which represents a saving of 33% compared to the scenario where the new approach was not applied.

Whenever the new approach was applied, favorable savings to the customer have always been obtained. Therefore, this new approach helps promote the installation of production units for self-consumption, which will have a positive and significant impact on increasing the amount of energy produced from renewable sources.

1.2 Motivations

This work was developed for the satisfaction requirements of the curricular unit Dissertação/Estágio (TEDSEE).

The subject of the work was also the main motivation for this choice. Renewable energy generation at a residential level has become increasingly important and is expected to continue to grow. The new approach presented in this work brings a new solution to the surpluses produced, which could bring advantages to consumers, prosumers, for the grid and for the environment.

1.3 Objectives

The main objective of this work is to present a new approach to PV self-consumption at a residential level, focusing on the technical and commercial relationship between prosumers and the grid or the supplier entity. To this purpose, generation and consumption data will be evaluated, considering energy purchase and sale prices, in order to try to understand whether or not the approach presented can be technically and economically viable. Therefore, the effective research question can be formulated as "Is this new commercial relationship between the prosumer and the supplier entity viable?".

Briefly, the initial objectives proposed for this work are as follows:

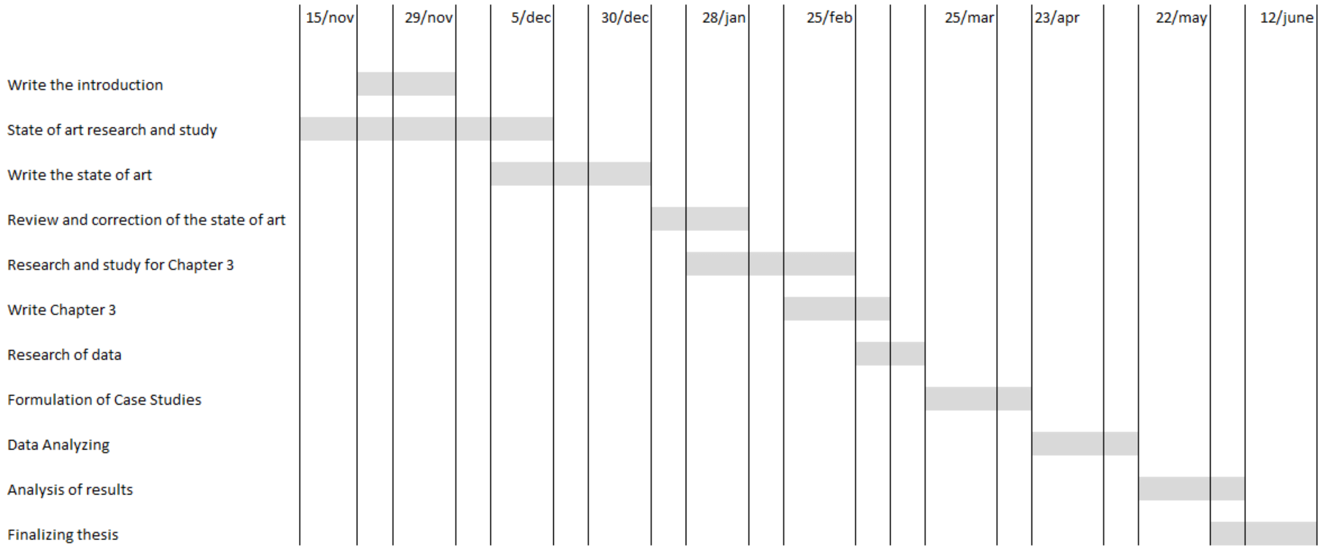
- Identify solar PV generation technologies;
- Identify current legislation on shared generation, self-consumption and electricity communities;
- Identify the current forms of commercial relationship between prosumer and network/suplier;
- Proposing new forms of technical relationship between prosumers and the grid/suplier;
- Computer simulation of case studies applied to the residential sector;

- Economic feasibility analysis.

1.4 Calendarization

The calendarization is presented in Table 1. In the first part of the work, is included the write of the introduction, state of art research and study, the write of state of art and the review and correction of the state of art. For the second part of the work, calendarization includes research, study and write chapter 3, research of data, formulation of case studies, data analyzing, and analysis of results. According to this table, this work will have a duration of seven months.

Table 1- Dissertation schedule



1.5 Document Organization

This thesis is composed of five main chapters, which are briefly described below.

- **Chapter 1: Introduction.**

Chapter 1 gives a brief contextualization of the theme that will be addressed in this dissertation. It also mentions its main objectives, the calendarization for the developed work and the organization of the document.

- **Chapter 2: State of the Art.**

  Chapter 2 presents the state of the art, that emphasizes how residential PV power generation can help to achieve net zero emissions and the technical challenges that it brings to the grid and how to reduce them.

- **Chapter 3: Photovoltaic generation**

Chapter 3 provides a more detailed description of the topic to be developed in this dissertation. It demonstrates the technologies used, all the necessary material in a PV system and all the relevant legislation in Europe and in Portugal for the installation of PV systems.

- **Chapter 4: Problem Statement**

Chapter 4 presents the problem and analyzes the data that has been obtained to develop the case study.

- **Chapter 5: Mathematical Formulation**

Chapter 5 provides all the mathematical formulation needed to develop the case study. It presents all the necessary equations for all the scenarios and sub-scenarios created to obtain the results and the comparison between the two principal scenarios.

- **Chapter 6: Case Study and Results**

In chapter 6, the scenarios and sub-scenarios created for the study are explained in detail and then the results obtained are presented, analyzed, discussed and compared with each other.

- **Chapter 7: Conclusions**

To conclude, chapter 7 presents the main conclusions reached with the development of the dissertation, as well as the main limitations encountered during the development of the work and some suggestions for future work, to develop the topic further.

2 State of the Art

This chapter’s main purpose is to present a review of the current state of the art within the scope of the role of residential PV power generation in the Net Zero targets, the technological challenges in grid integration of PV energy generation and how to reduce their impact.

2.1 Net Zero Strategy: The Role of Residential PV Power Generation

To combat the challenges of climate change and global warming, in 2016 the European Commission (EC) developed a strategy called Net-Zero Gas Emissions by 2050 which, as the name suggests, means eliminating greenhouse gas (GHG) emissions as much as possible. To achieve this target, the energy sector is of major significance since it is the source of around three quarters of GHG emissions from energy generation. Replacing energy generation from polluting sources such as gas and fossil fuels with renewable energy sources (RES) such as wind and solar energy would drastically reduce GHG emissions [1].

In 2021, the EC adopted a set of proposals to make the European Union's (EU) climate, energy, transport, and taxation policies suitable for reducing GHG emissions by at least 55% by 2030 compared to 1990 levels, making the process towards carbon neutrality [2,3].

In Portugal, with the aim of achieving carbon neutrality by 2050 and following the EU’s targets, the goals and objectives for 2030 are to incorporate 49% of energy from renewable sources into gross final energy consumption, increase energy efficiency by 35% and reduce GHG emissions by between 45 and 55% compared to 2005 [4-6].

Renewable energy systems, such as solar PV systems, offer a decentralized and sustainable source of energy at increasingly competitive costs [7]. In recent years, PV solar energy has been increasingly gaining importance and has become one of the most promising major sources of renewable energy. This is due to the modular, simple, and secure nature of the installations, which usually require low maintenance costs. In addition, the costs of PV technology have reduced substantially over the last few years and Portugal, given its extraordinary potential for harnessing solar energy, stands as a favorable environment for its utilization [8-12].

Due to the mentioned advantages, PV energy generation systems also favor decentralized energy generation since they can be applied in places where the availability of space is not as extensive as required for a large-scale generation plant. This means that solar PV energy generation systems can be implemented in residential, industrial, and commercial buildings, increasing self-consumption, and enabling the supply of energy to consumers with lower transportation costs and lower energy distribution losses [8]. With the increase in decentralized solar energy generation, there is also a rise in energy self-consumption. Consequently, with surplus generation, this energy can be injected into the grid. Therefore, the installation of PV panels allows consumers to produce energy to self-consumption in their homes but also to inject into the grid, transforming them into "prosumers" – a combination of producers and consumers.

Figure 1 presents a grid-connected photovoltaic residential system which consists in solar panels, an inverter, electricity meter, battery, and the distribution grid. In this case, photovoltaic energy can be used for self-consumption, to charge the battery storage and, when there are generation surpluses, they can be injected into the grid.

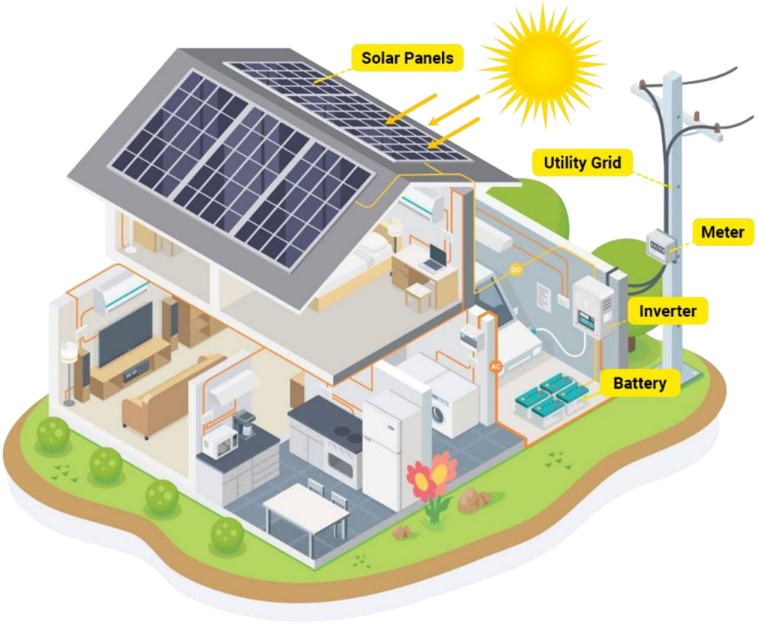


Figure 1- Grid Connected Photovoltaic Residential System [13]

The increase of decentralized solar energy generation will have a positive and fundamental effect on the energy transition. As the generation of renewable energy increases, dependence on fossil fuels is drastically reduced, promoting energy independence, and making this technology essential for meeting Portugal's 2030 goals [10, 14].

Figure 2 shows the total national energy generation from renewable sources from 2014 to 2023, considering that the data from 2023 only goes up to the end of October. It is possible to observe that renewable energy generation has increased year after year and that PV solar energy has increased substantially in the last few years [15].

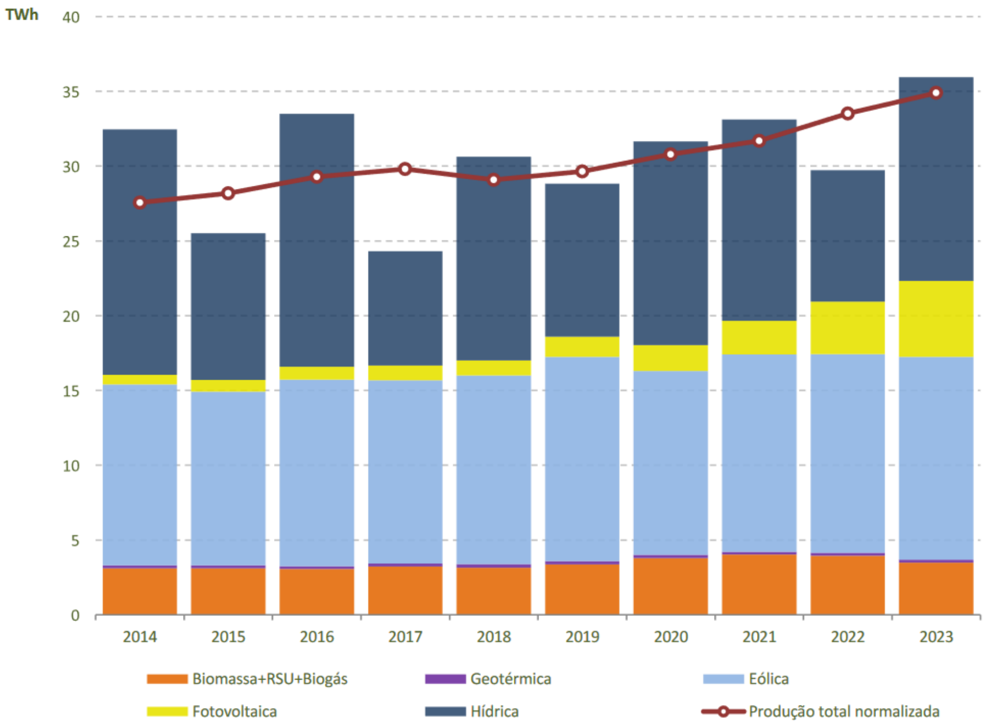


Figure 2- Evolution of renewable energy generation in Portugal [15]

Figure 3 shows the evolution of the incorporation of renewable energies in gross final energy consumption according to the targets to be achieved [16].

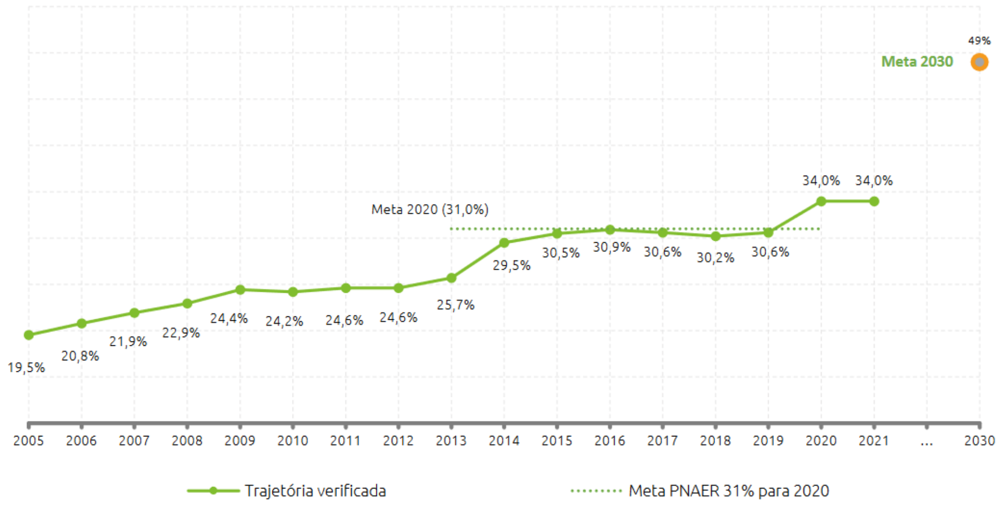


Figure 3- Evolution of the incorporation of renewable energy in gross final energy consumption [16]

2.2 Solar Energy Grid Integration Challenges

Despite all the technical, economic, and environmental advantages that solar PV energy brings, the technology also presents some challenges that need to be studied and resolved, as they might imply problems and changes in the present distribution grid.

As self-consumption increases, energy consumption from the grid decreases, which has positive effects, but also negative ones. In addition, there is a greater injection of energy from decentralized generation into the grid.

The decrease in grid consumption may lead, in the current scenario, to a lack of cost recovery for grids that ensure the maintenance and proper functioning of energy distribution and transmission networks. This is due to the fact that most energy tariffs are volumetric tariffs, where the price per unit of consumed energy remains the same regardless of the total energy consumed, and with lower consumption, there will consequently be a lower associated network cost. To address this challenge, dynamic tariffs will need to be adopted, where the price of energy varies depending on several variables [17]. Also for this reason, indexed tariffs already exist in Portugal and, since May 2024, energy suppliers with more than two hundred thousand customers have to offer to consumers with smart meters the possibility of contracting dynamic tariffs [18].

PV solar energy has another characteristic that sets it apart from conventional energy sources, as it is a form of energy with an intermittent nature. This means that energy generation is directly influenced by environmental factors, such as the time of day, the availability of sunlight, and weather conditions, causing energy generation to vary throughout the day and at different times of the year [19]. This characteristic presents a challenge for grid stability, since energy consumption does not follow the pattern of solar PV energy generation, causing power ramps due to the injection of surplus energy produced into the grid [7, 20, 21]. However, it is necessary to consider that, despite there being low residential consumption during peak PV generation hours, at the industrial and commercial levels, there is higher consumption during the same hours.

Although the weather is now predictable with some degree of accuracy, the grid still faces a significant challenge in responding quickly to the decrease in solar energy generation when the demand remains at the same level. Figure 4, referred to as the Net Load curve or duck curve, illustrates the difficulties the grid encounters in balancing and controlling a system with a high injection of PV energy [22] . As more PV energy is injected into the grid, the curves become increasingly pronounced. Subsequently, the moment the sun starts to set and energy generation declines, the curve shows abrupt changes, and the grid needs to compensate immediately as the available energy decreases. These changes in the curves helps to understand how the energy system becomes unstable [23].

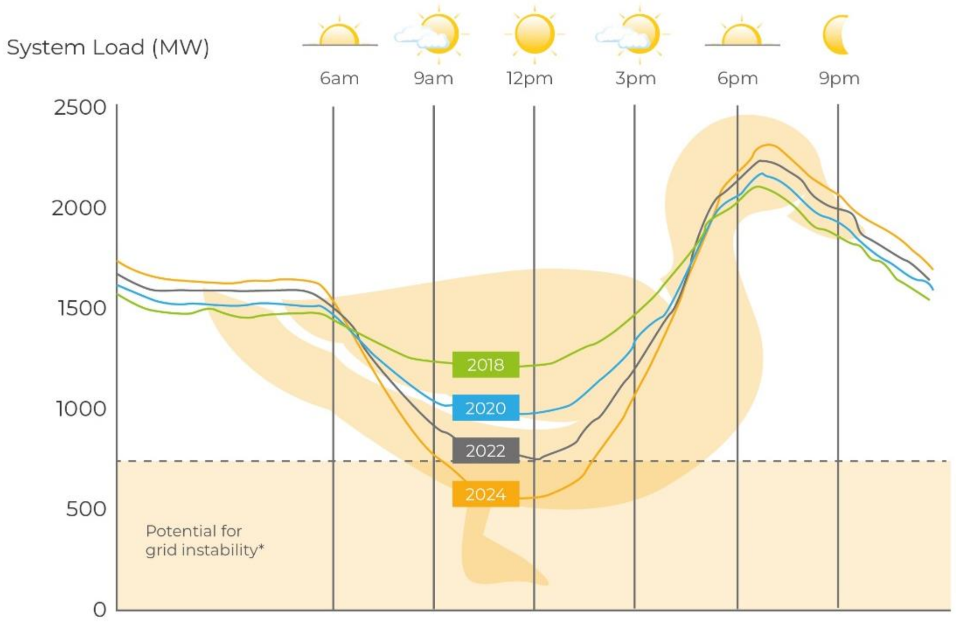


Figure 4– The Net Load curve or The Duck curve [23]

Figure 5 shows the PV solar energy generation curve compared to the consumption load diagram. You can see the negative relationship between peak energy generation hours and peak consumption hours, confirming that generation surpluses exist.

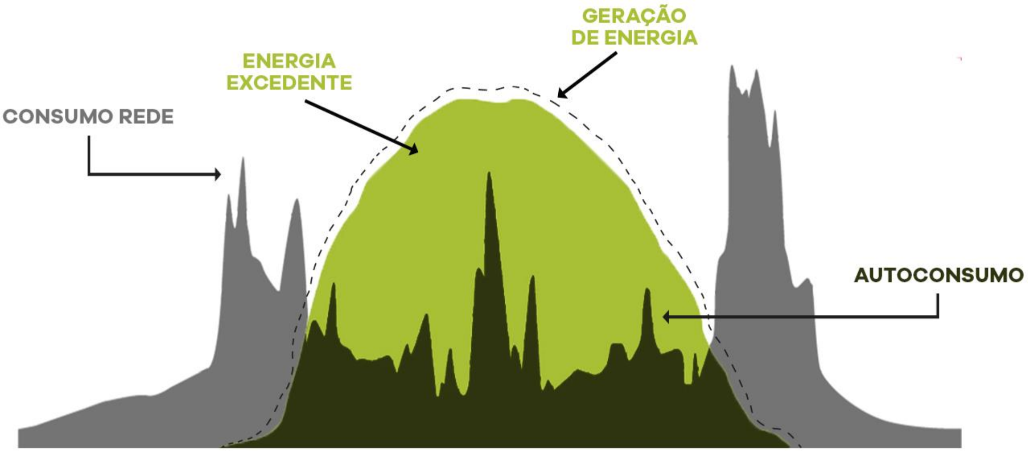


Figure 5- Photovoltaic solar energy generation curve compared to the consumption load diagram [24]

In addition to instability, the injection of PV energy into the grid can lead to overvoltage, overloads on lines and transformers and the inversion of the energy flow since the infrastructure of the distribution grid has only been dimensioned to deliver energy to the consumer and without bidirectional flow [17]. These issues, the fact that PV energy is intermittently produced, and the increase in its generation leading to an increase of the pre-existing network capacity, means that there are challenges in grid management [19, 25].

2.3 How to Reduce the Impact of Photovoltaic Energy Generation on the Grid

This daily and seasonal mismatch in generation and consumption must be considered when expanding PV energy generation in a decentralized manner [21]. The impact can be partially offset by load shifting, through demand side management, flexible charging of electric vehicles using vehicle-to-grid or vehicle-to-home, electricity storage or electrification of the transport sector [7, 21].

2.3.1 Batteries Energy Storage Systems

Throughout several studies, the authors have mentioned that it would be possible to reduce the amount of PV applied by using, for example, only the roofs with the higher efficiency for energy generation [21]. However, despite controlling sudden increases in energy on the grid, it doesn't control the decreases. Therefore, one of the ways to control and avoid the power ramp caused by PV variability is to use energy storage systems (ESS), such as batteries. Due to the intermittency and high variability of the energy source, careful analysis is required when designing the battery sizing strategy [20].

While, for some, the simultaneous investment on solar PV system and storage may not be significant and may not have a major impact on the choice of installation, for others the high investment may lead them not to opt for the application of storage batteries [7, 26]. Taking this into account, energy storage in batteries can also be more applied in large solar PV plants, providing flexibility in their operation and offering support to the grid. Nevertheless, due to the large scale of the investment, it is strictly necessary to ensure maximum use of the storage in the largest plants [20, 27].

Thus, batteries can be used with four control functions in mind: rest, surplus energy storage, backup energy support and charge maintenance functions [20]. It would be ideal for storage batteries to be able to maintain a load profile specified by the user (both for small generation units and large plants), allowing the storage of excess PV energy produced. This stored energy can be used either for consumption during periods of lower energy generation or to avoid further grid injection when it is already overloaded. At the same, batteries can provide support to the grid when necessary, mitigating the variability that solar energy causes in the grid [20, 27].

2.3.2 Electrical Vehicles

Currently, the transport sector remains unsustainable, with most vehicles still relying on fossil fuels, contributing significantly to GHG emissions. It is estimated that, by 2021, the transport sector was responsible for a quarter of GHG emissions in the EU [28]. However, it is noteworthy that electric vehicles (EV) have become increasingly popular in recent years and their demand and sales has grown increasingly.

Figure 6 illustrates the sales of EV from 2016 to 2023. Through the graph, it is evident that the sales of EV have significantly increased since 2020, with China leading in terms of the highest volume of purchased electric cars.

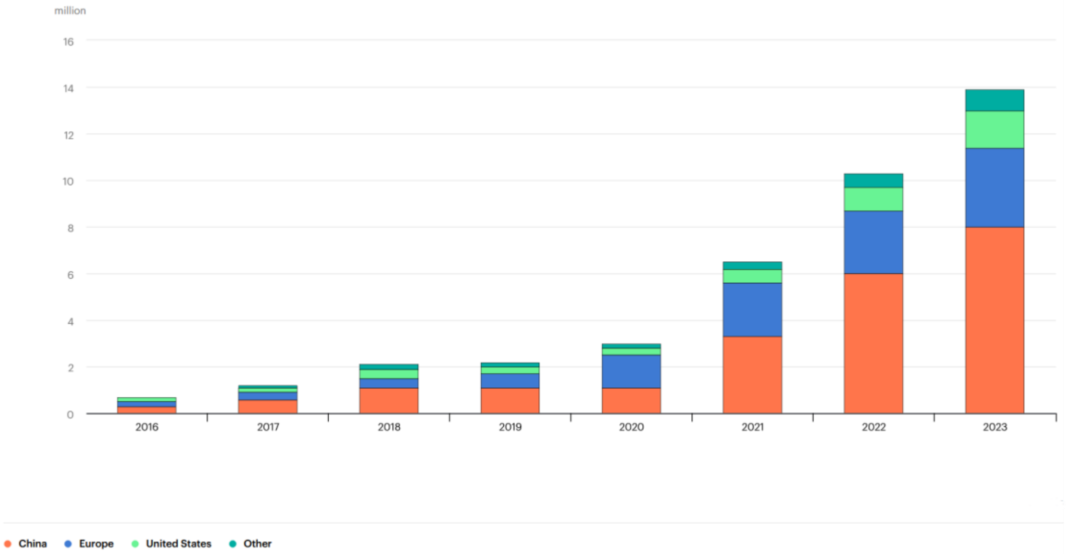


Figure 6- Car sales worldwide [29]

Increasing self-consumption at a residential level can help to maintain the grid more stable, since the injection into the grid is reduced, preventing it from becoming overloaded. One of the ways for this to happen is by improving the coordination between PV energy generation and household consumption. When there is no significant consumption during peak energy generation times, one of the solutions for increasing self-consumption has already been mentioned, which is the use of ESS, such as batteries. Another solution involves charging EV during peak energy generation periods [19].

Besides increasing self-consumption, through EV with large energy storage capacities, vehicle-to-grid and vehicle-to-home systems can be implemented. With the bidirectional use of energy, the car is being charged when there is more generation but, when necessary, it can also supply energy to the grid or to the home, respectively. With this solution, not only does it contribute to making energy generation more sustainable, but it also supports the decarbonization of the transportation sector [8].

2.3.3 Grid Management

A correct and effective network management makes and will make all the difference as the generation of solar PV energy increases. To achieve this, grid operators are and will have to progressively work to improve techniques and voltage control technologies in the grid, aiming to reduce power ramps that may occur.

Some of the strategies include the implementation of active grid congestion management by applying limits on the injection of solar energy into the grid and the introduction of dynamic operating envelopes (DOE) that can use smart inverters to actively monitor and control exports to the grid before it reaches its limits [7, 27]. In extreme cases of grid instability, emergency mechanisms should be introduced to reduce or stop the injection of solar PV energy until grid stability and security are re-established [27]. However, if these strategies are not implemented correctly, it could result in losses and in a reduction in energy generation, ultimately limiting the potential that PV solar energy has in environmental and technical-economic terms.

In Australia, the regulations require inverters to have power quality response modes that react to the voltage present on the grid, so that they have an automated response to ensure that the voltages on the grid remain within the limits specified. Additionally, inverters are required to temporarily stop working in extreme overvoltage situations on the grid [27].

Therefore, these systems enable real-time monitoring of generation, consumption and of energy in the distribution network, enabling grid operators to respond to energy fluctuations. By implementing proper network management, it is possible to increase the reliability of the grid, optimize energy flow and promote an effective and efficient use of the energy produced.

2.4 Conclusions

This chapter provides a literature review on the topic of this thesis. It presents the role that residential solar PV generation plays in achieving net zero GHG emissions and decarbonizing the electricity sector. The review also addresses some of the technical challenges associated with this technology and presents ways to minimize its impact on the grid and the systems it communicates with.

Increasingly, residential buildings incorporate energy resources such as PV energy generation, energy storage batteries and EV. The application of energy storage batteries, the increasing use of EV and an improved grid management system (GMS) are all strategies that will help solar PV energy generation in achieving the designated targets, both for Portugal and Europe.

Reducing the impact of the negative effects that PV energy generation has, will be even more important with the increase of injected energy into the grid, as it helps to increase energy generation from RES, making the energy sector increasingly sustainable.

3 Solar Photovoltaic Generation

3.1 Technology

In a solar Photovoltaic (PV) system, there are several important elements that guarantee its operation, efficiency, and safety. Solar panels are the main component of the system, but there are other equally important devices without which, energy generation would be impossible. In addition to the photovoltaic panels, an inverter, consumption meter, monitoring system, bidirectional meter in the case of installations with a rated power equal to or higher than 5kW, and batteries, if applicable, are also required [30, 31]. In the photovoltaic system, an Alternating Current (AC) and Direct Current (DC) switchboards for system protection, DC and AC connection wiring and structures to place the modules in the designated areas are also necessary.

In residential PV systems, the photovoltaic panels are typically located on rooftops, in strategic places to maximize solar exposure. All other electrical equipment is placed in easily accessible locations, where their performance is optimal and with care to minimize its visual impact. The photovoltaic installation is integrated into the existing electrical system so that the energy produced is consumed, thus reducing energy consumption from the grid.

Through Figure 7, you can observe the architecture of the residential PV system.

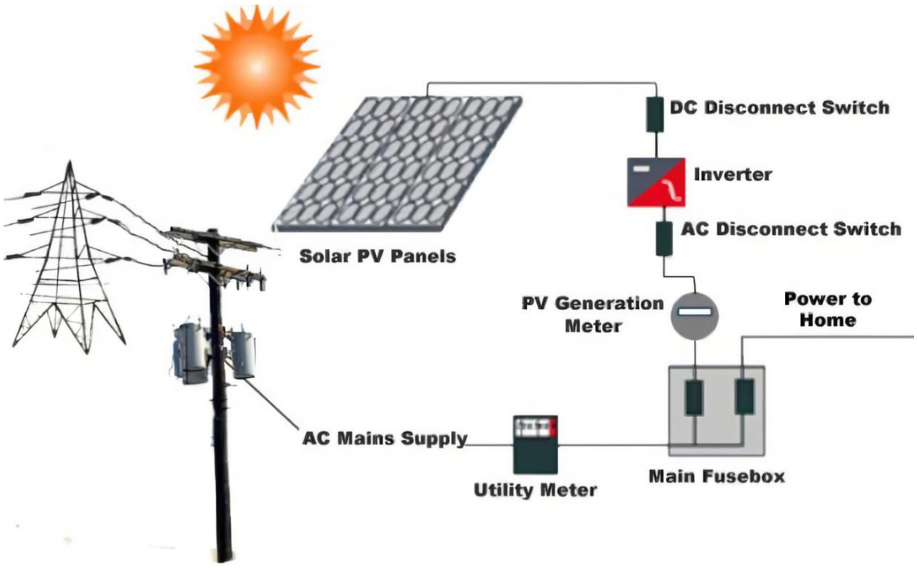


Figure 7- Residential photovoltaic system architecture [32]

3.1.1 Photovoltaic Panels

As mentioned previously, photovoltaic modules are the main component of the generation system, as they are where solar energy is converted into electrical energy. Each photovoltaic module is composed of photovoltaic cells where, through the photovoltaic effect, solar energy is transformed into electrical energy. In simple terms, the photovoltaic effect is a characteristic of certain materials, known as semiconductors, which allows them to produce electric current when exposed to solar radiation [33, 34].

When solar radiation strikes the photovoltaic modules, the sun's photons, absorbed by the photovoltaic cells, energize the electrons in the cells, causing them to enter in motion, causing them to free themselves from the semiconductor material [35, 36]. In photovoltaic cells, the semiconductor material most used is silicon, which is applied in two layers specially treated in different ways to create an electric field at the junction zone of the two layers. In these layers, besides silicon, there are two elements used as doping agents, phosphorus, and boron, to add more or fewer electrons, consequently giving a negative charge to one layer and a positive charge to the other, respectively [33, 34, 37]. The electric field formed by the difference in charges causes loose electrons to flow within the photovoltaic cell and move away from the junction zone, creating electric current. Through the metal plates on the sides of each photovoltaic cell, the electrons are forced to move to be transferred to the connecting wires [33].

In Figure 8, it’s possible to see the representation of the two layers of silicon, each with its charge where the creation of electric current occurs.

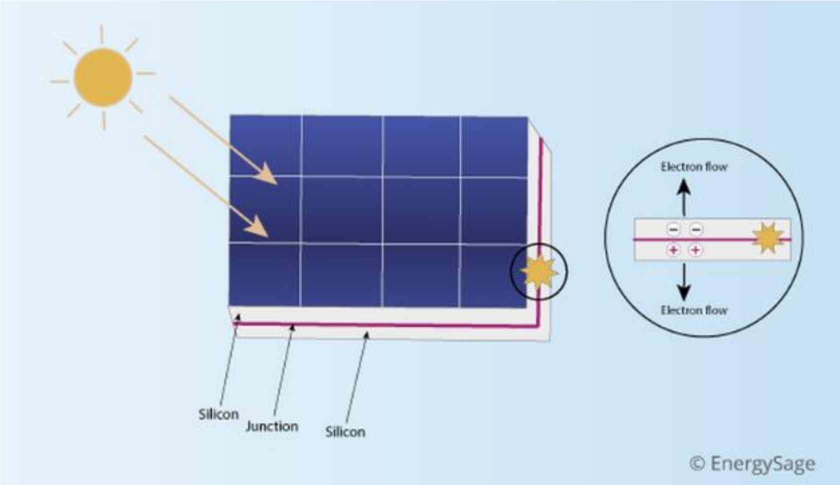


Figure 8– Representation of silicon layers of solar panels [33]

However, photovoltaic panels are not only composed of photovoltaic cells, they also contain other parts that are essential for their proper functioning: a glass enclosure, which provides durability and protection to the photovoltaic cells; a back insulation layer, which protects against heat dissipation and humidity inside the photovoltaic module, since increased temperature and humidity directly affect its efficiency; and an anti-reflective coating that provides better absorption of sunlight, giving the cells maximum exposure to the sun for maximum energy generation [33].

In the market for solar energy generation through photovoltaic systems, there are two main technologies used in the photovoltaic panels: monocrystalline and polycrystalline. As the name suggests, monocrystalline cells are made up of a single silicon crystal, while polycrystalline cells are made up of multiple silicon fragments [33, 36].

3.1.1.1 Monocrystalline Modules

Monocrystalline modules are manufactured from blocks or ingots of silicon that are cut into rounded sheets. Although a significant part of the material is discarded, this material has a high purity and, as the photovoltaic cells are composed of single crystal, electrons have more space to move, creating an electric current, resulting in a cell with high performance [38, 39].

When using monocrystalline panels in an installation, fewer panels are needed on the roof to produce the same power compared to polycrystalline panels [38, 40].

In addition to the efficiency advantage, they also have an extended lifespan since they have better resistance to heat. They are also very useful in places with limited sunlight exposure during the day, as they continue to offer better performance in low radiation conditions. However, since the manufacturing process is slower and more expensive, due to the use of silicon in a purer state and in greater quantities, this type of technology becomes more expensive [39].

Through Figure 9, we can observe that the efficiency of either type of module has been increasing over the years. However, it is also evident that monocrystalline panels have consistently outperformed polycrystalline ones.

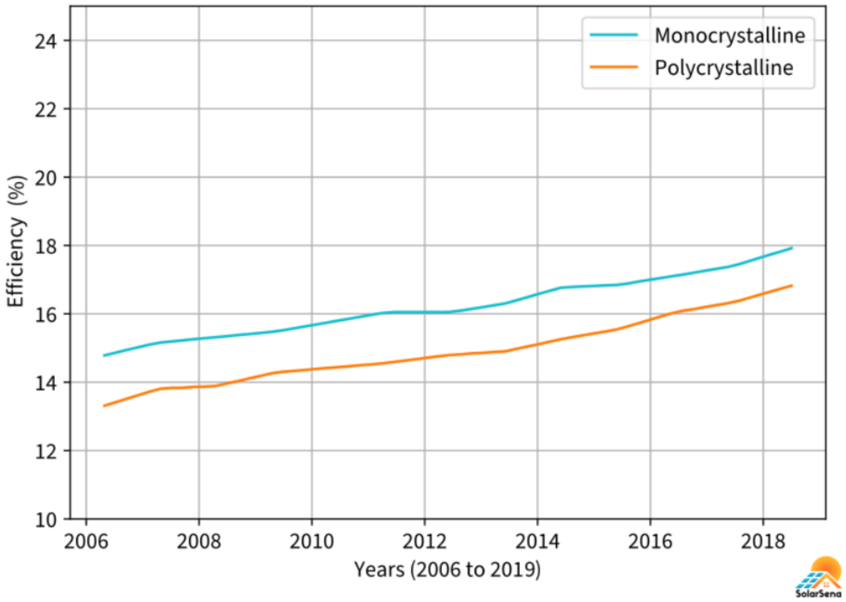


Figure 9– Efficiency of Solar Modules overtime [41]

3.1.1.2 Polycrystalline Modules

Polycrystalline modules are composed by multiple silicon fragments, manufactured quickly and cheaply by melting raw silicon blocks and then placing them in square molds. Despite the distinct manufacturing process, photovoltaic cells serve the same function, although they are less efficient because they contain impurities in their constitution. Additionally, having more crystals in each cell restricts the movement of electrons, resulting in less space for them to generate as much electrical current [38, 39]. This is also why polycrystalline panels have bluish tones, while monocrystalline modules have a darker color [39, 40].

Figure 10 shows the differences between the physical appearance of monocrystalline and polycrystalline photovoltaic modules.

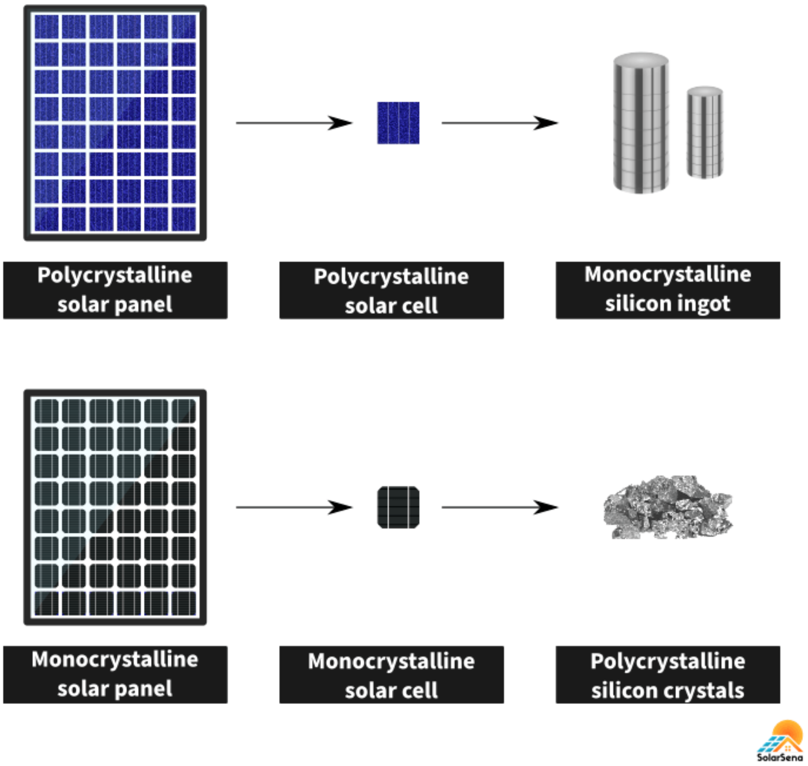


Figure 10– Differences between monocrystalline and polycrystalline photovoltaic modules [41]

3.1.2 Solar Inverters

Solar inverters are another essential component of any photovoltaic system. They convert the DC current produced by the panels into AC current so that it can be integrated into the existing electrical installations, since all the equipment operates on AC power [42, 43]. Although all solar inverters have the same purpose and operating principle, there are three different types of inverters: string inverters, microinverters and hybrid inverters.

3.1.2.1 String Inverters

In string inverters, a circuit of photovoltaic panels connected in series forms a string where the energy produced in each module flows through the solar cable that is connected to a single inverter, as illustrated in Figure 11. Each inverter can have multiple strings, depending on the number of strings and on the power of each inverter[43-45].

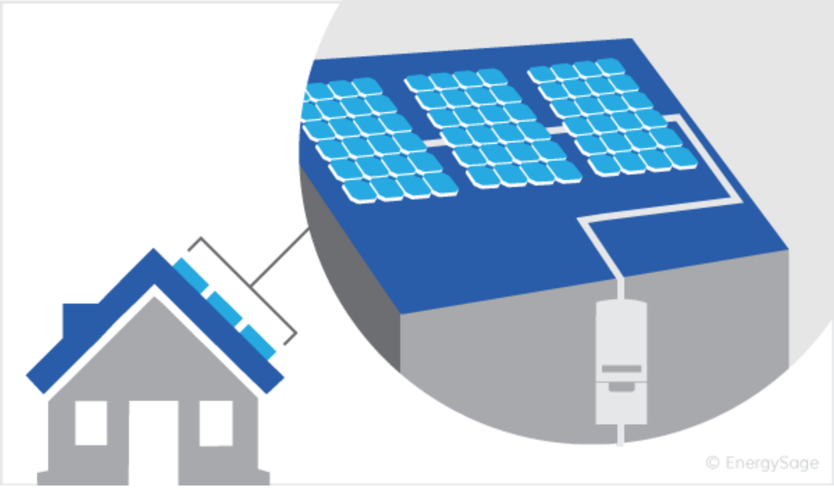


Figure 11- Graphic representation of the connection of photovoltaic panels to a string inverter [46]

In most photovoltaic systems, whether residential or not, this type of inverter is the most used, as it has good performance and durability at an affordable price. It can handle higher power capacities depending on its nominal power and has high efficiency ratings. In terms of installation, these inverters don't need to be as close as possible to the photovoltaic panels. However, it's important to consider that inverters require a direct connection to DC current, which is less safe compared to AC current due to the higher risk of associated fire hazards [42].

Despite being the most advantageous type of inverter, it can also be less efficient if one or more panels are shaded or if the panels are positioned in different directions in the same string. In a string, when a photovoltaic module produces less energy, the remaining photovoltaic panels in the same string will also produce energy at the same level and, consequently, generation will be lower than expected [43, 44, 47]. In Figure 12, it's possible to understand the explained phenomenon.

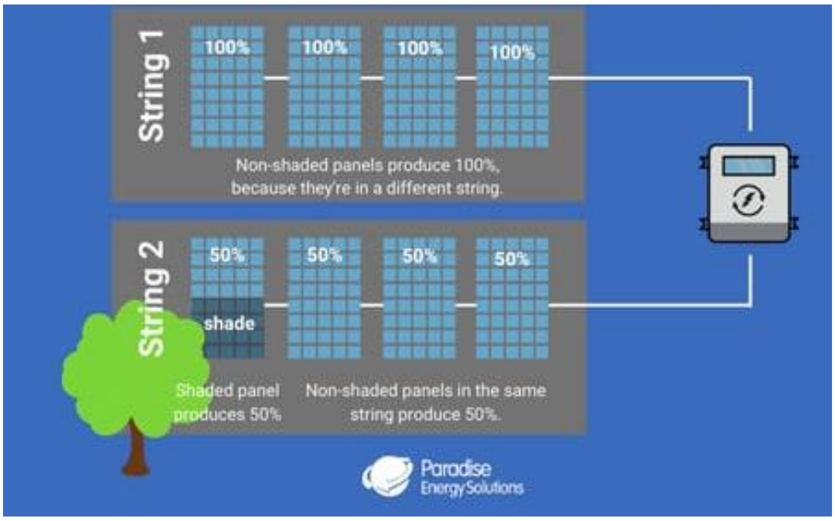


Figure 12- How a shaded panel affects the remaining string in a string inverter [47]

It’s possible to solve this problem by applying power optimizers to all or only some of the photovoltaic panels, in cases where it is possible to see which panels are in the most favorable conditions for lower generation. These power optimizers, whether integrated or located next to the panels, do not convert DC current to AC current, but condition the DC current by fixing the voltage that is sent to the central inverter. In this way, it is possible to make the inverter more efficient in scenarios where shading is likely or where the roof layout is complex and it’s not possible to install all the panels in the same direction [44].

3.1.2.2 Microinverters

If a string inverter can be considered a central inverter, microinverters can be considered distributed inverters, since they are applied next to the panels or integrated into them singularly or in small groups of panels (typically up to 4 photovoltaic panels). Therefore, a microinverter converts DC current to AC current at the level of the PV module, making the entire installation, apart from the panels themselves, operate on AC current, without the need for a central inverter [43, 44].

The use of microinverters optimizes energy generation in each individual panel, resulting in better energy yields, even in situations where power optimizers would be necessary [44, 45]. Furthermore, these types of inverters are capable of operating at lower currents, allowing them to function on days with reduced sunlight, as they are more sensitive and can produce more than string inverters, for example on cloudy days [42].

However, the application of microinverters in photovoltaic systems makes them more expensive compared to systems with string inverters, even when power optimizers are applied. Additionally, their maintenance becomes more complex since microinverters are harder to access [43].

Figure 13 provides an example of a microinverter placed next to the panel, as explained above.

Figure 13– Microinverter installed next to the photovoltaic module [48]

3.1.2.3 Hybrid Inverters

Hybrid inverters fit into both inverter technologies previously discussed. A hybrid solar inverter is designed for the installation of energy storage batteries. The hybrid inverter is prepared not only to convert the energy produced by the photovoltaic system from DC to AC, but also to receive AC energy from the grid and convert it into DC so that it can be stored for later consumption [43].

These inverters interact with the batteries through a DC coupling system, which means that both the batteries and the photovoltaic panels use the same inverter to store energy in DC current [45].

3.1.3 Monitoring System

Although the monitoring system is not mandatory in photovoltaic systems, it is an important component for monitoring the system's operation. The monitoring system tracks the amount of energy being produced to compare whether the photovoltaic system is producing the expected amount of energy or if, for some reason, it is producing less than expected. This makes it clearer and easier to understand when there is a problem or malfunction in the system, helping to ensure that the photovoltaic system remains efficient and that any technical problems are resolved quickly [49, 50].

In the photovoltaic systems market, most solar inverters already include monitoring system software that can be used from a website or an app that can be installed on any mobile device. The software, whether included in the inverter or not, needs to have internet access, either through Wi-Fi or WLAN, to share the collected data. However, as it is not a mandatory element in photovoltaic systems, there are some brands that do not include a monitoring system initially, and other components are required for this purpose [49, 51].

In the monitoring system, in addition to showing the amount of energy produced, it should also show consumption, both for the energy produced by the self-consumption system and for the energy consumed from the grid, and it should also show the energy being exported to the grid [49]. Through the different data obtained, the visualization system creates tables, graphs and images that simplify the understanding of the data to make it accessible for users. With this information, users can understand at what times of the day the photovoltaic system has its peak generation, allowing them to adapt their highest energy consumption during these periods, thereby maximizing the use of the solar energy produced [51, 52]. The information displayed on the monitoring system also makes it easier to guide decisions regarding maintenance, optimization, and expansion of the system. Furthermore, if an error occurs in the system, the user and the installer have access to the information needed to resolve the error [50].

Figure 14 shows an example of a monitoring system for a PV system in a mobile app, where it is possible to track the energy produced, the energy consumed, the energy stored in the batteries and the energy injected into the grid.

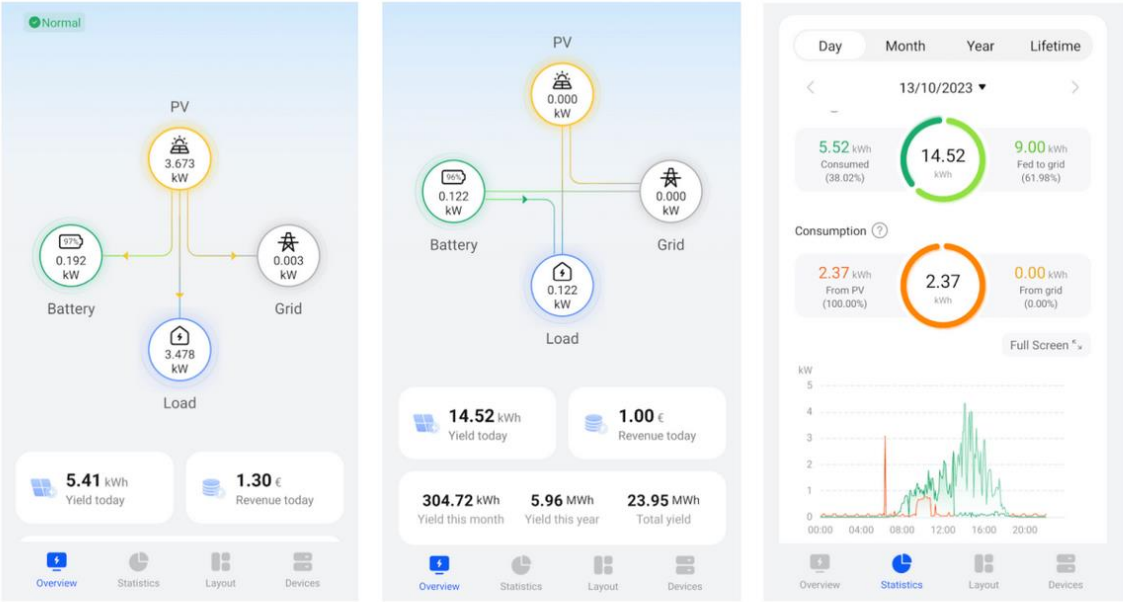


Figure 14- Monitoring system example [53]

For the monitoring system to function and display all the data needed to control the installation, it is necessary to install a consumption meter that will monitor all energy generation and consumption, both from the photovoltaic system and from the grid [49]. These consumption meters measure the total amount of energy consumed and produced continuously, and they can also detect energy surpluses at any time. These meters provide the cumulative data that will appear in the information provided by the monitoring system [52, 54].

3.1.4 Bi-directional Meters

As previously mentioned, meters are legally required whenever photovoltaic installations have a nominal power equal to or higher than 5kW. These meters are bi-directional meters, as they need to measure in two directions: the energy consumed from the grid and the energy injected into the grid when there are generation surpluses that are not stored [52]. These differ from traditional meters, as traditional meter only measure energy in one direction, allowing the grid operator to know the amount of energy consumed from it [54].

Currently, in most installations, both traditional and bi-directional meters are smart meters, which are more technologically advanced devices with digital and communication capabilities. Therefore, these meters allow electricity consumption and injection into the grid to be monitored in real time between the grid operator and the owner of the photovoltaic system[52, 55].

3.1.5 Batteries Energy Storage

When there’s a photovoltaic generation system, there may be times when there is surplus generation, in moments when energy generation exceeds electrical consumption. In this case, the owner has two options: inject the surplus generation into the grid and then obtain compensation for the energy consumed from the grid through a surplus sales contract, or have a system equipped with energy storage batteries [56-58]. But even with batteries for storing these surpluses, it can still happen that the batteries are fully charged, and generation continues to exceed consumption. In that case the surplus energy will continue to be injected into the grid [59].

By storing the surplus produced by the system in batteries, this energy can be consumed at times when photovoltaic generation is not as high or non-existent, reducing consumption from the grid. However, batteries are not just used to store surplus generation. The batteries can be charged from the grid at times when energy tariffs are cheaper, and then discharged for consumption at times when energy tariffs are higher [56].

Energy is produced in DC current and for consumption it needs to be converted into AC current. However, when charging batteries, it may not have to go through the conversion process. This is because batteries can operate on AC or DC current, but most commonly on DC current. In typical systems, the energy produced by the panels flows directly to the battery, where it charges it and is then converted into AC current so that it can be integrated into the existing electrical system. In the case of batteries that operate on AC current, the energy is converted into AC by the inverter and then flows to the battery to charge it, already in the correct type of current to be integrated into the electrical system [59].

Despite the advantages that storage batteries bring to the system and the fact that they are not a mandatory element, some owners of photovoltaic systems decide not to install them. Either because their needs aren't as high, because of the high cost of batteries, or because a good surplus sales contract will compensate for the investment needed to buy storage batteries.

3.2 Legislation

The legislation on self-consumption of photovoltaic solar energy generation has been keeping pace with the technological development of the systems and has been following the growing awareness of the importance of renewable energies in the energy sector. In Portugal, this development has been particularly notable over the past few years.

Until 2019, the legal frameworks for self-consumption of solar photovoltaic energy in Portugal were quite restrictive and unspecific, which limited their adoption by consumers. However, with the development of the technologies involved, the greater demand for renewable energy sources and the decreasing cost of technologies making them more accessible, legislation has begun to meet needs and, consequently, simplify access to energy generation and self-consumption.

In 2014, Decree Law no. 153/2024, of October 20th, was published, which, for the first time, created legal frameworks applicable to the generation of electricity for self-consumption in the installations associated with the respective generation units using renewable or non-renewable sources, and also for the sale of the entire electricity generation to the public service electricity grid, through small generation units, using renewable resources [60].

In 2018, Directive (EU) 2018/2001 of the European Parliament and of the Council of December 11, reformulated the previous Directive 2009/28/EC, which established the legal framework for promoting the use of renewable energy sources, setting national targets for energy consumption and in the transport sector to be achieved by 2020. Considering the Paris Agreement and the cost reduction in renewable energy technologies at the time, the European Parliament understood that the European Union should be more ambitious. Thus, in the new Directive published in 2018, new targets were considered, proposing to reach at least 32% renewable energy by 2030. However, it was stipulated that the targets should be reviewed in case of reductions in the cost of renewable energy generation or the European Union's international commitments regarding decarbonization or in the event of a significant reduction in energy consumption in the European Union. Therefore, the Directive establishes rules on financial support for electricity from renewable sources and for self-consumption of this electricity [61].

As previously mentioned, in Portugal, self-consumption gained greater attention in 2019 when Decree-Law No. 162/2019 was published, which introduced essential legal changes to electricity generation and self-consumption. The Decree-Law reduced existing legal obstacles and aimed to promote and simplify access to energy self-consumption, while also introducing renewable energy communities, as decentralized energy generation from renewable sources began to receive more attention [30].

Currently, the generation of electricity through Generation Units for Self-Consumption (UPAC) is regulated by Decree-Law no. 15/2022, of January 14, which establishes rules for the generation activity associated with installations used by self-consumers of renewable energy and establishes renewable energy communities (RECs). This Decree-Law also defines the conditions for access and start to the activity, which are summarized in Table 2 [62-64].

Table 2- Conditions for access to energy generation [63]

Installed Capacity	Access Conditions (with or without surplus injection)
≤ 700 W	Exempt from prior control (without injecting surpluses into the Public Service Electricity Grid)
> 700 ≤ 30kW	Prior Notice Required
> 30kW ≤ 1MW	Prior registration and operating certificate required
≥ 1MW	Generation license and operating license required

Through Decree-Law no. 84/2022, of December 9, the targets for 2030 were updated considering the background at the time in relation to the development of renewable energy generation technology. Thus, the share of energy from renewable sources in the gross final energy consumption and the minimum share of energy from renewable sources in the final energy consumption in the transport sector in 2030 are now set to be equal to or greater than 49% and 29%, respectively. These targets replace the previously defined 47% and 20% set through Council of Ministers Resolution no. 53/2020, of July 10 [65, 66]. This Council of Ministers resolution is still in place, since it approved the National Energy and Climate Plan 2030 (NECP2030), which is still in effect, despite some changes made through new Decree-Laws, as mentioned earlier [66].

In 2024, Dispatch No. 1170/2024, of January 31st, was published, establishing the conditions for exemption from the charges corresponding to the Costs of General Economic Interest (CGIEs) that apply to the access tariffs to the networks determined by Energy Services Regulatory Authority (ERSE), to be applied to self-consumption transmitted through the public service electricity grid. This is yet another measure to promote individual and collective self-consumption, to create conditions that encourage the development of self-consumption projects [67].

The legal development regarding photovoltaic solar energy self-consumption at both national and European level demonstrates the European Union's and Portugal's commitment to achieving the defined targets for carbon neutrality, as well as their commitment to technological advances in the energy sector, essentially in the generation of energy from renewable sources.

3.3 Conclusions

This chapter presented a more detailed description of photovoltaic systems. All the technologies used, and all the components required in PV systems are presented, as well as the relevant legislation in Portugal and Europe over the last few years.

Although the main component of a PV generation system are the solar panels, there are several other components without which the installation would not work. In this chapter, these are presented, and it is possible to understand that the technology is effectively modular, simple and safe. Furthermore, given the different options on the market for all preferences and budgets, it is possible to install an energy generation system to suit each customer.

As attention to the environment has grown due to the climate crisis and global warming, and as well as technological development, legislation has needed to be revised in order to keep up with environmental and technological needs. It is therefore possible to see that, in recent years, legal developments in Europe and Portugal have demonstrated the commitment that both have to technological development and to achieving the defined targets set for carbon neutrality.

4 Problem Statement

This chapter describes the problem and analyzes the data that has been obtained to simulate energy billing and the economic savings that can be achieved by simulating the implementation of the new approach to how surpluses injected into the grid are repaid.

4.1 Case Study: New approach to PV self-consumption

In this case study, it’s intended to apply a new approach to the self-consumption of energy produced by residential photovoltaic systems. Currently, the surplus energy produced by photovoltaic systems can be delivered free to the electricity grid or can be sold to the grid through an energy surplus sales contract. From January 1st, 2023, legislation has defined new rules for the sale of self-consumption surplus, requiring the self-consumer to open an activity with the tax authority and enter a contract with a company that buys the surplus electricity [68, 69].

With the case study in practice, the surpluses produced continue to be injected into the grid, making it function as an energy storage battery. Subsequently, when the consumer needs energy from the grid, they will have the same amount of energy they injected, available at a reduced price, defined as subsidized tariff, which will only reflect the tariff for access to the grid, since the electricity grid is being used and its maintenance is extremely important.

4.2 Database

The data used in this work was obtained from Huawei's FusionSolar monitoring system, where it is possible to check all the photovoltaic system's generation data, consumption, both photovoltaic system and of the energy consumed from the grid, and also the amount of energy injected into the grid. All the values obtained on the platform are hourly, but Huawei's consumption measurement systems obtain their values every 5 minutes, based on an average of the last 5 minutes of measured values. Therefore, the values obtained through FusionSolar and used for the simulation may not correspond exactly to reality.

The residential photovoltaic system, applied to a house in the city of Maia with an installed and contracted power of 20.7kVA, is a 12kW installation made up of 22 photovoltaic modules placed in 3 different directions (South, East, West) and a Huawei inverter with 10 kW of power. Figure 15 shows the simulation of the implementation of the photovoltaic system using the Helioscope software.

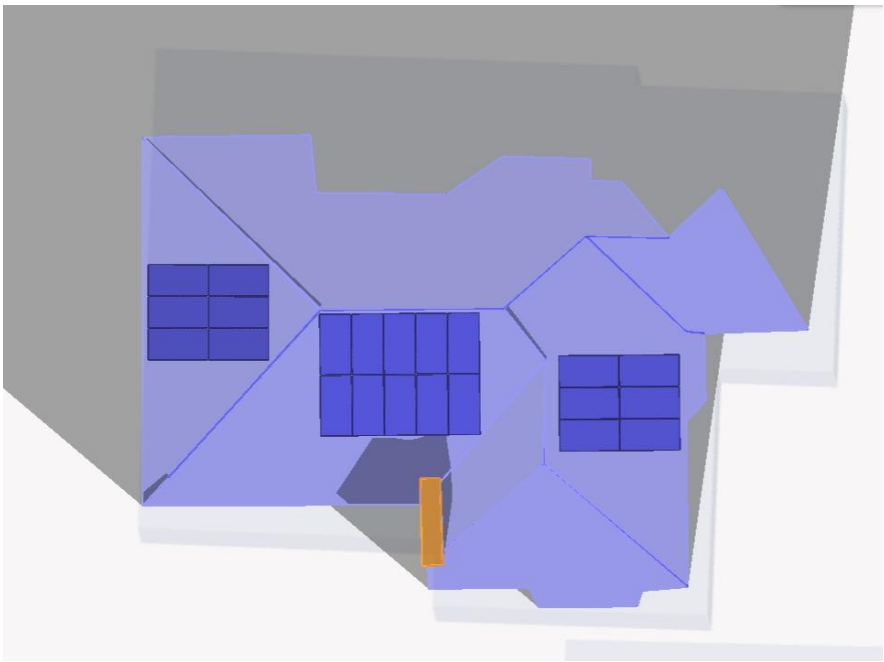


Figure 15- Simulation of the implementation of the photovoltaic system used as an example

The data was taken from a week in April 2024 (from the 6th to the 13th), where part of the week had good conditions for producing solar energy. As such, this week was considered a typical week to be extrapolated to annual values, so that it would be possible to evaluate the results in an annual time frame. Table 3 shows the total energy produced per day during the days used for the simulation. The values obtained on an hourly basis, per day, can be found in Appendix A. Figure 16 and Figure 17 show graphs where you can see the energy produced by the photovoltaic system and the consumption from the existing generation in the house. The best and worst generation days were chosen, respectively.

Table 3- Total generation of the residential photovoltaic system used as an example, per day

Day	Total Energy generation (kWh)
06/04/2024	28.37
07/04/2024	53.44
08/04/2024	49
09/04/2024	70.97
10/04/2024	65.6
11/04/2024	67.46
12/04/2024	67.45
13/04/2024	65.63

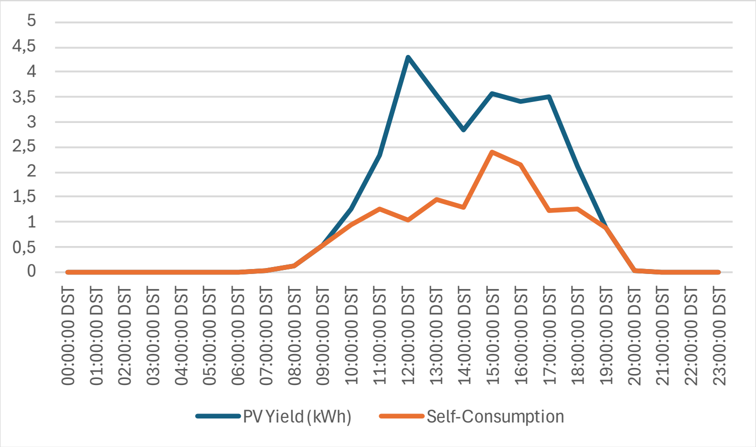


Figure 16- PV Generation and self-consumption per hour, on 06/04/2024

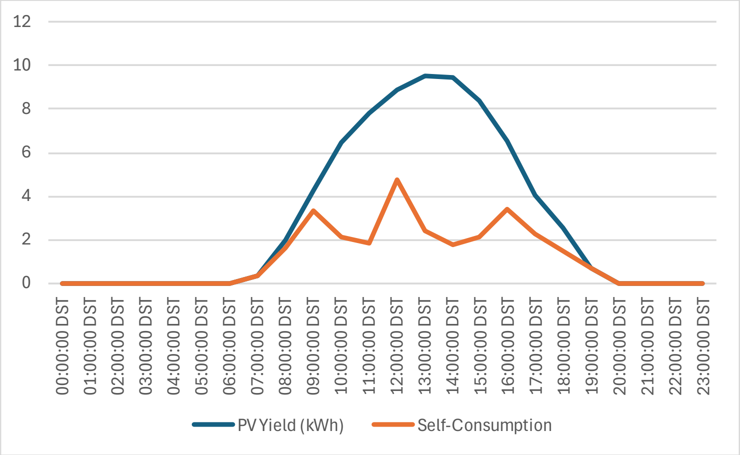


Figure 17- PV Generation and self-consumption per hour, on 09/04/2024

4.3 Data Pre-processing phase

To carry out the study and analyze the data, all the data obtained from the Huawei FusionSolar platform was put into Excel in chronological order and data that was not necessary for the study was removed.

New columns were added, with values calculated using those obtained from the monitoring system, so that it was easier to see how much energy was totally consumed, how much came from photovoltaic generation and how much came from the grid. Columns were also added where the type of period for each hour was identified, considering the flat, bi-hourly and tri-hourly tariffs in a daily cycle in the summer period, as well as the price of energy per kWh in these periods.

For the energy prices for each period, the continental region, the summer period and the daily cycle were considered. Since some hourly tariffs change at 30 minutes, the tariffs considered at that time were the cheapest, since this is the most unfavorable case for the customer, since the savings, if a subsidized tariff is applied, are lower. The values for each tariff were obtained by considering the indicative prices for energy tariffs indicated by ERSE in the report "Tariffs and Prices for Electricity and Other Services in 2024"[70]. The tariffs used in the simulation only consider the cost of energy per kwh, and do not include grid access tariffs or taxes associated with energy consumption. Table 4 and Table 5 shows the daily cycle of tri-hourly tariff in the summer period and the hourly tariffs and the prices per kWh charged, respectively.

Table 4- Daily Cycle of Tri-Hourly Tariff in the Summer Period [71]

Summer Period Hours		
Off-peak hours	**Mid-peak hours**	**Peak hours**
06h00 to 08h00 22h00 to 02h00	08h00 to 10h30 13h00 to 19h30 21h00 to 22h00	10h30 to 13h00 19h30 to 21h00

Table 5- Energy Tariff Prices used in the simulation [70]

Tariff	**Peak**	**Mid-peak**	**Off-peak**
Flat	0.122 €/kWh		
Bi-hourly	0.1302 €/kWh		0.1071 €/kWh
Tri-hourly	0.1360 €/kWh	0.1280 €/kWh	0.1071 €/kWh

During the simulation, the price applied when the tariff is subsidized was chosen to be 0.0365€/kWh, reflecting the price currently applied in Portugal before the update on June 1st for access to low voltage (LV) grid in the case of flat tariffs, since, as explained above, the subsidized tariff only takes this factor into account.

4.4 Conclusions

In this chapter, the problem description was presented. First, the case study and how it will function is explained. Being a new approach, it was necessary to define how it would be applied and how the data would be prepared.

Then, the development of the database necessary to carry out the case study is explained. Details about the residential photovoltaic system used as the basis for the study are presented, as well as an explanation of how the data were obtained and which data were used. The residential photovoltaic system is a real UPAC with 12kW located in the city of Maia.

Finally, it was explained how de data was pre-processed. It details how the database was developed using the data obtained from the photovoltaic monitoring system and was specified what values were used for normal energy tariffs and subsidized tariff.

5 Mathematical Formulation

5.1 Database

As stated in the previous subchapter, in order to make it clear in the database how much energy is totally consumed in the house under study and how much of the energy consumed comes from the photovoltaic system's generation and how much comes from the grid, the following mathematical expressions (1), (2) and (3) were needed, calculated for the 24 hours of each day, respectively.

$$Total_{Consumption} = PV_{Yiedl} + Imported_{Energy} \quad (1)$$

$$PV_{Consumption} = PV_{Yield} - Exported_{Energy} \quad (2)$$

$$Grid_{Consumption} = Total_{Consumption} - PV_{Consumtion} \quad (3)$$

5.2 Notation

During mathematical development, various nomenclatures were developed. To make it easier to understand, the nomenclatures used are shown in Table 6.

Table 6- Presentation of each nomenclature developed

Parameter	Description	Index
i	Bi-hourly Tariff periods	i ϵ I
j	Tri-hourly Tariff periods	j ϵ J

k	Number of periods, except period 0	k ϵ K
z	Number of days, except day 6	z ϵ Z
y	Number of years of project lifespan	y ϵ Y
$\text{Energy Cost (€)}_{sample\ week}$	Energy Cost in the sample week	
$Energy\ Cost\ (€)_{year}$	Energy Cost in one year	
$\text{Energy Cost (€)}_{\text{period 0}}$	Energy Cost in period 0	
$\text{Energy Cost (€)}_{period\ k}$	Energy Cost in period k	
$\text{Energy Cost (€)}_{\text{day 6}}$	Energy Cost in day 6	
$\text{Energy Cost (€)}_{day\ z}$	Energy Cost in day z	
$Grid_{Consumption}$	Quantity of energy consumed from the grid	
$Grid_{Consumption\ \mathrm{i}}$	Quantity of energy consumed from the grid in period i	
$Grid_{Consumption\ j}$	Quantity of energy consumed from the grid in period j	
$Grid_{Consumption\ k}$	Quantity of energy consumed from the grid in period k	
$Grid_{Consumption\ z}$	Quantity of energy consumed from the grid in day z	
$Grid_{Consumption\ Off-Peak\ z}$	Quantity of energy consumed from the grid in Off-peak in day z	
$Grid_{Consumption\ Peak\ z}$	Quantity of energy consumed from the grid in Peak in day z	
$Grid_{Consumption\ Mid-peak\ z}$	Quantity of energy consumed from the grid in Mid-peak in day z	
$Grid_{Consumption\ ki}$	Quantity of energy consumed from the grid in bi-hourly periods in period k	
$Grid_{Consumption\ kj}$	Quantity of energy consumed from the grid in tri-hourly periods in period k	
$Flat\ Tariff_{per\ hour}$	Flat Tariff cost per hour	
$Tariff_{\ per\ hour\ \mathrm{i}}$	Tariff cost for period i	
$Tariff_{per\ hour\ j}$	Tariff cost for period j	
$Tariff_{Subsidized\ per\ hour}$	Subsidized tariff cost	
$Tariff_{Off-peak\ hours}$	Tariff cost for Off-peak hours	
$Tariff_{peak\ hours}$	Tariff cost for Peak hours	
$Tariff_{Mid-peak\ hours}$	Tariff cost for Mid-peak hours	
$Exported_{energy\ k-1}$	Exported Energy in Period k-1	
$Exported_{Energy\ z-1}$	Exported Energy in day z-1	

5.3 Scenario 1

Using equations (4), (6) and (7), it is possible to obtain the energy price for the entire week used as an example and, using equation (5), the result for the example week is extrapolated to obtain the result for one year, in all scenarios.

5.3.1 Scenario a

$$\text{Energy Cost }(€)_{sample\ week} = \sum(Grid_{Consumption} * Flat\ Tariff_{per\ hour}) \tag{4}$$

$$Energy\ Cost\ (€)_{year} = 52 * Energy\ Cost\ (€)_{week\ sample} \tag{5}$$

5.3.2 Scenario b

$$\text{Energy Cost }(€)_{sample\ week} = \sum_{i}(Grid_{Consumption\ \mathrm{i}} * Tariff_{\ per\ hour\ \mathrm{i}}) \tag{6}$$

,where i ϵ I={off-peak, peak} hours

5.3.3 Scenario c

$$\text{Energy Cost }(€)_{sample\ week} = \sum_{j}(Grid_{Consumption\ j} * Tariff_{per\ hour\ j}) \tag{7}$$

,where j ϵ J={off-peak, mid-peak, peak} hours

5.4 Scenario 2

5.4.1 Scenario a

5.4.1.1 Scenario a.1

On day 1, there is no injected energy that can be accounted for when applying the case study, so for this period, indicated as period 0, the equation required is (8) but it is used for period 0 only.

$$\text{Energy Cost (€)}_{\text{period 0}} = \sum (Grid_{Consumption} * Flat\ Tariff_{per\ hour}) \tag{8}$$

From period 1 to period 8, the equations that can be applied are (9) and (10), depending on two constraints. If, in a certain day, total consumption is bigger than exported energy, the equation that is applied is (9). But if exported energy is bigger than total consumption, the equation that is applied is (10). With equation (11) is obtained the value for the whole week used as an example for the study.

$$\begin{aligned}\text{Energy Cost (€)}_{period\ k} &= Exported_{energy\ k-1} * Tariff_{Subsidized\ per\ hour} \\ &+ \left(Grid_{Consumption\ k} - Exported_{Energy\ k-1}\right) \\ &* Flat\ tariff_{per\ hour}\end{aligned} \tag{9}$$

$$\text{Energy Cost (€)}_{period\ k} = Grid_{Consumption\ k} * Tariff_{Subsidized\ per\ hour} \tag{10}$$

$$\begin{aligned}\text{Energy Cost (€)}_{week\ sample} \\ = \sum_{k} (Energy\ Cost(€)_{period\ k}) + Energy\ Cost(€)_{period\ 0}\end{aligned} \tag{11}$$

,where k ϵ K={1,2,3,4,5,6,7,8} periods

To extrapolate the value obtained for the example week into an annual value, equation (5), presented above, is applied.

5.4.1.2 Scenario a.2

Similar to what happens at the beginning of scenario a.1, the equation used to calculate the energy price for the 1st day is different from the one to calculate the prices on the remaining days, being equation (12).

$$\text{Energy Cost (€)}_{\text{day 6}} = \sum (Grid_{Consumption} * Flat\ Tariff_{per\ hour}) \tag{12}$$

For the following days, the equation used to obtain the cost of energy per day is (13).

$$\begin{aligned}\text{Energy Cost (€)}_{day\ z} &= Exported_{Energy\ z-1} * Tariff_{Subsidized\ per\ hour} \\ &+ \left(Grid_{Consumption\ z} - Exported_{Energy\ z-1}\right) \\ &* Flat\ Tariff_{per\ hour}\end{aligned} \tag{13}$$

$$\begin{aligned}\text{Energy Cost (€)}_{week\ sample} \\ = \sum_{k} (Energy\ Cost\ (€)_{period\ k}) + Energy\ Cost\ (€)_{period\ 0}\end{aligned} \tag{14}$$

,where z ϵ Z={7,8,9,10,11,12,13} days

As with the previous scenario, equation (5) is used to extrapolate the value obtained in the example week to the annual value.

5.4.2 Scenario b

5.4.2.1 Scenario b.1

For period 0, as there is no injected energy that can be accounted, the equation required is (15) but it is used for period 0 only.

$$\text{Energy Cost (€)}_{\text{period 0}} = \sum_i (Grid_{Consumption\ i} * Tariff_{per\ hour\ i}) \tag{15}$$

From period 1 to period 8, the equations applied are (16) and (17), depending on two constraints. If, in a certain day, total consumption is bigger than exported energy, the equation that is applied is (16). But if exported energy is bigger than total consumption, the equation that is applied is (17). With equation (18) is obtained the value for the whole week.

$$\begin{aligned}\text{Energy Cost (€)}_{period\ k} & \\ &= Exported_{energy\ k-1} * Tariff_{Subsidized\ per\ hour} \\ &+ \sum_i \big((Grid_{Consumption\ ki} - Exported_{Energy\ k-1}\big) \\ &* Tariff_{per\ hour\ i})\end{aligned} \tag{16}$$

$$\text{Energy Cost (€)}_{period\ k} = Grid_{Consumption\ k} * Tariff_{Subsidized\ per\ hour} \tag{17}$$

$$\begin{aligned}\text{Energy Cost (€)}_{week\ sample} & \\ &= \sum_k (Energy\ Cost\ (€)_{period\ k}) + Energy\ Cost\ (€)_{period\ 0}\end{aligned} \tag{18}$$

,where k ϵ K={1,2,3,4,5,6,7,8} periods and i ϵ I={off-peak, peak} hours

To extrapolate the value obtained for the example week into an annual value, equation (5), presented above, is applied.

5.4.2.2 Scenario b.2

On day 1, the equation is different from the others. In this scenario, the equation for the cost of energy on day 6 is shown in (19).

$$\text{Energy Cost (€)}_{day6} = \sum_i Grid_{Consumption\ i} * Tariff_{per\ hour\ i} \tag{19}$$

,where i ϵ I={off-peak, peak} hours

For the following days, the equations that can be applied are (20), (21) or (22), depending on two conditions and then two hypotheses.

If, per day, the energy consumed in off-peak is higher than the energy injected, the equation to be used is (20). However, if the energy injected is higher than the energy consumed in off-peak, two hypotheses arise. The 1st hypothesis is shown in (21) and the 2nd hypothesis is shown in (22).

$$\begin{aligned}\text{Energy Cost (€)}_{Day\ z} &= Grid_{Consumption\ Off-Peak\ z} * Tariff_{Off-peak\ hours} \\ &+ Exported_{Energy\ z-1} * Tariff_{Subsidized\ per\ hour} \\ &+ (Grid_{Consumption\ peak\ z} - Exported_{Energy\ z-1}) \\ &* Tariff_{peak\ hours}\end{aligned} \tag{20}$$

$$\begin{aligned}\text{Energy Cost (€)}_{Day\ z} &= Grid_{Consumption\ Peak\ z} * Tariff_{Subsidized\ per\ hour} \\ &+ \left(Exported_{Energy\ z-1} - Grid_{Consumption\ Peak\ z}\right) \\ &* Tariff_{Subsidized\ per\ hour} \\ &+ \Big(Grid_{Consumption\ Off-Peak\ z} \\ &- \left(Exported_{Energy\ z-1} - Grid_{Consumption\ Peak\ z}\right)\Big) \\ &* Tariff_{Off-peak\ hours}\end{aligned} \tag{21}$$

$$\begin{aligned}\text{Energy Cost (€)}_{Day\ z} &= Grid_{Consumption\ Peak\ z} * Tariff_{Subsidized\ per\ hour} \\ &+ Grid_{Consumption\ Off-peak\ z} * Tariff_{Off-peak\ hours}\end{aligned} \tag{22}$$

$$\text{Energy Cost (€)}_{week\ sample} = \sum_{z} (Energy\ Cost\ (€)\ _{day\ z}) + Energy\ Cost\ (€)_{day6} \tag{23}$$

,where z ϵ Z={7,8,9,10,11,12,13} days

Equation (5) is still used to extrapolate the value obtained in the example week to the annual value.

5.4.3 Scenario c

5.4.3.1 Scenario c.1

For period 0, as there is no injected energy that can be accounted, the equation required is (24) but it is used for period 0 only.

$$\text{Energy Cost (€)}_{\text{period 0}} = \sum_{j} (Grid_{Consumption\ j} * Tariff_{per\ hour\ j}) \tag{24}$$

From period 1 to period 8, the equations applied are (25) and (26), depending on two constraints. If, in a certain day, total consumption is bigger than exported energy, the equation that is applied is (25). But if exported energy is bigger than total consumption, the equation that is applied is (26). With equation (27) is obtained the value for the whole week.

$$\begin{aligned}\text{Energy Cost (€)}_{period\ k} &= Exported_{energy\ k-1} * Tariff_{Subsidized\ per\ hour} \\ &+ \sum_j \big((Grid_{Consumption\ kj} - Exported_{Energy\ k-1}\big) \\ &* Tariff_{per\ hour\ j}\big)\end{aligned} \tag{25}$$

$$\text{Energy Cost (€)}_{period\ k} = Grid_{Consumption\ k} * Tariff_{Subsidized\ per\ hour} \tag{26}$$

$$\begin{aligned}\text{Energy Cost (€)}_{week\ sample} \\ = \sum_k (Energy\ Cost\ (€)_{period\ k} + Energy\ Cost\ (€)_{period\ 0})\end{aligned} \tag{27}$$

,where k ϵ K={1,2,3,4,5,6,7,8} periods and j ϵ J={off-peak, mid-peak, peak} hours

To extrapolate the value obtained for the example week into an annual value, equation (5), presented above, is applied.

5.4.3.2 Scenario c.2

As in all scenarios, the equation for day 1 is different from the others. In this scenario, the equation for the cost of energy on day 6 is shown in (28).

$$\text{Energy Cost (€)}_{day6} = \sum_j Grid_{Consumption\ i} * Tariff_{per\ hour\ j} \tag{28}$$

,where j ϵ J={off-peak, mid-peak, peak} hours

Scenario c.2 is divided into two scenarios, c.2.1 and c.2.2, where peak and mid-peak hours are preferred, respectively. However, for both, the value of the week sample is calculated in the same way, as shown in (29), and to obtain the annual value, the equation to be used remains (5).

$$\begin{aligned}\text{Energy Cost (€)}_{week\ sample} \\ = \sum_z (\,Energy\ Cost\ (€)\ _{day\ z} + Energy\ Cost(€)_{day6})\end{aligned} \tag{29}$$

,where z ϵ Z={7,8,9,10,11,12,13} days

5.4.3.2.1 Scenario c.2.1

For the following days, the equations that can be applied are (30), (31) or (32), depending on two conditions and then two hypotheses.

If, per day, the energy consumed at peak hours is higher than the energy injected, the equation to be used is (30). However, if the energy injected is higher than the energy consumed at peak hours, there are two hypotheses. The 1st hypothesis is shown in (31) and the 2nd hypothesis is shown in (32). Note that in the 1st hypothesis $Exported_{Energy} = Grid_{Consumption\ Peak}$.

$$\begin{aligned}\text{Energy Cost }(€)_{Day\ z} &= Grid_{Consumption\ off-peak\ z} * Tariff_{Off-peak\ hours} \\ &+ Exported_{Energy\ z-1} * Tariff_{subsidized\ per\ hour} \\ &+ \left(Grid_{Consumption\ Peak\ \mathrm{z}} - Exported_{Energy\ z-1}\right) \\ &* Tariff_{Peak\ hours} + Grid_{Consumption\ Mid-peak\ z} \\ &* Tariff_{Mid-peak\ hours}\end{aligned} \tag{30}$$

$$\begin{aligned}\text{Energy Cost }(€)_{Day\ z} &= Grif_{Consumption\ off-peak\ z} * Tariff_{Off-peak\ hours} \\ &+ Grid_{Consumption\ peak\ z} * Tariff_{Subsidized\ per\ hour} \\ &+ Grid_{Consumption\ Mid-peak\ z} * Tariff_{Mid-peak\ hours}\end{aligned} \tag{31}$$

$$\begin{aligned}\text{Energy Cost }(€)_{Day\ z} &= Grif_{Consumption\ off-peak\ z} * Tariff_{Off-peak\ hours} \\ &+ Grid_{Consumption\ peak\ z} * Tariff_{Subsidized\ per\ hour} \\ &+ \left(Exported_{Energy\ z-1} - Grid_{Consumption\ peak\ z}\right) \\ &* Tariff_{Subsidized\ per\ hour} \\ &+ \Big(Grid_{Consumption\ Mid-peak\ z} \\ &- \left(Exported_{Energy\ z-1} - Grid_{Consumption\ peak\ z}\right)\Big) \\ &* Tariff_{Mid-peak\ hours}\end{aligned} \tag{32}$$

,where z ϵ Z={7,8,9,10,11,12,13} days

5.4.3.2.2 Scenario c.2.2

As in the previous scenario, for the following days, the equations that could be applied are (33), (34) or (35), depending on two constraints and then two hypotheses.

If, per day, the energy consumed in mid-peak hours is higher than the energy injected, the equation to be used is (33). However, if the energy injected is higher than the energy consumed in peak hours, two hypotheses arise. The 1st hypothesis is shown in (34) and the 2nd hypothesis is shown in (35). Note that in the 1st hypothesis $Exported_{Energy} = Grid_{Consumption\ \mathrm{Mid-}peak}$.

$$\begin{aligned}\text{Energy Cost }(€)_{Day\ z} &= Grid_{Consumption\ off-peak\ z} * Tariff_{Off-peak\ hours} \\ &+ Exported_{Energy\ z-1} * Tariff_{subsidized\ per\ hour} \\ &+ \left(Grid_{Consumption\ \mathrm{Mid-}Peak\ z} - Exported_{Energy\ z-1}\right) \\ &* Tariff_{Mid-Peak\ hours} + Grid_{Consumption\ \mathrm{Peak}\ z} \\ &* Tariff_{Peak\ hours}\end{aligned} \tag{33}$$

$$\begin{aligned}\text{Energy Cost }(€)_{Day\ z} &= Grif_{Consumption\ off-peak\ z} * Tariff_{Off-peak\ hours} \\ &+ Grid_{Consumption\ \mathrm{mid-}peak\ z} * Tariff_{Subsidized\ per\ hour} \\ &+ Grid_{Consumption\ \mathrm{Peak}\ z} * Tariff_{Peak\ hours}\end{aligned} \tag{34}$$

$$\begin{aligned}\text{Energy Cost (€)}_{Day\ z} \\ &= Grid_{Consumption\ off-peak\ z} * Tariff_{Off-peak\ hours} \\ &+ Grid_{Consumption\ \text{Mid}-peak\ z} * Tariff_{Subsidized\ per\ hour} \\ &+ \left(Exported_{Energy\ z-1} - Grid_{Consumption\ \text{Mid}-peak\ z}\right) \\ &* Tariff_{Subsidized\ per\ hour} \\ &+ \Big(Grid_{Consumption\ peak\ z} \\ &- \left(Exported_{Energy\ z-1} - Grid_{Consumption\ \text{Mid}-peak\ z}\right)\Big) \\ &* Tariff_{Peak\ hours}\end{aligned} \tag{35}$$

,where z ϵ Z={7,8,9,10,11,12,13} days

5.5 Economical Study

To develop the economic study for the best result, the payback, net present value (NPV), internal rate of return (IRR) and the profitability index (PI) of the investment were calculated, through the equations (36), (37), (38) and (39), respectively.

To calculate the NPV, a previous calculation is required to obtain the net cash flow per year, calculated using the annual revenue and the operation and maintenance (O&M) costs: $C_y = Revenue_y - O\&M$.

$$Payback = \frac{\ln\frac{C_y}{(C_y - a \cdot I)}}{\ln(1+a)} \tag{36}$$

$$NPV = \sum_{y=1}^{25} \frac{C_y}{(1+a)^y} - \sum_{y=0}^{24} \frac{I}{(1+a)^y} \tag{37}$$

$$\sum_{y=1}^{25} \frac{C_y}{(1+IRR)^y} - \sum_{y=0}^{24} \frac{I}{(1+IRR)^y} = 0 \tag{38}$$

$$PI = \frac{NPV + I}{I} \tag{39}$$

,where y ϵ Y={1,2,3,….,25} years

a- Refresh rate (5%)

I- Initial Investment Cost

5.6 Conclusions

The mathematical formulation used throughout the study is presented in this chapter.

The first sub-section presents the calculations required to complete the database needed to carry out the studies for each scenario.

In the second sub-section, the entire mathematical formulation required for each scenario of the case study in practice is detailed.

In the third sub-section, the equations needed to obtain economic results are presented, to understand whether this new approach to photovoltaic energy self-consumption is economically beneficial for the customer.

6 Case Study and Results

This chapter implements and analyzes the methodology that was suggested in chapter 5. The two case study scenarios for this thesis are explained, and next the results are presented and discussed.

6.1 Scenarios Description

To obtain comparative results and reach conclusions, two scenarios were developed. To simplify understanding of the two scenarios, both of them are represented in Table 7.

Table 7- Representation of the scenarios and sub-scenarios created

	Scenario 1	Scenario 2
A- Flat Tariff		.1- Subsidized tariff is applied when PV generation stops
		.2- Subsidized tariff is only applied in the next day
B- Bi-Hourly Tariff		.1
		.2 h1- Subsidized tariff is applied in Peak and Off-peak periods h2- Subsidized tariff is applied only in Peak periods
C- Tri-Hourly Tariff		.1
		.2 .2.1- Subsidized tariff is applied with priority in Peak periods h1- Only applied in Peak periods h2- Applied in Peak and Mid-Peak periods .2.2- Subsidized tariff is applied with priority in Mid-peak periods h1- Only applied in Mid-peak periods h2- Applied in Mid-peak and Peak periods

6.1.1 Scenario 1

In Scenario 1, the weekly and then annual energy costs were obtained under the normal cost of energy per kWh, depending on the type of tariff, not applying the subsidized tariff. Thus, in this scenario, the energy injected into the grid is not repaid.

Scenario 1 is divided into three sub-scenarios, each reflecting a different type of tariff option. Scenario 1.a considers the flat tariff, Scenario 1.b considers the bi-hourly tariff and Scenario 1.c considers the three-hourly tariff.

This scenario was developed to compare it with scenario 2, which is the main case study in this thesis. By comparing the two scenarios, it is possible to understand whether the proposal in this work is advantageous and, if so, how advantageous it is.

6.1.2 Scenario 2

In scenario 2, the cost of weekly and then annual energy was obtained by considering the normal energy cost of per kWh, but also considering the subsidized tariff. The subsidized tariff is applied based on the amount of energy injected into the grid, allowing the customer to have the same amount of energy at a reduced price when they need energy from the grid. The method of applying the reduced tariff depends on the various scenarios created throughout the study. However, in all scenarios, the amount of energy available at a reduced price is the amount of energy injected into the grid during the previous period or day to which the reduced tariff will be applied.

As in scenario 1, sub-scenarios 2.a, 2.b and 2.c differ in the type of tariff option, following the same order. This means that in sub-scenario 2.a the flat tariff is applied, in 2.b the bi-hourly tariff is applied and in 2.c the tri-hourly tariff is applied.

Since the subsidized tariff is applied in scenario 2, two options have emerged for starting to consume energy at a reduced price. For this reason, sub-scenarios a/b/c.1 and a/b/c.2 were created. To simplify understanding Scenario 2 and the sub-scenarios that needed to be created, they are represented in the Figure 18.

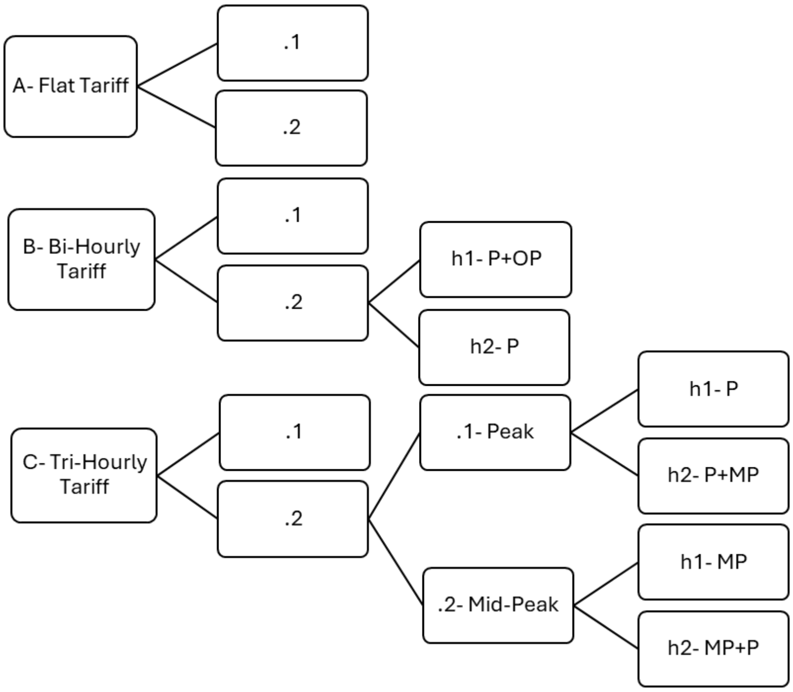


Figure 18- Representation of scenario 2 and sub-scenarios created

In sub-scenarios a/b/c.1, it is considered that energy can start to be consumed at a reduced price from the moment PV generation stops until the moment PV generation stops the next day. For this reason, in the mathematical formulation of these sub-scenarios, periods are referenced instead of days. Period 0 refers to April 6th from 00h01 until the moment PV generation stops, with no reduced-price energy to consider for this day. From this moment, period 1 is considered until PV generation stops on April 7th, and so on for the remaining periods.

In sub-scenarios a/b/c.2, it is considered that energy can only be consumed at a reduced price the following day. For this reason, in the mathematical formulation, there is a reference to the days of the week, from April 6th to April 13th, which are considered in the study as an example week.

Due to the different tariff options that have different prices in their periods, there was a need to create other sub-scenarios and hypotheses within sub-scenarios b/c.2 to address all the possible occurrences, even if they do not happen in the current study and, therefore, don't affect the result.

6.1.2.1 Sub-Scenario b.2

In this sub-scenario, the priority is for the reduced-price energy to be applied at times when energy is more expensive, during Peak periods, so that the customer can achieve greater savings. However, it may happen that the amount of energy injected is higher than the amount of energy consumed during Peak periods. For this reason, two hypotheses were considered.

In the first case, the energy at the subsidized price is first applied to Peak periods. However, if the amount of energy injected the previous day exceeds the amount of energy consumed in those periods, the remaining energy at the reduced price can be applied to the Off-Peak periods. This ensures that all the energy injected into the grid is repaid.

In the second hypothesis, it is assumed that the energy at reduced price can only be consumed during Peak periods, so that the remaining energy is not repaid and is instead offered to the grid.

6.1.2.2 Sub-Scenario c.2

In this sub-scenario, it was necessary to create two more sub-scenarios c.2.1 and c.2.2, since we can have two priorities where the reduced-price energy can be applied. So, for sub-scenario c.2.1, the priority is for the reduced-price energy to be applied during the hours when energy is most expensive, which is the Peak period. However, as there are more Mid-Peak hours, for sub-scenario c.2.2, it was considered that the priority is for energy at the subsidized price to be applied in these hours. Even though it may not be the period with the highest energy cost, it may be more advantageous for the customer.

Similar to the explanation provided in the previous point, it's possible that the amount of energy injected exceeds the amount consumed during Peak or Mid-Peak periods, for their respective sub-scenarios. For this reason, two additional hypotheses were considered for both sub-scenarios.

In the first hypothesis, the reduced-price energy is first and only applied to the Peak or Mid-Peak periods, for their respective sub-scenarios. If the amount of injected energy exceeds the amount consumed from the grid during these periods, any remaining energy is not repaid.

In the second hypothesis, the discounted-price energy is first applied to the Peak or Mid-Peak periods, depending on the specific sub-scenario. If the amount of discounted-price energy is not fully utilized during these periods, it can then be consumed during the Mid-Peak or Peak periods, respectively, which means that all the energy injected into the grid is repaid.

6.1.3 Economical Study

To visualize the economic impact that the case study has on the investment in the photovoltaic system for self-consumption, an economic study was carried out for the scenario with the best result. To do this, the payback, NPV, IRR and PI of the project were calculated, considering that the annual revenue is constant and is the best annual energy cost savings value obtained, the refresh rate is 5% since it is the value normally used in PV systems studies, the real annual investment costs of O&M are €150 and the real initial investment in the PV system was 11 000€. In addition, the lifetime project is set at 25 years, as this is the estimated lifespan of a PV system.

As the NPV and IRR results are positive and the PI is higher than 1, the project recovers the amount invested and generates a profit, making it an economically viable project.

6.2 Discussion of Results

The results of each scenario are shown in this section, alongside with some observations.

6.2.1 Scenario 1

In scenario 1, energy costs were calculated considering only the standard energy price per kwh, differentiating between the sub-scenarios solely by the type of tariff option. Thus, by applying the calculations presented in the mathematical formulation, which take into account the amount of energy coming from the grid and in which tariff period it was consumed, the results shown in Table 8 were obtained.

Table 8- Weekly and annual results obtained for scenario 1

	Scenario 1		
	1.a) Flat Tariff	**1.b) Bi-hourly Tariff**	**1.c) Tri-hourly Tariff**
Week Sample Results	60.95 €	61.65 €	61.68 €
Year Results based on Week Sample	3 169.65 €	3 205.70 €	3 207.23 €

Given these results, it's possible to understand that, considering the energy consumption from the grid of the example customer considered, the best tariff option would be the flat one, with only 1 period during the day and no differentiation in energy prices. Although the difference in results between the various scenarios is not very significant.

This happens because, despite photovoltaic generation and the energy consumed from it, there is a significant energy consumption during the day. This means that, especially on days with lower photovoltaic generation, the amount of energy consumed from the grid is higher during the day. For this reason, in the week used as an example, about 50% of the energy from the grid is consumed in the Mid-Peak period, which makes the simple tariff option the most economical for the customer. Figure 19 shows the total energy consumed from the grid in the example week, by time period.

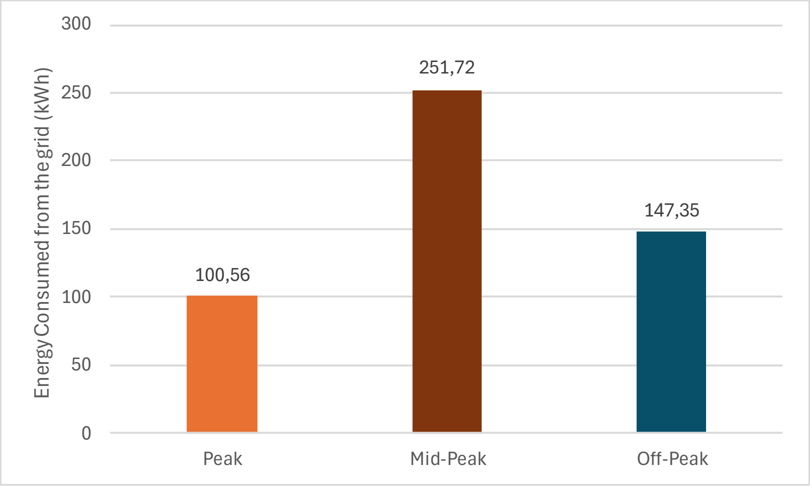


Figure 19- Energy consumed from the grid, in the example week, by hourly period

6.2.2 Scenario 2

In scenario 2, the energy costs were calculated not only considering the normal energy price per kwh, differentiated by the type of tariff option, but also the subsidized tariff that can be applied in different ways depending on the sub-scenario in question. By applying the calculations presented in chapter 5, which take into account the amount of energy sourced from the grid, in which tariff period it was consumed and also the amount of energy produced by the PV system that was injected into the grid, the results shown in Table 9 were obtained.

Table 9- Weekly and annual results obtained for scenario 2

	Scenario 2					
	2.a) Flat Tariff		**2.b) Bi-hourly Tariff**		**2.c) Tri-hourly Tariff**	
Week Sample Results	.1)	42.02 €	.1)	43.65 €	.1)	43.46 €
					.2.1.h1)	52.74 €
			.2.h1)	41.54 €	.2.1.h2)	41.93 €
	.2)	42.60 €	.2.h2)	41.54 €	.2.2.h1)	43.85 €
					.2.2.h2)	41.88 €
Year Results based on Week Sample	.1)	2185.26 €	.1)	2 270.00 €	.1)	2 259.83 €
					.2.1.h1)	2 742.61 €
			.2.h1)	2 159.89 €	.2.1.h2)	2 180.56 €
	.2)	2 215.36 €	.2.h2)	2 159.89 €	.2.2.h1)	2 280.04 €
					.2.2.h2)	2 177.75 €

Observing the results, for the sub-scenario developed with the flat tariff option, the two results are very similar. This occurs because, due to the times when the subsidized tariff can be applied, the quantities of reduced-price energy considered differ from one sub-scenario to the other. Therefore, it is possible to understand that there is more injected energy being considered in the sub-scenario where the subsidized tariff can be applied as soon as the PV generation stops. Since the simple tariff has only one rate throughout the day, it makes sub-scenario 2.a.1 more advantageous for the customer.

For the sub-scenario where the bi-hourly tariff option was applied, it is evident that there is an advantage for the customer when the subsidized energy price is only applied on the following day. This occurs because, if the reduced-price energy were applied from the moment the PV generation stops, most of the energy would be paid at the discounted price during the Off-peak period, resulting in lower savings and less benefit for the customer. This is because, as seen in Figure 19, most of the energy consumption from the grid is consumed during Peak periods, which does not take full advantage of the subsidized tariff at these times.

For the two hypotheses applied in sub-scenario 2.b.2, it is noticeable that they do not differ in their results since, for this specific case, the energy injected into the grid never exceeds the consumption during Peak hours. Therefore, the equation applied in this case is only (20), without the need to apply the equations defined in the hypotheses.

In the sub-scenario where the tri-hourly tariff option is applied, as expected, the results for the 2nd hypothesis are better than for the 1st hypothesis. This happens because the energy at a reduced price that would be "lost" to the grid in hypothesis 1 is applied in hypothesis 2 in another tariff period, ensuring that no energy goes unrepaid, bringing greater advantage and savings for the customer.

In the 1st hypothesis for sub-scenario 2.c.2.1, the result is so high because a lot of energy is being "lost" to the grid, with only one day where the amount of energy consumed from the grid during Peak hours is higher than the amount of energy injected into the grid the previous day. Furthermore, as we can see in Figure 19, only 20% of the energy is consumed during Peak hours. Therefore, the customer's benefit from this sub-scenario is the worst, despite the priority for applying the subsidized tariff being associated with the period with the highest tariff. Also, in sub-scenario 2.c.2.1, there is a significant difference in cost between the two hypotheses, considering that, for the second hypothesis, there is no longer any energy "lost" to the grid and the subsidized tariff is also applied in the period when there is the highest consumption.

Between the two values obtained in 2.c.2.1 and 2.c.2.2 in the 2nd hypotheses, there is a slight difference in their results precisely because of the priorities defined previously. Since there is more consumption at Mid-Peak times, the hypothesis with priority in the Mid-Peak periods achieves better results, resulting into more profitability for the customer.

Observing all the results obtained, it is possible to verify that the scenario with the best outcome is scenario 2.b.2, presenting a lower weekly and, consequently, annual cost compared to the other results.

6.2.3 Comparison of Scenarios

To obtain a comparison between the scenarios, the savings achieved when applying scenario 2 were calculated for each sub-scenarios in relation to scenario 1. For this purpose, the annual values obtained were used and the equation (40) was applied.

$$Savings_{Annual} = Scenario1_{result\ x} - Scenario2_{result\ x,w} \tag{40}$$

,where x ϵ X={a, b, c} and w={.1,.2,.2.h1,.2.h2,.2.1.h1,.2.1.h2,.2.2.h1,.2.2.h2} sub-scenarios

Table 10- Savings obtained by comparing the two scenarios presented

<table>
<tr><td></td><th colspan="6">Scenario 2</th></tr>
<tr><td></td><th colspan="2">2.a) Flat Tariff</th><th colspan="2">2.b) Bi-hourly Tariff</th><th colspan="2">2.c) Tri-hourly Tariff</th></tr>
<tr><th rowspan="7">Savings - Year Results</th><td rowspan="4">.1)</td><td rowspan="4">984.39 €</td><td rowspan="2">.1)</td><td rowspan="2">935.70 €</td><td>.1)</td><td>947.40 €</td></tr>
<tr><td rowspan="2">.2.1.h1)</td><td rowspan="2">464.63 €</td></tr>
<tr><td rowspan="3">.2.h1)</td><td rowspan="3">1 045.81 €</td></tr>
<tr><td rowspan="2">.2.1.h2)</td><td rowspan="2">1 026.67 €</td></tr>
<tr><td rowspan="3">.2)</td><td rowspan="3">954.29 €</td></tr>
<tr><td rowspan="2">.2.h2)</td><td rowspan="2">1 045.81 €</td><td>.2.2.h1)</td><td>927.19 €</td></tr>
<tr><td>.2.2.h2)</td><td>1 029.48 €</td></tr>
</table>

As expected, the best result achieved in terms of costs is also the best result in terms of savings. Therefore, in this specific example, by applying the bi-hourly tariff and ensuring that the energy consumed from the grid have a subsidized price for the same amount of energy injected into the grid the previous day, it is possible to obtain a saving of 1,045.81 € on the energy bill at the end of the year.

6.2.4 Economical Study

Given the best result obtained in the case study, the (constant) annual revenue to be considered for the economic study is 1 045.81 €.

Taking into account the initial investment, the (constant) annual revenue, the discount rate and the annual O&M expenses considered, the following results were obtained in the economic study:

NPV= 1 625€;

IRR= 6.43 %;

Payback= 19.5 years;

PI= 1.15.

Observing the results and considering that the NPV and IRR values are positive, that the PI is greater than 1 and that the payback is less than the time considered for the investment (25 years), it's possible to conclude that, for the case study in question, the project is economically viable.

6.3 Conclusions

In this chapter, the results of each scenario were presented. Weekly and annual electricity costs were calculated for the two scenarios to understand the potential savings that could exist by applying scenario 2 in energy billing when there is a photovoltaic system with surpluses to be injected into the grid. Following the results obtained, economic indices were calculated to determine whether the case study actually has any economic interest.

According to the results, in scenario 1, despite being developed to able comparison with scenario 2 to determine possible savings, it is clear that, for the customer used as an example and based on their consumption history, the tariff option that is most suitable is the flat tariff.

According to the results obtained in scenario 2, it is possible to understand that the tariff that obtains the best results and the greatest savings is the bi-hourly tariff, since injection into the grid allows to have energy from the grid at a reduced cost. Therefore, although when the energy injected into the grid is not in question, the best tariff option is the simple one, when the energy injected into the grid is in question, the best option becomes the bi-hourly one.

Through this study, it is possible to understand the impact that different tariff options have when the case study is applied. Additionally, by using the electricity grid as a storage battery for the surpluses produced, it is possible to obtain savings when energy from the grid is needed and, as the proposal is for the reduced tariff to, at least, cover the use of the grid costs, the maintenance of the grid is not impacted negatively by the lower cost of energy.

Furthermore, since this case study is associated with a simple, less administrative process and does not require an extra contract compared to the surplus sales contracts currently in practice, it becomes an incentive for the sale of surpluses and the installation of photovoltaic systems for energy generation, allowing for a lower investment, since there is no need to invest in storage batteries. As a result, it will increase the renewable energy available on the grid, helping to achieve the targets set under NECP2030.

7 Conclusions

This chapter summarizes this thesis and states the main conclusions about the implemented case study. Also, the contributions, some limitations found along the developed work and a few suggestions for future research work, aligned with the results obtained in this thesis are identified.

7.1 Final Conclusions

Increasing decentralized energy generation will have a fundamental effect on the energy transition. By increasing energy generation from renewable sources, it will reduce dependence on fossil fuels, promoting energy dependence and helping Portugal and the EU to achieve the targets set for 2030.

By promoting and encouraging the installation of solar PV systems, it is possible to increase decentralized energy generation, with energy consumers themselves becoming producers and participants in the energy transition, also increasing self-consumption and, through the surpluses produced and injected into the grid, increasing the amount of energy produced by renewable sources available for consumption.

Through the case study developed and studied throughout this work, a new approach to self-consumption is presented, focusing on the sale of surpluses produced by residential photovoltaic systems. This new approach proposes a new way of selling the surpluses produced in a way that is less time-consuming, less bureaucratic and more practical for everyone. Currently, through the surplus sales contract in practice and due to the low prices paid for the generation of this energy, some customers choose not to sell surpluses to the grid, as it is not economically advantageous for them, opting instead to install storage batteries.

The case study presented proposes that generation surpluses continue to be injected into the grid, but with the grid acting as an energy storage battery. It will work like a battery since, when the customer needs energy from the grid, they will have the same amount of injected energy available on the grid at a reduced price compared to the price normally charged. In this case study, the costs of using the grid are guaranteed so that the maintenance of the grid is not affected, as it is extremely important.

To develop the case study, it was necessary to create various scenarios and sub-scenarios, taking into account the three existing tariff options and also how and when the reduced tariff could be applied to the energy consumed from the grid.

At the end of the study, it can be concluded that, despite the various limitations, this could be a good proposal for selling surpluses to the grid since, by comparing the final results of the two scenarios developed, it was possible to see that there are good savings for the customer in terms of energy costs.

7.2 Contributions

To carry out this work and to achieve the outlined objectives in order to identify solar PV generation technologies, the current legislation on shared generation, self-consumption and electricity communities, it was necessary to conduct research on the subject. In particular, research on how the generation of renewable and decentralized energy, such as residential solar energy generation, can help to achieve the targets set for Portugal and Europe for 2030, the challenges that the integration of solar energy presents to the electricity grid and how to reduce the impact of these challenges, the technologies and components associated with energy generation through photovoltaic systems and, perhaps the most extensive research, on the legislation applied in Portugal and Europe for energy generation for self-consumption and energy communities.

In order to achieve the objective of proposing a new form of technical relationship between prosumers and the grid/supplier, this new approach to self-consumption has been proposed. It brings a new way of relating between the prosumer and the energy supplier, making the sale of surplus produced by self-consumption systems less bureaucratic and more practical for both sides.

To complete the remaining objectives, such as computer simulation of case studies applied to the residential sector and economic feasibility analysis, a comprehensive methodology was developed and implemented to support the conducted case studies. This required data collection for analysis, as well as data preprocessing and treatment, which were crucial for carrying out the work and ensuring the reliability of the results. Due to data protection concerns, the presentation of the collected data and, essentially, the simulation of the photovoltaic system used for the study had to be handled with greater care.

Finally, to demonstrate the entire development of the work, the results obtained, the analyses conducted, and the conclusions drawn, the entire dissertation was written.

7.3 Limitations and Future Work

Some limitations were encountered during the development of the case study:

- In the energy prices considered, both for the normal price of energy consumed from the grid and for the price of the subsidized tariff, fees and taxes associated with energy consumption, commercial margins, the costs associated with services and equipment and the Value Added Tax (VAT) were not considered. For the normal price of energy consumed from the grid, only the energy price suggested by ERSE for the year 2024 was considered and, for the subsidized tariff, only the cost of using the grids was considered.
- Solar energy generation is influenced by environmental factors, such as time of day, the availability of sunlight and weather conditions, causing energy generation to vary throughout the day. This means that the results can vary considerably, since the amount of energy that will have a reduced cost depends directly on the amount of energy injected into the grid, which in turn depends not only on energy consumption but also on the energy produced by the PV system.
- The study was applied by taking into account only one example week, and the annual value was extrapolated, making the result limited and slightly unrealistic.

Given these limitations, future work could essentially involve applying the study for a month or even several months in order to obtain average values that are closer to reality and, consequently, obtain more realistic savings results. Furthermore, if the proposed case study were to be put into practice in reality, energy cost billing would continue to be monthly, so instead of applying the reduced energy price based on the energy injected the previous day, it would make more sense to take into account the energy injected in the previous month or even in the month itself.

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Appendix A. Database

							Tariff						
							Flat		Bi-Hourly		Tri-Hourly		Subsidized
Statistical Period	PV Yield (kWh)	Export (kWh)	Import (kWh)	Total Consumption (kWh)	PV Consumption	Grid Consumption	Period?	€/kWh?	Period?	€/kWh?	Perriod?	€/kWh?	€/kWh?
06/04/2024 00:00:00 DST	0	0	4,13	4,13	0	4,13	S	0,122	V	0,1071	VN	0,1071	0,0365
06/04/2024 01:00:00 DST	0	0	1,93	1,93	0	1,93	S	0,122	V	0,1071	VN	0,1071	0,0365
06/04/2024 02:00:00 DST	0	0	1,67	1,67	0	1,67	S	0,122	V	0,1071	VN	0,1071	0,0365
06/04/2024 03:00:00 DST	0	0	1,98	1,98	0	1,98	S	0,122	V	0,1071	VN	0,1071	0,0365
06/04/2024 04:00:00 DST	0	0	1,56	1,56	0	1,56	S	0,122	V	0,1071	VN	0,1071	0,0365
06/04/2024 05:00:00 DST	0	0	1,31	1,31	0	1,31	S	0,122	V	0,1071	VN	0,1071	0,0365
06/04/2024 06:00:00 DST	0	0	1,46	1,46	0	1,46	S	0,122	V	0,1071	VN	0,1071	0,0365
06/04/2024 07:00:00 DST	0,01	0	3,33	3,34	0,01	3,33	S	0,122	V	0,1071	VN	0,1071	0,0365
06/04/2024 08:00:00 DST	0,11	0	6,65	6,76	0,11	6,65	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 09:00:00 DST	0,53	0	1,73	2,26	0,53	1,73	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 10:00:00 DST	1,25	0,31	0,06	1,31	0,94	0,37	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 11:00:00 DST	2,32	1,06	0,79	3,11	1,26	1,85	S	0,122	FV	0,1302	P	0,1360	0,0365
06/04/2024 12:00:00 DST	4,3	3,26	0	4,3	1,04	3,26	S	0,122	FV	0,1302	P	0,1360	0,0365
06/04/2024 13:00:00 DST	3,53	2,09	0,4	3,93	1,44	2,49	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 14:00:00 DST	2,83	1,53	0,13	2,96	1,3	1,66	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 15:00:00 DST	3,58	1,19	0,08	3,66	2,39	1,27	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 16:00:00 DST	3,41	1,25	0,83	4,24	2,16	2,08	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 17:00:00 DST	3,5	2,28	0	3,5	1,22	2,28	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 18:00:00 DST	2,1	0,84	0,09	2,19	1,26	0,93	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 19:00:00 DST	0,89	0	1,95	2,84	0,89	1,95	S	0,122	FV	0,1302	C	0,1280	0,0365
06/04/2024 20:00:00 DST	0,01	0	3,07	3,08	0,01	3,07	S	0,122	FV	0,1302	P	0,1360	0,0365
06/04/2024 21:00:00 DST	0	0	2,37	2,37	0	2,37	S	0,122	FV	0,1302	P	0,1360	0,0365
06/04/2024 22:00:00 DST	0	0	2,77	2,77	0	2,77	S	0,122	V	0,1071	VN	0,1071	0,0365
06/04/2024 23:00:00 DST	0	0	3,25	3,25	0	3,25	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 00:00:00 DST	0	0	1,79	1,79	0	1,79	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 01:00:00 DST	0	0	1,54	1,54	0	1,54	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 02:00:00 DST	0	0	1,36	1,36	0	1,36	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 03:00:00 DST	0	0	1,37	1,37	0	1,37	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 04:00:00 DST	0	0	1,46	1,46	0	1,46	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 05:00:00 DST	0	0	1,46	1,46	0	1,46	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 06:00:00 DST	0	0	1,4	1,4	0	1,4	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 07:00:00 DST	0,21	0	1,54	1,75	0,21	1,54	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 08:00:00 DST	0,81	0,1	1,62	2,43	0,71	1,72	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 09:00:00 DST	2,91	0,7	0,98	3,89	2,21	1,68	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 10:00:00 DST	4,76	2,74	0,61	5,37	2,02	3,35	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 11:00:00 DST	7,07	3,03	0,96	8,03	4,04	3,99	S	0,122	FV	0,1302	P	0,1360	0,0365
07/04/2024 12:00:00 DST	9,04	4,47	0,08	9,12	4,57	4,55	S	0,122	FV	0,1302	P	0,1360	0,0365
07/04/2024 13:00:00 DST	7,88	5,47	0	7,88	2,41	5,47	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 14:00:00 DST	7,71	6,54	0	7,71	1,17	6,54	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 15:00:00 DST	6,2	3,66	0	6,2	2,54	3,66	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 16:00:00 DST	3,66	1,75	0,08	3,74	1,91	1,83	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 17:00:00 DST	1,66	0,44	0,17	1,83	1,22	0,61	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 18:00:00 DST	1,23	0,06	1,83	3,06	1,17	1,89	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 19:00:00 DST	0,3	0	1,94	2,24	0,3	1,94	S	0,122	FV	0,1302	C	0,1280	0,0365
07/04/2024 20:00:00 DST	0	0	1,67	1,67	0	1,67	S	0,122	FV	0,1302	P	0,1360	0,0365
07/04/2024 21:00:00 DST	0	0	3,81	3,81	0	3,81	S	0,122	FV	0,1302	P	0,1360	0,0365
07/04/2024 22:00:00 DST	0	0	3,77	3,77	0	3,77	S	0,122	V	0,1071	VN	0,1071	0,0365
07/04/2024 23:00:00 DST	0	0	1,94	1,94	0	1,94	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 00:00:00 DST	0	0	1,71	1,71	0	1,71	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 01:00:00 DST	0	0	1,5	1,5	0	1,5	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 02:00:00 DST	0	0	1,43	1,43	0	1,43	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 03:00:00 DST	0	0	2,48	2,48	0	2,48	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 04:00:00 DST	0	0	1,44	1,44	0	1,44	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 05:00:00 DST	0	0	2,92	2,92	0	2,92	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 06:00:00 DST	0	0	3,58	3,58	0	3,58	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 07:00:00 DST	0,14	0	1,48	1,62	0,14	1,48	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 08:00:00 DST	0,27	0	2,19	2,46	0,27	2,19	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 09:00:00 DST	0,44	0	2,41	2,85	0,44	2,41	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 10:00:00 DST	2,02	0,69	1,21	3,23	1,33	1,9	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 11:00:00 DST	4,76	1,31	1,31	6,07	3,45	2,62	S	0,122	FV	0,1302	P	0,1360	0,0365
08/04/2024 12:00:00 DST	7,18	2,31	1,21	8,39	4,87	3,52	S	0,122	FV	0,1302	P	0,1360	0,0365
08/04/2024 13:00:00 DST	7,9	3,79	0,44	8,34	4,11	4,23	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 14:00:00 DST	7,44	4,92	0,06	7,5	2,52	4,98	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 15:00:00 DST	6,49	4,79	0	6,49	1,7	4,79	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 16:00:00 DST	6,52	3,41	0,08	6,6	3,11	3,49	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 17:00:00 DST	3,41	1,15	0,36	3,77	2,26	1,51	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 18:00:00 DST	1,86	0,59	0,52	2,38	1,27	1,11	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 19:00:00 DST	0,57	0,03	2,06	2,63	0,54	2,09	S	0,122	FV	0,1302	C	0,1280	0,0365
08/04/2024 20:00:00 DST	0	0	2,21	2,21	0	2,21	S	0,122	FV	0,1302	P	0,1360	0,0365
08/04/2024 21:00:00 DST	0	0	4,04	4,04	0	4,04	S	0,122	FV	0,1302	P	0,1360	0,0365
08/04/2024 22:00:00 DST	0	0	3,79	3,79	0	3,79	S	0,122	V	0,1071	VN	0,1071	0,0365
08/04/2024 23:00:00 DST	0	0	2,09	2,09	0	2,09	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 00:00:00 DST	0	0	3,43	3,43	0	3,43	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 01:00:00 DST	0	0	2,65	2,65	0	2,65	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 02:00:00 DST	0	0	1,61	1,61	0	1,61	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 03:00:00 DST	0	0	1,43	1,43	0	1,43	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 04:00:00 DST	0	0	1,5	1,5	0	1,5	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 05:00:00 DST	0	0	1,42	1,42	0	1,42	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 06:00:00 DST	0	0	1,37	1,37	0	1,37	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 07:00:00 DST	0,37	0	1,8	2,17	0,37	1,8	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 08:00:00 DST	1,99	0,34	0,89	2,88	1,65	1,23	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 09:00:00 DST	4,25	0,89	1,9	6,15	3,36	2,79	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 10:00:00 DST	6,44	4,34	0	6,44	2,1	4,34	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 11:00:00 DST	7,78	5,96	0,04	7,82	1,82	6	S	0,122	FV	0,1302	P	0,1360	0,0365
09/04/2024 12:00:00 DST	8,88	4,11	0,06	8,94	4,77	4,17	S	0,122	FV	0,1302	P	0,1360	0,0365
09/04/2024 13:00:00 DST	9,55	7,16	0	9,55	2,39	7,16	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 14:00:00 DST	9,48	7,7	0	9,48	1,78	7,7	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 15:00:00 DST	8,39	6,28	0	8,39	2,11	6,28	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 16:00:00 DST	6,5	3,1	0	6,5	3,4	3,1	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 17:00:00 DST	4,06	1,78	0,08	4,14	2,28	1,86	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 18:00:00 DST	2,56	1,08	0,92	3,48	1,48	2	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 19:00:00 DST	0,72	0	3,19	3,91	0,72	3,19	S	0,122	FV	0,1302	C	0,1280	0,0365
09/04/2024 20:00:00 DST	0	0	2,04	2,04	0	2,04	S	0,122	FV	0,1302	P	0,1360	0,0365
09/04/2024 21:00:00 DST	0	0	3,77	3,77	0	3,77	S	0,122	FV	0,1302	P	0,1360	0,0365
09/04/2024 22:00:00 DST	0	0	4,61	4,61	0	4,61	S	0,122	V	0,1071	VN	0,1071	0,0365
09/04/2024 23:00:00 DST	0	0	2,14	2,14	0	2,14	S	0,122	V	0,1071	VN	0,1071	0,0365

10/04/2024 00:00:00 DST	0	0	1,67	1,67	0	1,67	S	0,122	V	0,1071	VN	0,1071	0,0365
10/04/2024 01:00:00 DST	0	0	1,5	1,5	0	1,5	S	0,122	V	0,1071	VN	0,1071	0,0365
10/04/2024 02:00:00 DST	0	0	1,52	1,52	0	1,52	S	0,122	V	0,1071	VN	0,1071	0,0365
10/04/2024 03:00:00 DST	0	0	1,39	1,39	0	1,39	S	0,122	V	0,1071	VN	0,1071	0,0365
10/04/2024 04:00:00 DST	0	0	1,94	1,94	0	1,94	S	0,122	V	0,1071	VN	0,1071	0,0365
10/04/2024 05:00:00 DST	0	0	3,94	3,94	0	3,94	S	0,122	V	0,1071	VN	0,1071	0,0365
10/04/2024 06:00:00 DST	0	0	2,13	2,13	0	2,13	S	0,122	V	0,1071	VN	0,1071	0,0365
10/04/2024 07:00:00 DST	0,47	0	2,04	2,51	0,47	2,04	S	0,122	V	0,1071	VN	0,1071	0,0365
10/04/2024 08:00:00 DST	1,93	0,66	0,64	2,57	1,27	1,3	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 09:00:00 DST	4,04	1,49	0,98	5,02	2,55	2,47	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 10:00:00 DST	6,22	4	0	6,22	2,22	4	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 11:00:00 DST	7,62	3,51	0	7,62	4,11	3,51	S	0,122	FV	0,1302	P	0,1360	0,0365
10/04/2024 12:00:00 DST	8,37	2,88	0	8,37	5,49	2,88	S	0,122	FV	0,1302	P	0,1360	0,0365
10/04/2024 13:00:00 DST	9,05	5,91	0,02	9,07	3,14	5,93	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 14:00:00 DST	9	7,62	0	9	1,38	7,62	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 15:00:00 DST	7,89	3,71	0,02	7,91	4,18	3,73	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 16:00:00 DST	5,84	3,5	0	5,84	2,34	3,5	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 17:00:00 DST	3,4	2,31	0	3,4	1,09	2,31	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 18:00:00 DST	1,33	0,38	0,21	1,54	0,95	0,59	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 19:00:00 DST	0,44	0	1,65	2,09	0,44	1,65	S	0,122	FV	0,1302	C	0,1280	0,0365
10/04/2024 20:00:00 DST	0	0	3,29	3,29	0	3,29	S	0,122	FV	0,1302	P	0,1360	0,0365
10/04/2024 21:00:00 DST	0	0	4,23	4,23	0	4,23	S	0,122	FV	0,1302	P	0,1360	0,0365
10/04/2024 22:00:00 DST	0	0	3,33	3,33	0	3,33	S	0,122	V	0,1071	VN	0,1071	0,0365
10/04/2024 23:00:00 DST	0	0	2,48	2,48	0	2,48	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 00:00:00 DST	0	0	1,38	1,38	0	1,38	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 01:00:00 DST	0	0	1,48	1,48	0	1,48	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 02:00:00 DST	0	0	1,5	1,5	0	1,5	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 03:00:00 DST	0	0	1,41	1,41	0	1,41	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 04:00:00 DST	0	0	1,36	1,36	0	1,36	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 05:00:00 DST	0	0	1,37	1,37	0	1,37	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 06:00:00 DST	0	0	1,06	1,06	0	1,06	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 07:00:00 DST	0,4	0,01	1,11	1,51	0,39	1,12	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 08:00:00 DST	2,02	0,66	1,46	3,48	1,36	2,12	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 09:00:00 DST	4,23	1,31	0,14	4,37	2,92	1,45	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 10:00:00 DST	6,33	4,2	0	6,33	2,13	4,2	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 11:00:00 DST	7,9	2,72	0	7,9	5,18	2,72	S	0,122	FV	0,1302	P	0,1360	0,0365
11/04/2024 12:00:00 DST	8,8	3,5	0,02	8,82	5,3	3,52	S	0,122	FV	0,1302	P	0,1360	0,0365
11/04/2024 13:00:00 DST	9,16	6,19	0	9,16	2,97	6,19	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 14:00:00 DST	8,87	7,68	0	8,87	1,19	7,68	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 15:00:00 DST	7,71	4,83	0	7,71	2,88	4,83	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 16:00:00 DST	5,89	2,97	0	5,89	2,92	2,97	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 17:00:00 DST	3,63	2,49	0	3,63	1,14	2,49	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 18:00:00 DST	1,91	0,7	0,34	2,25	1,21	1,04	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 19:00:00 DST	0,61	0	1,31	1,92	0,61	1,31	S	0,122	FV	0,1302	C	0,1280	0,0365
11/04/2024 20:00:00 DST	0	0	1,73	1,73	0	1,73	S	0,122	FV	0,1302	P	0,1360	0,0365
11/04/2024 21:00:00 DST	0	0	3,66	3,66	0	3,66	S	0,122	FV	0,1302	P	0,1360	0,0365
11/04/2024 22:00:00 DST	0	0	2,8	2,8	0	2,8	S	0,122	V	0,1071	VN	0,1071	0,0365
11/04/2024 23:00:00 DST	0	0	3,06	3,06	0	3,06	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 00:00:00 DST	0	0	0	0	0	0	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 01:00:00 DST	0	0	0	0	0	0	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 02:00:00 DST	0	0	0	0	0	0	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 03:00:00 DST	0	0	0	0	0	0	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 04:00:00 DST	0	0	0	0	0	0	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 05:00:00 DST	0	0	0	0	0	0	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 06:00:00 DST	0	0	0	0	0	0	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 07:00:00 DST	0,36	0	0	0,36	0,36	0	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 08:00:00 DST	2,01	0,04	0	2,01	1,97	0,04	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 09:00:00 DST	4,19	1,44	0,08	4,27	2,75	1,52	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 10:00:00 DST	6,19	2,95	0	6,19	3,24	2,95	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 11:00:00 DST	7,6	2,88	0,02	7,62	4,72	2,9	S	0,122	FV	0,1302	P	0,1360	0,0365
12/04/2024 12:00:00 DST	8,47	3,47	0	8,47	5	3,47	S	0,122	FV	0,1302	P	0,1360	0,0365
12/04/2024 13:00:00 DST	9,12	5,13	0	9,12	3,99	5,13	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 14:00:00 DST	8,99	5,48	0	8,99	3,51	5,48	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 15:00:00 DST	7,81	4,51	0	7,81	3,3	4,51	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 16:00:00 DST	6,18	3,33	0	6,18	2,85	3,33	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 17:00:00 DST	3,78	2,5	0	3,78	1,28	2,5	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 18:00:00 DST	2,21	1,14	0,02	2,23	1,07	1,16	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 19:00:00 DST	0,54	0,04	2,42	2,96	0,5	2,46	S	0,122	FV	0,1302	C	0,1280	0,0365
12/04/2024 20:00:00 DST	0	0	2,04	2,04	0	2,04	S	0,122	FV	0,1302	P	0,1360	0,0365
12/04/2024 21:00:00 DST	0	0	1,73	1,73	0	1,73	S	0,122	FV	0,1302	P	0,1360	0,0365
12/04/2024 22:00:00 DST	0	0	2,08	2,08	0	2,08	S	0,122	V	0,1071	VN	0,1071	0,0365
12/04/2024 23:00:00 DST	0	0	2,96	2,96	0	2,96	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 00:00:00 DST	0	0	2,29	2,29	0	2,29	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 01:00:00 DST	0	0	1,44	1,44	0	1,44	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 02:00:00 DST	0	0	1,44	1,44	0	1,44	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 03:00:00 DST	0	0	1,47	1,47	0	1,47	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 04:00:00 DST	0	0	1,46	1,46	0	1,46	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 05:00:00 DST	0	0	2,32	2,32	0	2,32	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 06:00:00 DST	0	0	1,37	1,37	0	1,37	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 07:00:00 DST	0,46	0	1,6	2,06	0,46	1,6	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 08:00:00 DST	2,04	0	2,36	4,4	2,04	2,36	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 09:00:00 DST	4,07	2,13	0,08	4,15	1,94	2,21	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 10:00:00 DST	6,11	5,05	0	6,11	1,06	5,05	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 11:00:00 DST	7,6	3,49	0,02	7,62	4,11	3,51	S	0,122	FV	0,1302	P	0,1360	0,0365
13/04/2024 12:00:00 DST	8,63	4,66	0	8,63	3,97	4,66	S	0,122	FV	0,1302	P	0,1360	0,0365
13/04/2024 13:00:00 DST	8,95	6,48	0	8,95	2,47	6,48	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 14:00:00 DST	8,76	7,69	0	8,76	1,07	7,69	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 15:00:00 DST	7,87	4,44	0	7,87	3,43	4,44	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 16:00:00 DST	5,94	3,43	0	5,94	2,51	3,43	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 17:00:00 DST	3,58	2,52	0	3,58	1,06	2,52	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 18:00:00 DST	1,26	0,19	0,02	1,28	1,07	0,21	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 19:00:00 DST	0,35	0	2,42	2,77	0,35	2,42	S	0,122	FV	0,1302	C	0,1280	0,0365
13/04/2024 20:00:00 DST	0,01	0	2,04	2,05	0,01	2,04	S	0,122	FV	0,1302	P	0,1360	0,0365
13/04/2024 21:00:00 DST	0	0	1,73	1,73	0	1,73	S	0,122	FV	0,1302	P	0,1360	0,0365
13/04/2024 22:00:00 DST	0	0	2,08	2,08	0	2,08	S	0,122	V	0,1071	VN	0,1071	0,0365
13/04/2024 23:00:00 DST	0	0	2,96	2,96	0	2,96	S	0,122	V	0,1071	VN	0,1071	0,0365

ISEP INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

P.PORTO

DECLARAÇÃO DE INTEGRIDADE

DECLARAÇÃO DE INTEGRIDADE

Declaro ter conduzido este trabalho académico com integridade. Não plagiei ou apliquei qualquer forma de uso indevido de informações ou falsificação de resultados ao longo do processo que levou à sua elaboração.

Declaro que o trabalho apresentado neste documento é original e de minha autoria, não tendo sido utilizado anteriormente para nenhum outro fim.

Declaro ainda que tenho pleno conhecimento do Código de Conduta Ética do P.PORTO.

ISEP, Porto, 25 de junho de 2024

Joana Filipa Pinheiro Leite